Doctoral theses at NTNU, 2024:86

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Aspects of development strategy and design performance

ISBN 978-82-326-7766-8 (printed ver.)
ISBN 978-82-326-7766-5 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (electronic ver.)

Doctoral thesis

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NTNU
Norwegian University of Science and Technology
Thesis for the degree of Philosophiae Doctor
Faculty of Engineering
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PRINTED IN NORWAY
NO - 1598

NORDIC SWAN ECOLABEL
Printed matter
2041 0731

Printed by Skipnes Kommunikasjon AS

"Notwithstanding all the pains I have bestowed on its execution, I am fully aware of its numerous deficiencies and imperfections, and of its falling far short of the degree of excellence that might be attained. But, in a work of this nature, where perfection is placed at so great a distance, I have thought it best to limit my ambition to that moderate share of merit which it may claim in its present form; trusting to the indulgence of those for whose benefit it is intended, and to the candour of critics who, while they might find it easy to detect faults, can at the same time duly appreciate difficulties."

Peter Roget (1853) | [1]

Preface

This thesis is submitted in partial fulfilment of the requirements for the degree of Philosophiae doctor (PhD) at the Department of Mechanical and Industrial Engineering (MTP) at the Norwegian University of Science and Technology (NTNU). The research presented in this thesis is the result of doctoral studies being funded by the Norwegian Research Council under the KPN project Value. My supervisors have been Professor Geir Ringen (MTP, NTNU) and Professor Torgeir Welo (MTP, NTNU).

Acknowledgements

I would like to thank my supervisors Geir Ringen and Torgeir Welo for providing guidance and support throughout my work on this thesis. I am also grateful to Ruben Bjørge & Harald Vestøl for their trust and openness for my involvement in various endeavours that helped form this thesis. I would like to thank my co-authors Jørgen Sørhaug, Øystein Grong, Catalina H. Musinoi Hagen, Sigrid Lædre, Niklas Magnusson & Cecilia Haskins for their expertise and feedback. I would also like to thank Erik Bjerrehorn for his assistance at SINTEF's Energy laboratory. And I would like to thank my colleagues Carina, Gaute, Christian, Håkon, Lise, Ali & Njål for enjoyable lunches and amusing discussions.

I am also indebted to my family and friends for helping me develop the skills needed to complete this project. In particular, I would like to thank Johan Mürer for his engineering mentorship, inspirational creativity and contagious enthusiasm. I would like to thank my sister Hanne for always having my best interest at heart. And finally, I would like to thank my dearest Therese for being by my side throughout.

Summary

Aluminium's electrical conductance per-unit mass and per-unit cost is unequalled. These are two desirable properties in a world undergoing widespread electrification. Electricity generation, transmission and utilisation is fundamental in transitioning from non-renewable energy sources and is placing greater demand for low-cost electrical conductors. Considering also the importance of transportation in global economies and our dependence on fossil fuel vehicles, the need for lightweight conductors is evident.

Alas, aluminium's properties are not all favourable to electrical applications, so copper has risen as the dominant conductor material in all but high-voltage long-distance power transmission. Successfully developing aluminium conductors in new applications requires overcoming several challenges, from technical limitations in material properties and manufacturing processes, to programmatic obstacles in development scope and organisation.

This thesis explores the barriers to aluminium innovation in electrical applications, starting from a broad perspective of material substitution innovation down to specific technical bottlenecks. The thesis investigates aluminium substitution with both a broad strategic perspective and a targeted technical analysis. The thesis includes analysis of literature, interviews with experienced project managers, reliability testing of design solutions and evaluation of a new manufacturing process.

The first contribution in the thesis takes a broad perspective on the product development process for material substitution. The thesis challenges a prevailing perception of material substitution which posits that the *material selection process* is decisive for the success of material substitutions. A material selection process involves deriving material requirements then ranking the performance and cost of suitable candidates. Utilising such a selection process ensures that the material that best fulfils the application's requirements is chosen. A material substitution which is not successful is then blamed on an inadequate ranking methodology or missing requirements. The belief being a more detailed selection process will lead to successful designs. In contrast, this thesis takes the perspective that most of the material substitution projects that fail, do not fail because the wrong material was chosen, but because the barriers for its implementation were not identified and addressed appropriately during development. A framework is proposed in the thesis to identify from where these development barriers arise. The framework is based on comparing the knowledge of the material in the existing product and the knowledge of the substitute material. Interestingly, a significant potential for improving substitution projects is identified from ignorance in the existing product. Through the lens of organisational theory, the thesis suggests applying explorative processes for discovering the entrenched barriers to substitution and exploitative processes for tackling the established substitution barriers.

The thesis then goes on to tackle the primary limitation of aluminium conductors: the ability to form reliable connections. The thesis covers both detachable connection methods for aluminium-aluminium interfaces and permanent connection methods for aluminium-copper interfaces.

Detachable connection methods are essential for the assembly, maintenance and reconfiguration of electrical circuits. Press-fit and bolted connection methods are common for copper conductors; however, aluminium's highly insulating oxide layer reduces the reliability of such mechanical connections. In this thesis, the design of bolted aluminium connections for transportation battery systems are investigated through corrosion and thermal cycling reliability testing. The findings show that nickel plating provides a robust electrical connection for bolted aluminium busbars. The contact resistance remained stable under operational and environmental conditions above those typical for transportation battery systems.

However, bolted connections between aluminium and copper, even with nickel plating, are unreliable due to their difference in thermal expansion coefficients. Instead, welded connections are preferred as they can provide complete contact and are not dependent on surface roughness interactions. Unfortunately, welding aluminium and copper is also challenging as their high chemical affinity leads to the rapid formation of poorly conducting intermetallic compounds. Therefore, maintaining low temperatures during welding and throughout the operational life of the conductor is important to reduce the formation of intermetallic compounds.

In this thesis, a new solid-state state welding process, called Hybrid Metal and Extrusion Bonding (HYB), has been evaluated for Al-Cu joining. This novel joining process was evaluated by measuring the weld's electrical resistance and establishing its temperature stability. As part of this thesis, a new metric for comparison of bimetallic welding performance is proposed. The new metric allows different weld configurations to be compared in a normalised manner which allows the functional performance of joining processes to be assessed. The comparison showcases the exciting potential of Hybrid Metal and Extrusion Bonding as a new and superior joining process for Al-Cu conductors. The results indicated that the new process creates welds that can operate reliably at higher temperatures than existing processes, while also offering greater dimensional freedom of joint configuration. In addition, an error in a foundational paper for Al-Cu joining was discovered and highlighted in a separate commentary letter.

Overall, the thesis provides insight into the development of aluminium conductors from several perspectives. Starting first with the development process, unique characteristics of material substitution projects are proposed. Then specific technical obstacles are tackled, providing both design reliability evidence and discovery of a new joining process's performance.

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Part I

Chapter 1

Introduction

"...the age of electricity and of copper will be short. At the intense rate of production that must come, the copper supply of the world will last hardly a score of years. ...our civilization based on electrical power will dwindle and die."

Ira Joralemon, Engineering and Mining Journal (1924) | [3]

1.1 Motivation

Ira Joralemon's dire prediction in 1924 may have underestimated the abundance of copper and our ability to profitably extract lower concentrations of copper from the Earths crust; however the concern remains. What other materials can support a civilisation with an ever increasing dependence on electricity?

Copper has been the material of choice for conductors since the discovery of electricity to the current ubiquity of electrical circuits. Copper is well suited as an electrical conductor due to its high conductivity and its ability to form reliable connections. Copper is a popular metal ranking third in metal production, surpassed only by iron and aluminium. Copper's mechanical, thermal and electrical properties make it a desirable metal however, copper ores are more scarce and less universal across the globe compared to iron and aluminium. As such, it is more expensive with global resources, reserves and production closely monitored [2].

An interesting alternative conductor material is aluminium, the most abundant metal in the Earth's crust! Aluminium is a compelling alternative as it offers higher conductivity per unit mass than copper. While copper has a higher volumetric conductivity, aluminium's even lower density compensates so that, for equal resistance, aluminium will be the lightest solution. A high conductance however is only half of the story when selecting a conductor material. Perhaps more importantly, the conductor must be able to form reliable connections with low resistance. Unfortunately, aluminium has several inherent properties that make achieving reliable connections challenging, namely: it oxidizes rapidly forming a non-conductive and hard interface; it thermally expands at a greater rate than common interfacing materials; and its low strength increases susceptibility to creep over time.

The demand for conductors is increasing as the use of electrical systems continues to grow globally. Aluminium's greater prevalence on Earth has resulted in a considerable price advantage in recent years. Considering the growing demand and difference in supply for these two materials, there is growing interest in using aluminium in electrical applications.

> The motivation of this thesis is to support the development of aluminium conductors and aid substitution from copper conductors.

This chapter will introduce the thesis by presenting a brief history of aluminium conductors and identifying the research problem.

1.2 Background

1.2.1 Aluminium's electrical history

Aluminium was not produced on an industrial scale until the late 19th century [4] and therefore postdates the discovery and commercialisation of industrial electricity. Copper, on the other hand, has been used by man for thousands of years. It was therefore copper (along with iron) that took the initial role of electrical conductors for power transmission and telecommunication networks [5].

Aluminium production increased throughout the 20th century as its production process was improved [6] and was quickly adopted for long distance high voltage power transmission [7]. Aluminium's low density was well suited to overhead cables spanning long distances but use in low voltage (end-use) applications was limited for the first half of the century. Then at the end of World War II a surplus of aluminium raised interest in using aluminium conductors in more applications. The safety organisation, Underwriters Laboratories Inc. (UL), first approved aluminium wiring for residential applications in 1946 [8] and the increasing price advantage by the mid-1960s resulted in significant use of aluminium wiring in the USA.

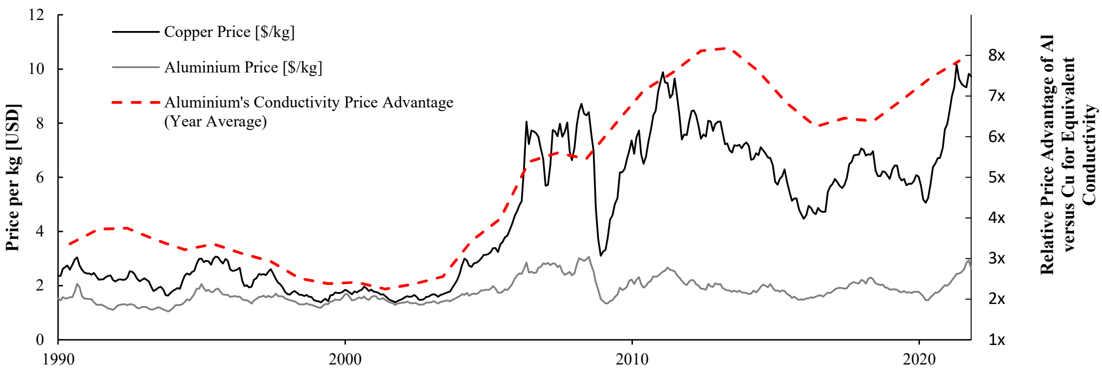

Figure 1.1: Commodity market metal prices of aluminium and copper since 1990 from IMF primary commodity price data portal [9]. The dashed-line shows aluminium conductivity price advantage versus copper for equivalent conductivity. The conductivity price advantage was calculated considering a Cu:Al conductivity ratio as 100:62 and density ratio of 9.0:2.7

Unfortunately, failures were not uncommon and in some cases caused fires with fatal consequences [8]. Failure investigations pointed to technical design errors, such as mismatched thermal expansion coefficients in fasteners or inadequate margin for creep relaxation, as well as workmanship errors due to the greater design complexity (compared to the existing copper connections). While efforts were made to improve connection methods, a scepticism towards aluminium, combined with a reducing cost advantage throughout the 70s and 80s, resulted in copper maintaining its dominant position as the low voltage conductor [10]. However, since 2005 the price of copper has risen and since 2010 has cost 6x more than aluminium for the same conductivity, see Fig 1.1. As such, aluminium is poised to substitute copper in new and existing applications once again.

1.2.2 Battery systems

At the same time, a new market for battery systems is under dramatic growth. In particular, demand for lithium-ion battery technology has increased whilst its cost has decreased. Fig 1.2 shows both demand and price trends for li-ion batteries over the last 10 years.

Battery systems are proving vital for storage of renewable energy and electric transportation. Li-ion battery systems are made by combining numerous standardised cells together to form a battery pack with the desired capacity. Typical battery systems include tens to hundreds to even thousands of cells connected together by conductors. Each cell requires two connections to form a circuit and reliable connections are critical for safe operation. Therefore, whilst aluminium's low cost and weight would make it an ideal conductor for battery systems, there is an acute need to understand and confirm connection reliability for battery applications.

Battery systems pose new requirements to conductors. The unique set of requirements include: operating under high amperage direct current; in a variety of atmospheric and thermal conditions; often without inspection possibilities; and interfacing to new components. This requires new research to establish design performance of conductors for battery systems.

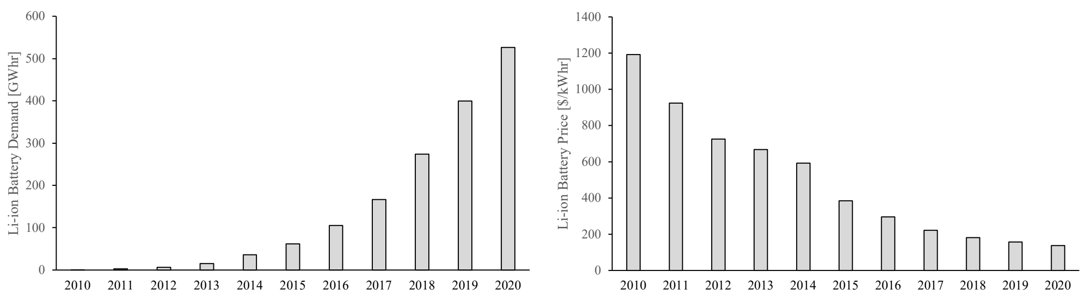

Figure 1.2: (left) Growing demand for Li-ion batteries per year showing exponential rise (right) Yearly reduction in cost of Li-ion batteries showing 90% reduction between 2010 - 2020. The data for both figures was reported by BloombergNEF Electric Vehicle Outlook 2021 [11]

1.2.3 Development challenges

Messner [10] has studied the substitution of copper and aluminium from 1945 to 2000 by looking directly at how material price influences the selection of conductor material. Messner concluded that despite the price being the fundamental driver, so called path dependencies, are critical in determining material use. Path dependencies are factors that prevent material substitution in products and include: (i) knowledge advantage of the existing material, (ii) established cooperation networks, (iii) the need to rearrange capital goods, (iv) risk of adverse product quality changes and (v) fluctuating material prices. Messner's analysis shows path dependencies can delay or even negate a substitution despite a significant price advantage.

Similarly, Maine et al. [12] have highlighted how effective management is particularly important for change in the material industry. Introducing substitute materials requires facilitating the interchange of "...knowledge across disciplinary fields, functional roles, organisational boundaries, and the marketplace." to be successful. Such challenges are acutely applicable in the case of aluminium conductors for battery systems, where knowledge is diffuse across battery cell suppliers, battery pack manufacturers, customers and regulatory bodies. As such, this thesis set outs to investigate both effective management practices in the development process and the specific technical obstacles to support the utilisation of aluminium conductors.

1.3 Research problem

Considering aluminium's inherent technical limitations and historical usage compared to copper, the development of aluminium conductors for battery applications faces two challenges. New knowledge is required to establish aluminium performance in battery system applications and effective development methods are needed to aid efficient substitution of copper.

1. To develop aluminium conductors for battery systems will require an effective product development process to generate knowledge, coordinate supplier networks and reduce quality risks. Substituting materials in products requires going beyond the comparison of raw material prices and primary performance metrics. Instead effective development processes that can identify and overcome the barriers limiting substitution are needed. In engineering and technology management the ability to "improve or develop products, processes and existing technology, as well as generating new knowledge and skills" is called technological capabilities [13]. Currently, the technological capabilities needed to facilitate material substitution development projects are lacking in the literature. Indeed, this problem is not specific to aluminium conductors but is relevant to any material substitution.

2. Focusing next on the specific challenges of substituting aluminium for copper conductors; there is a need to understand suitable connection methods and determine the reliability in battery systems. In particular, there are two connection methods of primary importance for battery systems. The first are detachable connections methods that can be used to install, maintain and reconfigure battery systems, and the second is aluminium to copper

connections that can withstand the physical and chemical incompatibilities between the two materials.

1.4 Research aim

Aim: To aid the development of aluminium conductors in battery systems through the evaluation of connection methods and assessment of development processes.

In order to achieve the aim the work has been divided into the following tasks:

- To review the current limitations for using aluminium in battery systems (§2)
- To describe the development process for material substitutions (§3)
- To investigate the managerial implications and technological capabilities needed to facilitate material substitutions (Paper I)
- To evaluate the reliability of detachable aluminium connection for battery systems (Paper II)
- To establish the performance of a new aluminium - copper joining process (Paper III)

1.5 Contributions

The thesis is a paper-based thesis comprised of four scientific papers and a commentary letter. The publication sources are listed below. Three of the papers are published while one paper and the commentary letter have been submitted for publication at the identified source. An overview of the contributions is presented in § 5 with full papers provided in Part II.

Paper I Barriers and Enablers for Material Substitution Innovations: Positioning Exploration and Exploitation Learning Processes
A. Elkjaer & G. Ringen
Business Strategy and the Environment
Submitted September 2023

Paper II Reliability of Bolted Aluminium Busbars for Battery Systems: Effect of Nickel Coating and Corrosive Environment
A. Elkjaer, G. Ringen, R. Bjørge, C. Musinoi Hagen, S. Lædre & N. Magnusson
IEEE Transactions on Transportation Electrification
Published 2022

Paper III Electrical and Thermal Stability of Al-Cu Welds: Performance Benchmarking of the Hybrid Metal Extrusion and Bonding Process
A. Elkjaer, J. A. Sørhaug, G. Ringen, R. Bjørge & Ø. Grong
Journal of Manufacturing Processes
Published 2022

Paper IV A Literature Review of the Integration of Test Activities into the Product Development Process
A. Elkjaer, G. Ringen & C. Haskins
Conferences on Systems Engineering Research, Recent trends and advances in Model Bases Systems Engineering, Springer
Published 2022

Letter Correction to Braunovic & Alexandrov's 1994 Article on Intermetallic Compounds at Aluminum-to-Copper Electrical Interfaces
A. Elkjaer
MRS Communications
Published 2024

1.5.1 Authors contributions statements

A. Elkjaer is the first author on all papers comprising this thesis and has been responsible for conceptual definition, methodology, presentation of results and writing in each study. A detailed overview of each author contributions is provided below:

Paper I A. Elkjaer (AE) was responsible for the research design proposing the use of interview case study to investigate past material substitution projects. AE defined the interview guide, conducted, transcribed and analysed all interviews. AE proposed the material substitution knowledge framework and relationship to exploration and exploitation processes. AE wrote the original draft. Geir Ringen (GR) supervised AE throughout the study providing input to all stages. GR reviewed and validated the findings providing editorial input to the final manuscript.

Paper II AE was responsible for the research design proposing the use of corrosive pre-exposure followed by current cycling procedure to evaluate the performance of bolted connections. AE was responsible for the test specification, sample configurations and electrical test setups. C. Musinoi Hagen (CH) and S. Lædre (SL) were responsible for defining the accelerated corrosion environments and the corrosion test sequence. AE was responsible for all electrical test measurements and definition of the current cycling environment. R. Bjørge was responsible for project administration, material resources and test facilities. AE assembled the test specimens performing electrical measurements during corrosion testing and current cycling. AE processed all data and generated all figures. N. Magnusson reviewed and validated the final results. AE wrote the original draft and all co-authors reviewed the final paper.

Paper III AE was responsible for the research design proposing the use of heat treatment, electric resistance and intermetallic thickness measurements to establish the functional performance of a novel joining process. AE defined the methodology and proposed the electrical performance metric. AE was responsible for definition of the test specimens, electrical measurements and heat treatment. J. Sørhaug was responsible for all transmission electron microscopy, generated the electron image figures and described the imaging methodology and microstructure findings in the pa-per. R. Bjørge conducted scanning electron microscopy. AE analysed the thickness measurements using the diffusion model and compared results to existing processes for diffusion and electrical performance. Ø. Grong reviewed and validated the final results. AE wrote the original draft and all co-authors reviewed the final paper

Paper IV AE was responsible for the research design proposing a literature review into the role of test activities in product development. AE defined the search strategy and processed all findings according to the inclusion and exclusion criteria. AE proposed the test process framework and described its relation to the key insights from the identified literature. Geir Ringen supervised AE throughout the study providing input to all stages. Cecilia Haskins reviewed and validated the findings providing editorial input to the final manuscript.

1.6 Research funding background

This PhD thesis has been funded by the V-ALU-E research project which has the vision to increase the competitiveness of the Norwegian-based aluminium industry. Currently, the Norwegian aluminium industry consists predominantly of primary metal production or semi-finished product manufacturing, while the market for finished aluminium products is limited. As such, the industry is reliant on other end-users and designers with a need for aluminium.

Developing a product can be seen as adding value to raw materials. The engineering process creates value by turning raw materials into products that maximise benefits to the customer and minimise disadvantages (e.g. cost). The Norwegian aluminium industry relies on aluminium being a competitive material and used to its full potential. However, transforming raw materials into valuable products is complicated and success is often outside the control of an individual company alone. The V-ALU-E research project posits that the "value potential" of aluminium can be increased by cultivating the latest technological advancements, through the most appropriate development methods and in cooperation with the complete value chain. As such, the V-ALU-E research project aims increase the competitiveness of the Norwegian-based aluminium industry by:

- Finding new applications for aluminium
- Building stronger cooperation along the aluminum value chain and with academia to aid aluminium utilisation
- Researching design methodology to reduce the development risk of using aluminium in new applications and improve product performance.

This thesis has contributed to all three aims by:

1. Pushing the boundaries of electrical conductor applications in battery systems
2. Building stronger collaboration between university and industry through cooperation in industrial research projects
3. Investigating development methodology to reduce the risk of material substitutions development projects.

The full project identification is VALUE - Cross Industry, Cross-Science Collaboration Strategies for Value Driven Aluminium Product Development, Project number: 267768/O20

1.7 Thesis structure

The thesis is organized into two parts. The first part is structured into the six chapters shown below and the second part contains the resulting scientific publications:

Chapter 2 Describes aluminium's properties and battery systems to outline the challenge ahead.

Chapter 3 Maps out existing theory on the development process for material substitution.

Chapter 4 Describes the methodology for the each of the subsequent studies.

Chapter 5 Presents a summary of the scientific contributions from the performed studies.

Chapter 6 Provides concluding remarks.

"The contact resistance of aluminium is necessarily influenced to a very large extent by the slight film of oxide normally present on the surface. This oxide forms so rapidly that the usual method of cleaning the bars and immediately clamping them together is not satisfactory"

Melsom & Booth, Journal of the Institution of Electrical Engineers (1922) | [14]

Chapter 2

Aluminium Conductors & Battery Systems

This chapter provides an overview of aluminium conductors and battery systems. The chapter outlines requirements for conductors in battery systems and the technical challenges faced when using aluminium conductors.

2.1 Aluminium conductors

Electrical conductors can be categorised based on the required amperage they shall transfer. Table 2.1 shows a list of conductor applications organised loosely by their current carrying capability. The required current carrying capability is critical to conductor selection as it is the primary factor in determining the conductor cross sectional area. An assembled high voltage power transmission conductor may exceed 1000 mm^2 while printed circuit boards could be less than 1 mm^2. A larger cross section provides lower resistance and can therefore transfer more current without over heating.

Once the conductor cross section is determined, additional characteristics such as, structural integrity, electrical insulation and connection method are then accommodated to the intended conductor dimensions. For overhead power transmission, aluminium's lower density and lower cost is favourable for large conductor cross sections that need to span long distances. As the required conductor cross section for an application decreases the benefits of aluminium diminishes. Furthermore, smaller dimensions increase the importance of structural properties and maintaining a reliable connection with aluminium becomes more challenging, hence copper is the prevalent solution.

Historically, the market for aluminium conductors has been high voltage overhead power transmission cables. High voltage power transmission cables are conductors that transfer high currents (Table 2.1) but in recent years the aluminium's cost advantage has driven the use of aluminium in new applications. This has led manufacturers for transformer windings, switch

Table 2.1: List of conductor applications sorted by current carrying capacity

> 1000 A	⇑	High & medium voltage overhead power transmission
		Transformer windings
		Switchgears
		Building trunking systems
		Vehicle battery packs
		Static battery packs
		Motor windings
		Building wire
		Domestic appliances
		Battery Cell Electrodes
< 1 A		Printed Circuit Boards

gears and building trunking systems to explore aluminium substitution in lower current/smaller dimension applications. Below are example endorsements from corporate publications published in the last 10 years.

This thesis targets the next step down in Table 2.1, conductors for battery systems. In the following chapter the important characteristics of battery systems conductors are highlighted.

> *"Improvements in technology regarding the use of aluminum in transformers have made aluminum-wound transformers the ideal choice for today's applications."*
>
> EATON Electric 2016 [15]

> *"... aluminium based Bus Way systems are the perfect alternative to traditional Copper systems, as they offer reduced cost whilst maintaining the mandatory reliability and sustainability criteria."*
>
> Siemens 2014 [16]

> *As is stands, all electrical equipment with aluminium conductors (designed and tested to perform to the same level of copper), prove to be a more cost-effective option to the end user."*
>
> Wilson Power Solutions 2018 [17]

2.2 Battery systems

In this thesis the terminology battery system is used following the trend setting example laid out by the Tesla Motors Roadster battery system [18]. A battery system is comprised of scalable units typically referred to as battery packs, battery modules and battery cells. Individual battery cells are connected in parallel or series to form a module. These modules are then also connected in parallel or series to form a battery pack. Connecting units in parallel increases capacity while connecting in series increases supply voltage. This allows the total number of cells and their configuration to be suited to the required capacity and power for the application.

Yet, a battery system is more than a collection of battery cells. Major features include a housing to ensure structural integrity, cooling system to ensure thermal control, and electrical system to monitor the charge and health of the stored energy. In this thesis, the scope is limited to the conductors used in joining cells or groups of cells (modules/packs) into larger units. As the units become larger and deliver more current larger conductors are required. Aspects of battery system design that are not related to conductors are not addressed in this thesis.

The fundamental building block for many battery systems has become lithium ion (Li-ion) battery cells. Initially fueled by a market pull for portable consumer electronics the continued up-scaling of production has dramatically decreased the price of this commodity product. This decrease in price has fueled further demand for li-ion cells becoming the basis for transport applications.

An explanation of Li-ion technology and discussion on energy density is beyond the scope of this thesis on aluminium conductors. However, some important characteristics of Li-ion cells shall be highlighted that are relevant to the conductors used to join them together. Fundamental to joining a Li-ion battery cell to an external component are the cell's *current collectors*. Current collectors are the component inside the cell that bridges the cell electrodes to cell terminals for connection to a external circuit. For Li-ion batteries these current collectors are aluminium (for the cathode) and copper (for the anode). Both aluminium and copper are needed due to their respective electrochemical stability at the anode and cathode locations [19]. This means aluminium is inherent at a foundational level in Li-ion battery systems.

However, the current collector is not necessarily the conductor that interfaces to the external circuit. The external interface is called the cell terminal and its design is related to the cell form. There are three common cell forms for Li-ion cells; cylinder, pouch and prismatic [20]. The chosen cell form determines the interface geometry and materials, which in turn influences the suitable joining processes for connecting the cell terminal to an external conductor. In cylindrical cells the current collectors are connected to the cell casing. Typically this casing has been nickel plated steel but recently aluminium casing have been explored [21]. Similarly, prismatic cells provide dedicated terminals where connection between the cell electrodes and cell terminals occur within the cell. Prismatic cells can be large enough so that these terminal even include threaded holes so that a bolted connection can be made to the terminal. Pouch cells, on the other hand, provide contact directly to the current collectors by allowing the copper anode and aluminium cathode to extrude from the cell. Example sketches of each cell form are shown in Figure 2.1.

A conductors suitability to join cells is limited by its compatibility with the cell terminal. A joining processes that is capable of connecting the cell terminal and conductor must accommodate the chemical properties interfacing materials (e.g. melting temperatures, phase compatibility, thermal expansion). A reliable connection with low electrical resistance is a critical to the performance of the battery system. Existing joining processes used in battery systems include wire bonding, laser welding, resistance welding and mechanical fastening [20].

Tesla have been a leading innovator in up-scaling battery technology for transport applications and in 2014 released their patents for fair use in the industry. Tesla's battery busbar design,

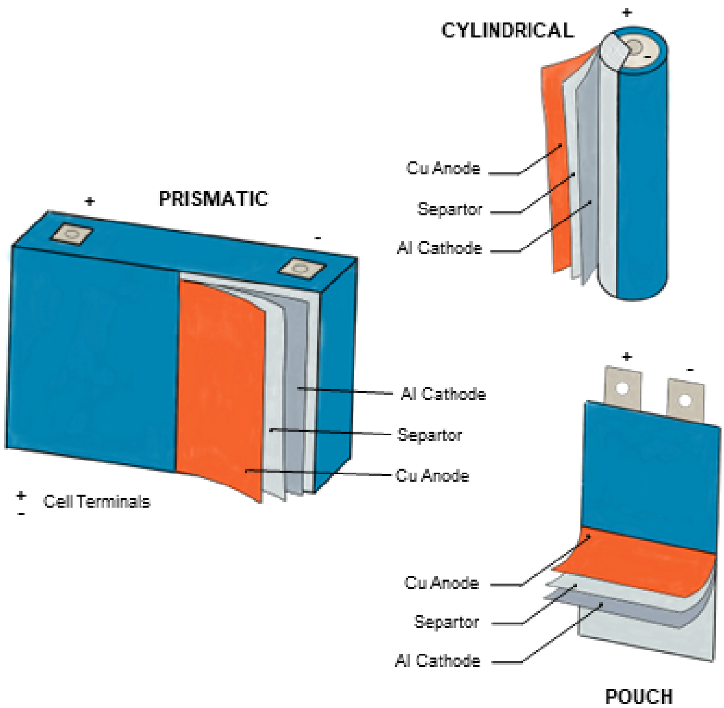

Figure 2.1: Illustration of battery cell forms showing cylinder, prismatic and pouch cell forms

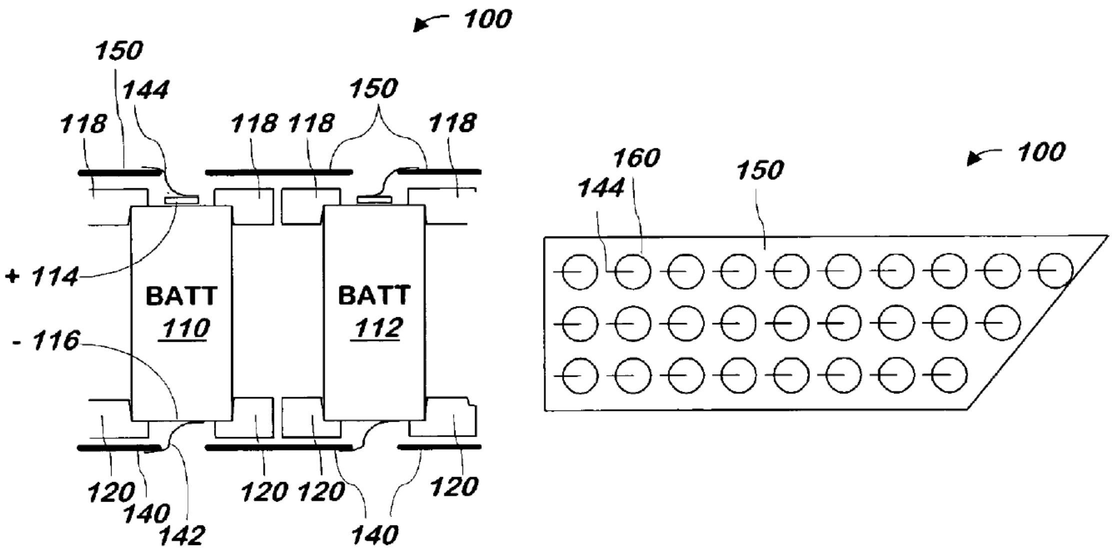

Figure 2.2: Illustration form Tesla Patent [22] showing wire bonding on cylindrical battery into a battery module

Figure 2.2, shows multiple cylindrical cells connected in parallel to form a module. Tesla introduced aluminium conductors into their battery system by using an aluminium wire bonding process to connect the cell to the module busbar [22]. Aluminium wire bonding is an established mass production process used in integrated circuits. The process is suited to battery systems as it can achieve reliable connections under high output rates. Studying Tesla's patents it evident that initially a nickel plated copper busbar was used as the module busbar and progressed onto using aluminium busbars (surface treatment unknown) on later models.

The discussion above has focused on the first connection level in a battery system, from cell to conductor. The same constraints on material compatibility apply to joining processes of high level connections (i.e. those used to connect battery modules to modules or battery packs to packs) but the dimensions increase. At these larger scales detachable joining process become more desirable for installation, maintenance and modularity.

The key points to highlight about battery system conductors are:

- Li-ion cells are the most popular energy storage technology for portable/transport applications. Li-ion cells use Cu and Al current collectors to bridge the cell electrodes to the cell terminals for external connection. In some cases (pouch cells), the current collectors also act as cell terminals and therefore the chosen conductors used to join cells together shall be compatible with both metals. In other cases, the current collector is connected to a terminal inside the cell and the conductor used to join cells together shall be compatible with the cell terminal's material and geometry.
- A reliable connection method suited to mass production is key for the manufacturing and performance of battery systems. The combination of cell terminal and joining process must be compatible with an aluminium conductor to ensure a reliable and low resistance connection is made.
- Detachable connection methods are key for installation, maintenance and modularity. The importance of detachable connection methods increase as the number of cells increase.

Based on existing technology for aluminium busbar in battery systems two key focus area for future development are identified. 1) Detachable connections 2) Al/Cu connections

2.3 Detachable bolted connections

Detachable bolted connections are a versatile connection method for battery systems. A reliable connection method that can be quickly established and removed aids integration, maintenance and safety. Unfortunately electrical contact between bulk metal surfaces is more challenging than meets the eye. For example, a metal conductor bar with a cross section of 3 mm x 25 mm may be assumed to be well equipped if connected to another bar with a 25 mm x 25 mm overlap, figure 2.3. Such overlap provides a 625 mm^2 contact area which exceeds the conductor nominal cross section over 8 times. However, while cross-sectional area is the key property for a bulk conductor the same does not apply at the interaction of surfaces. As such, the current carrying capability of the 25 mm x 25 mm contact may be much lower than the 3 mm x 25 mm bulk conductor material.

An electrical connection between two surfaces is dependent on the amount of physical contact between the surfaces. First recorded in Leonardo da Vinci's work on friction, the interaction between two surfaces is not governed by its apparent contact area but by the contact force between the two surface [23]. Surprisingly, increasing the apparent contact area has negligible impact on the actual physical contact between two surfaces. This is because microscopic roughness is preventing the apparent area from matching the actual contact area between two surfaces. While the nominal area may be 25 mm x 25 mm the microscopic roughness (and flatness deviations in the surfaces) limits the contact to a small fraction of the apparent contact area as illustrated in Figure 2.4. Increasing the contact area will have little effect on this real contact area as the contacting area is already able to support the interfacing surface. Therefore, increasing the area will likely provide few extra connection points. In locations where new contacts do occur, this will likely only lift the surface so that other previously contacting locations loose contact. Instead, increasing the real contact area requires increasing the load being transferred. Increasing the load (contact force) increases the deformation of the contacting spots therefore increasing the real contact area. However, increasing the load too much can introduce new failure mechanisms while providing little benefit if the deformed contacting spots are now able to support a much higher load.

The relationship between contact force and electrical resistance follows a negative exponential. Measurements of both copper and aluminium show the same relationship; initially contact resistance decreases rapidly with contact force but then the decrease in contact resistance flattens out and further increase in contact force does not provide significant reduction in resistance [24–27]. This relationship is more pertient for aluminium contacts than copper due to aluminium's lower strength. This is because a high contact load increases the stress in the bulk material which makes the material more susceptible to creep over time, which in turn can cause relaxation in the contact load. Contact resistance under loading and unloading has been measured by Braunovic [25] & Schoft [26] and relationship is illustrated in figure 2.5. A relaxation in the contact load, or in worst case a loss of contact load, will return the high contact resistance. And high contact resistance can then cause the temperature to increase, which reduces the efficiency of power transmission, accelerates degradation or in worst case may ignite the surrounding environment.

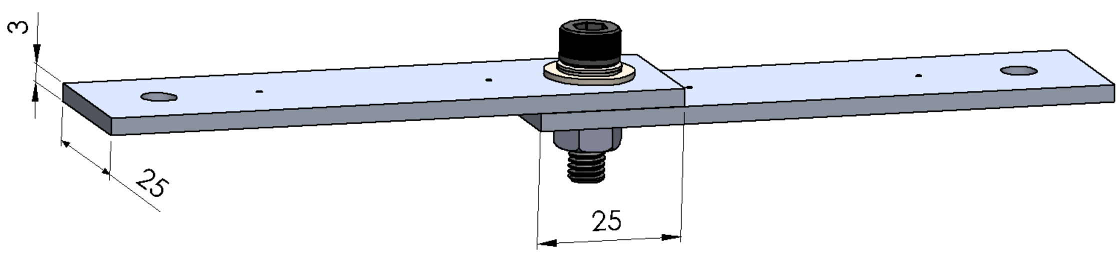

Figure 2.3: Illustration of two 25 mm x 3 mm conductors bolted together with a 25 mm overlap

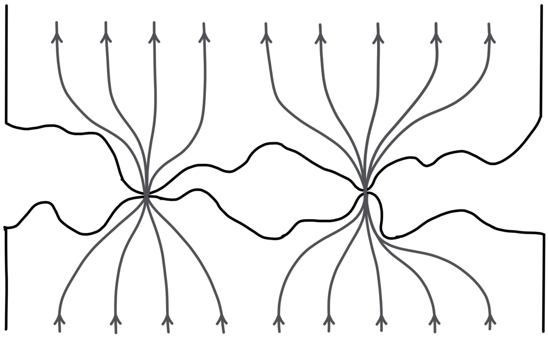

Figure 2.4: Illustration of asperities interaction between two surfaces

As such, preventing the temperature rise of contacts is key to preventing the degradation of the contacts.

There are several factors that determine the quality of a contact and as such its ability to maintain a low and reliable resistance. Factors that adversely affect contact quality include oxidation, thermal expansion and stress relaxation. Comparing aluminium to copper in each of these factors shows a clear advantage to copper. Aluminium's oxide has much higher electrical resistance than copper oxides, aluminium coefficient of thermal expansion is higher than copper and its structural strength is lower, Table 2.2. This makes aluminium contacts particularly susceptible to the combined effects of these properties into a failure mechanism called fretting.

Fretting occurs when the surface oxide between to contacting interfaces is disturbed and builds up between the two surface. As aluminium oxide is a hard and abrasive substance it can

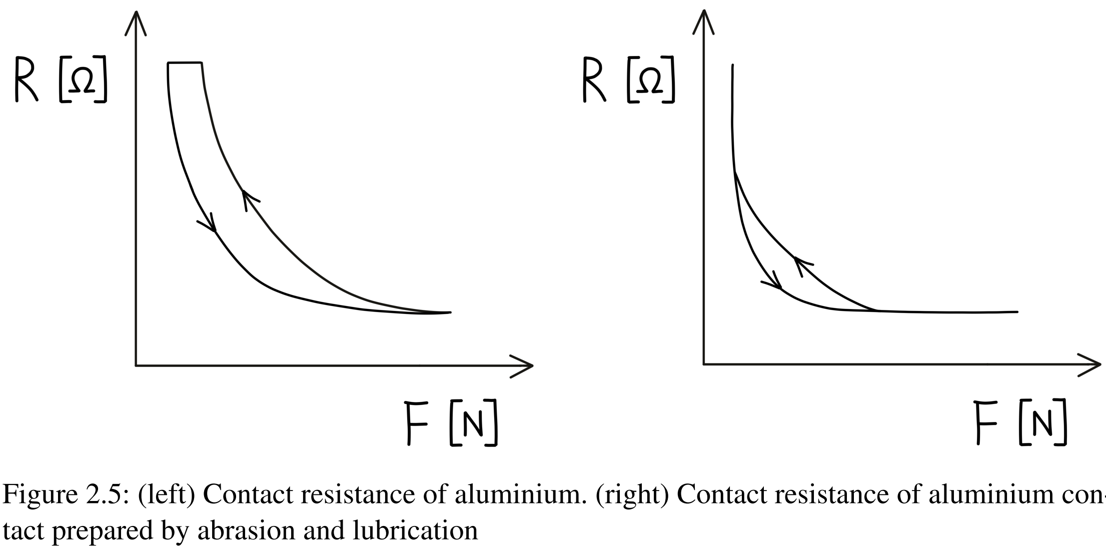

Figure 2.5: (left) Contact resistance of aluminium. (right) Contact resistance of aluminium contact prepared by abrasion and lubrication

Table 2.2: Electrical and mechanical material properties of aluminium and copper [28]

Material	Oxide Conductivity [Ω m]	Coeff. thermal expansion [K^{-1}]	Yield Strength [MPa]
Aluminium	10^{12} - 10^{14}	24	28 (annealed)
Copper	1 - 10^{4}	17	69 (annealed)

aid the continued removal of oxide. More oxide can form rapidly on the surface of aluminium and can continue to wear. This build up of particles can then form a layer between the contacting surfaces and increase the electrical resistance. Such failure has a negative feedback where the increased resistance, increases the temperature, which increases the movement between the surface and generates more wear particles that accelerates the failure.

Several methods to prevent fretting of aluminium contact have been investigated. Intuitively, coating the contact interface with lubricant or a conductive plating that prevents aluminium oxide from forming would be a suitable mitigation. Research and field experience has shown applying a lubricant combined with brushing of the surface is a simple solution that can provide a reliable connection [29]. However, the clamping design is important and should include a compliant element (spring washer) to ensure the clamping force is maintained over time.

The performance of lubrication and brushing for bolted connections of aluminium has been tested for high power applications [29–31]. Such connections are transferring thousands of amps which require large conductor cross sections. The large dimensions allow several bolts to be used for one connection which provides multiple paths for the current. Such multiple paths reduce the resistance and provide redundancy. These configurations do not match the configurations applicable for battery systems. A compact battery system uses thinner busbars and ideally one bolt per connection to aid assembly and minimise weight. Currently, in the literature there is a lack of empirical evidence for brushed aluminium connections with small contact areas, lower loading and compact connection designs for battery systems.

A robust alternative to brushing with lubrication is plating of the contact surfaces. Research and industrial options include silver, tin, nickel surface plating [28]. However, the required processes are costly and can themselves introduce new corrosion risks. Silver is particularly vulnerable to sulphide environments and tin exhibits its own fretting failure. In a study comparing different plating options nickel was shown to provide the best performance [32]. Yet still, the performance of nickel coating in the smaller configurations suitable for battery systems and in particular under corrosive environments is lacking in the literature.

In summary:

- Detachable connections are versatile connection method necessary for the safety and assembly of battery systems
- Microscopic surface interactions reduce the integrity of electrical connections between surfaces. Aluminium oxide forming between the surfaces is highly detrimental to the elec-

trical performance of the connections.

- Brushing with lubrication or plating with nickel are the two most common and best performing solution to achieve reliable contacts between aluminium contacts. However testing has been performed on large high power connections which are not representative of those used in battery systems.

Unfortunately, both lubricated and nickel plated detachable aluminium conductors struggle to interface with copper connections under temperature variations. The difference in thermal expansion between the materials results in relative movement than can degrade the established metal-to-metal contact spots over time. As such detachable aluminium to copper connections have lower reliability in applications with high duty cycles. An alternative solution would be to weld the Al-Cu interface and provide a detachable connection downstream between between matching material interfaces. A welded interface between aluminium and copper avoids troublesome surface interactions however introduces new challenges that are outlined in the next chapter.

2.4 Dissimilar metal joining

As described in the chapter on battery systems above, aluminium and copper are inherent in Li-ion battery systems. Considering also the wide use of copper in downstream components, such has cables and motor windings, introducing aluminium conductors will require robust connections methods to copper. Welding aluminium and copper requires deliberate temperature control. Joining two materials with different melting temperatures, thermal conductances and thermal expansion rates are vulnerable to cracking and voids. To prevent defects forming it is necessary to minimise heat input. Yet, even defect free Al-Cu welds can be brittle due to their chemical compatibility. Aluminium and copper form a myriad of different compounds with most having undesirable mechanical and electrical properties. Therefore, while intermetallic bonds are necessary to achieve connection, their presence should be limited to avoid brittle and poorly conducting interfaces.

Welding techniques that are able reduce the formation of intermetallic compounds are solid state welding process. These processes have minimum energy input and are able to form bonds between the interfacing materials without melting the base materials. Friction welding, cold rolling and ultrasonic welding are all solid state joining processes that can join aluminium and copper with a intermetallic thickness below 2 µm [33–35]. These welding processes are used in a variety of electrical and non-electrical (heat exchangers) applications. Unfortunately, achieving a structurally sound weld is not sufficient to ensure reliable operation in electrical applications. This is because intermetallic compounds continue to grow over time as the two metals continue to diffuse [28]. The diffusion rate is dependent on the materials operating temperature. Therefore, the maximum temperature and duration under operational conditions needs to be considered to ensure the intermetallic compounds do not grow to an extent that would cause failure. In electrical applications a negative feedback loop is formed where the intermetallic compounds increase the resistance, which increases the temperatures, which further increases the resistance, which further accelerates the growth of intermetallics. Existing literature indicates operating temperatures must be maintained below 100 °C to ensure reasonable operating life [36]. This is undesirable for battery systems which target high current levels from fast charging or fault tolerance in failure cases.

In summary:

- Welding aluminium and copper achieves an electrical connections that avoids surface interaction failure mechanisms.
- Aluminium and copper bonding forms intermetallic compounds that are brittle and poorly conducting. These compounds form during the initial welding of the materials and continue to form over time due to temperature dependent diffusion inside the material.
- Solid state welding techniques can bond aluminium and copper while limiting the formation of intermetallic compounds, but the reliability of such welds are limited by their stability under operational conditions.

Chapter 3

"The net price of aluminium is now less than £130 per ton. Copper stood at £73 per ton on November 5, 1901. For equivalent conductivity the price is slightly in favour of aluminium. If the world's output of aluminium were doubled it would only be about 2%, of the world's output of copper, so that a considerable reduction in the price of aluminium might be effected without disturbing the price of copper."

Ernest Wilson, Journal of the Institution of Electrical Engineers (1902) | [41]

Material Substitution Product Development

3.1 Material substitution development process

"The road to hell is paved with good intentions" is an apt proverb for those setting out to substitute materials in products. The exciting potential of a new material can be enticing; however, material innovation is expensive and time-consuming [37]. Wield & Roy [37] attribute the failure of many well-intended material substitution to a complex innovation environment. This complex innovation environment is composed of various stakeholders in the supply chain; the need to invest in new manufacturing systems, and user reluctance in new materials without knowledge of performance over long time periods. This section reviews product development theory to understand how such substitution challenges are navigated. In doing so, the following three questions are addressed: (1) Whether to adopt a new material? (2) When to adopt a new material? and (3) How to adopt a new material?

3.2 Whether to adopt?

The starting point for any substitution is the decision to select a new material. Hence, material substitution innovations were first (and often still are) viewed from the perspective of material selection theory. Fisch and Ross [38] referred to this perspective as asking whether to adopt a new material or not.

Research tackling this question has focused on the material selection processes, trade-off analysis methods and quantitative ranking systems [39]. An effective selection process is necessary to be able to consider numerous materials and processes that themselves have numerous properties to consider. The optimal solution may be unknown to the designer considering the extensive number of permutations possible. Therefore, research has focused on quantitative organisation methods that can assess options efficiently. Perhaps the most elegant organisation of materials the designer may consider are so-called Ashby plots [40]. M. F. Ashby pioneered material selection processes by focusing on four key aspects of selection; material, feature, geometry and process. Ashby's method combines features and geometries to form functional performance metrics. The functional performance metric is then used to search a material database. Plotting the functional performance metric for several materials allows comparison of different materials and material groups.

Figure 3.1 shows an example of the technique. In this example, the conductance of four metals are compared with respect to their density and cost. The figure shows the variation in price over the last ten years (x-axis) and the conductivity available for different alloys (y-axis). Both axes are normalised for mass so that the diagonal gridlines show factor differences in cost for the same conductance. Four of the most common conductors are shown in the figure, but the quantitative approach allows any material with known conductivity, density and market price to be compared. The technique provides the designer with a concise and accessible format to compare materials.In the example below, the figure provides justification for selecting aluminium in applications that required high conductivity per kg at a low and stable price.

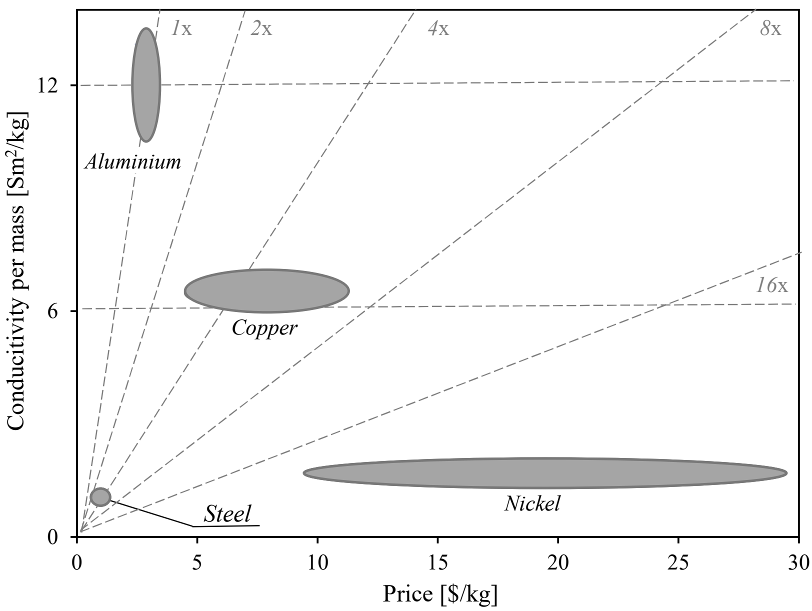

Figure 3.1: Relationship between conductivity and cost (normalised for mass) of aluminium, copper, steel and nickel. The defined regions cover variations in alloy conductivity and price variations over the last 10 years [42]. The diagonal lines show factor increases in cost for equal conductance.

While such tools help identify and compare candidates, they offer less utility in the final selection and development of the product. Cebon & Ashby [40] refer to the final selection as the

’supporting information’ step where unstructured information plays the most significant role. This information is often non-quantitative and highly detailed. It may relate to key information about necessary processes, availability, recyclability and overall cost. This unstructured information is difficult to gather and analyse. It may be contained within in-house reports, undocumented in purchasing relationships or diffuse across several suppliers, governing organisations or customer preferences. Furthermore, essential information may not exist, and a development project would be necessary to discover the performance.

Research tackling the question of whether to adopt a new material has established useful tools for the designer. Unfortunately, such quantitative tools struggle to incorporate the various economic, organisational, social and environmental factors that contribute to the success of material substitutions. Appropriately considering these factors involves asking a different, temporal question: When to adopt?

3.3 When to adopt?

When a new material offers a justifiable technical advantage over an existing is success guaranteed? Most cases are not straightforward. Success factors are multidimensional and competing with an incumbent solution can require more than performance or cost parity [43].

Fisch & Ross’s [38] analysis of 101 material substitution projects identified competition, expected development time and price fluctuations as key factors for initiating substitutions.

Product developers can make informed decisions on competition and expected development time by considering innovation diffusion theory. Material substitutions are excellent examples [44] of the classical S-shape curve of innovation adoption [43]. Positioning material substitutions on the innovation adoption curve provides insight into the market prevalence and technology maturity. Early adopters may face less competition, but the typically low technological maturity requires a long development time.

Historically, price fluctuations have been a primary driver for pushing materials along the innovation curve. Price fluctuations in material substitution are best observed through isoquant and isocost curves. Isoquant and isocost curves provide the relative price advantage of different materials by showing the quantity required for a set production (isoquant) versus the quantity available for a given cost (isocost). This comparison quantifies the cost barrier to substitution and clearly shows the sensitivity of material options to price fluctuations [38, 45]

While developments in price, maturity and market prevalence are foundational in the timing of substitution, the context in which material substitution decisions are being made is changing. Historically, material substitutions have been viewed as a source of innovation and technological transformation [46]. However, faced now at the cusp of a new transformation towards sustainable innovation, material substitution is no longer a source of transformation but a necessary solution across many product domains. The United Nations International Resource Panel report [47] identifies material substitution as a vital strategy in reducing emissions of greenhouse gases, which, in turn, emphasises the need for effective material substitution development processes.

As such, the question now facing product developers is not *when*, but instead, *how* to adopt substitute materials!

3.4 How to adopt?

Substituting a material in a product involves a development process. Researchers have proposed numerous different processes to describe how products are developed [48]. Figure 3.2 shows the typical stages in transforming an idea into a deliverable product by Ulrich & Eppinger [49]. The process shows the logical progression in maturity of a product. The process captures key characteristics of product development such as novelty through concept development and complexity management through detailed design.

The level of maturity for different material substitution projects can vary significantly. It may be possible to assess a minor change by modifying existing analysis work and conclude there is no impact to system level design. In such a case, it may be possible to performed only limited "testing and refinement" before progressing directly to the "production ramp up" phase. In comparison, another substitute material could allow entirely new concepts to be considered and require going through all stages in development.

Figure 3.2: The major stages in transforming an idea into a deliverable product [49].

Regardless of the development scope, testing will be a critical aspect for material substitution product development. In Ulrich & Eppinger's development process "testing and refinement" is a final activity in the sequential development of the product. However, inside (and across) each of these major stages is an iterative process that typically involves testing [50]. Iterations are a distinguishing feature of product development that enables progressive knowledge generation, the ability to perform concurrent efforts in different disciplines and a mechanism to accommodate changes that occur during development [51].

Managing iterations and different test activities is a crucial aspect for material substitutions. At an elementary level testing is fundamental in material characterisation and the discovery of material properties. Then further into development, testing is necessary to assess the product's performance against design requirements and as demonstrations for stakeholders or marketing purposes. The system engineering V-model describes test philosophy applied in product development [52]. The V-model break down the design of a complex system into its sub systems, assemblies, and parts. The components are then recombined through the development by verifying performance at each level. In this methodology a test is used to verify and validate the design decisions for customer approval or risk reduction. From this viewpoint, it is the stakeholders approach to risk that defines the scope of testing.

Existing research has covered a range of possible methods and process steps for developing products. While this research includes important aspects for material substitutions, such as test philosophy, there is limited guidance specifically focused on refining the process to tackle the unique development challenges faced in material substitutions projects.

Chapter 4

Methodology

4.1 Research strategy in brief

The aim of this thesis is to provide knowledge for the advancement of aluminium conductors in battery systems. To gain a broad understanding and explore the predominant challenges in this field, this thesis was conducted in parallel to involvement in a industry project developing aluminium busbars for marine battery systems. The methods applied in this thesis were defined to contribute to the challenges faced in the development project and by limitations identified in existing theory and empirical results. The specific activities performed in this thesis included: (i) interviewing engineering professionals to gather insights into material substitution development processes (ii) reliability testing aluminium conductor solutions adapted to the specific needs of battery system applications and (iii) establishing the electrical performance of a new bimetallic joining process.

A brief description of the marine battery development project is provided in the next section. Then in the following sections the methodology for four studies that form the thesis are described.

4.1.1 Discovering context: Developing aluminium busbars for marine battery systems

The research design for this thesis has been guided by involvement in an industrial development project. The project was called Aluminium Busbars for Marine Battery Systems (Grant ES635028) and its objective was to develop aluminium busbars for battery systems. The development project was initiated by a battery manufacturer with the goal to substitute the copper busbars used in their battery system with aluminium busbars. The project was performed in partnership with a material supplier and research institute.

My involvement in the project was over a two year period from autumn 2019 to autumn 2021. This included over 40 project meetings and 8 supplier meetings as well as further unstructured meetings between development teams. I conducted on-site observations over two visits to production facilities and provided test execution support to a suppliers conductor qualification testing. Reviewed documentation included project plans, status reports, test specifications and field notes taken throughout all activities.

The development project provided an industrial context and understanding of state of the art performance on aluminium conductors. These insights were used to guide the specific research studies that I conducted for this thesis.

4.1.2 Thesis methods overview

The specific research design, methods and measurements that constitute this thesis formed as it progressed but a guiding structure of past, present and future was evident from the early stages:

- Focusing on the past, I decided to explore product development and material substitution theory by investigating previous projects. Aluminium has been used as a conductor for over 100 years so its successful substitution will not require discovering its fundamental properties, but instead carefully considering its technical limitations and how these relate to all aspects of the product being developed. Hence, I considered a deep understanding of development strategy for material substitutions as critical starting point. From a material selection perspective, aluminium's price and performance are glaring advantages over copper, however, this in turn raises the question, what is preventing substitution and what product development strategies are suitable for tackling such substitution barriers? To understand these challenges, I interviewed engineering professionals about the development process for material substitution in previous projects and conducted a literature review on the integration of test activities into the development process.
- In the present, it was apparent that existing literature on aluminium's electrical contact reliability does not cover configurations suited for battery systems. Bolted configurations dimensioned for battery systems have not been tested under the operational and environmental conditions applicable for battery systems. Therefore, I performed reliability testing of aluminium busbar suited for battery systems. This included accelerated corrosion and current cycling life testing.
- Towards the future, there is a growing need for interfacing aluminium and copper conductors with reliable connections. Improving the operational limits of Al-Cu connections, while maintaining reliable performance, will be key in facilitating the growing demand for electrification. Therefore, I evaluated a new bimetallic joining process and benchmarked its performance versus existing processes. In doing I devised a new measurement method that can be used to compare the electrical performance of aluminium and copper joining processes.

An overview of the papers and methods that form the thesis is shown in Figure 4.1. The following sub chapters provide justification for the relevance and validity of the data gather in each study.

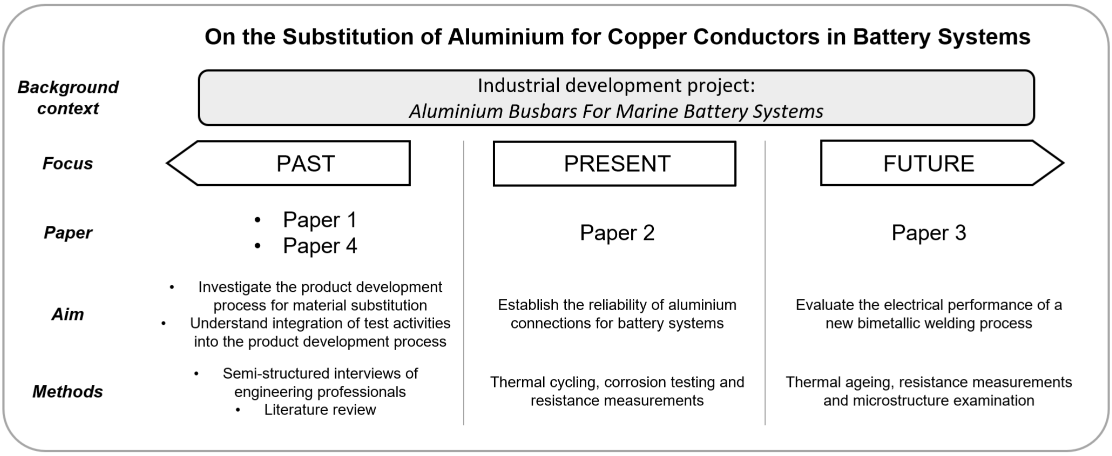

Figure 4.1: Overview of the thesis structure and methods. Background context was obtained through involvement in an industrial development project. Three research papers form the thesis each with a focus on previous experience, current challenges and future potential for aluminium conductors.

4.2 Paper I: Understanding Material Substitution Through Interview Case Studies

4.2.1 Objective

Substituting materials in products is in many cases a time consuming and expensive affair. The first paper in this thesis investigates why complications arise in material substitution projects. Starting from a broad perspective, the aim was to understand the product development barriers and enablers for material substitution innovations.

The barriers and enablers were analysed considering a technology and innovation management perspective that focused on technological capabilities. In a technology management context, *technological capability* is the ability to make effective use of technical knowledge and skills to develop products (or processes, existing technology and skills) in response to a competitive business environment [13].

4.2.2 Methodology

For this first paper, the objective was explanatory and required an understanding of a complex topic in a real-life business context. I therefore chose case study methodology as it is well-suited for explanatory investigations [53]. Applying case study methodology allowed previous development projects to be analysed and did not require control over the investigated phenomenon [53].

The cases studied were industrial development projects that involved material substitution. Such projects typically involve collaboration among several parties in a material supply chain from designers, suppliers, and customers. To find suitable interview candidates, I initially reached out to 14 companies using established contacts from known material substitution projects affiliated with my university. These initial contacts then led to further recommendations for suitable interview participants within their companies and five additional partner companies.

Before contacting any participant I conducted online research and customized the invitations to explain why their company was of interest to the study. This involved reviewing the company's product portfolio and examining online press releases related to material substitution innovations. I also identified their position within the material supply chain and company size. Five interview companies were finally chosen to exhibited diversity in terms of size, industry, and supply chain setting, providing a rich pool of data for qualitative analysis [54], similar to previous studies on material substitutions [55].

I conducted semi-structured interviews using the interview guide shown in Table 4.1. The interview guide was included in the meeting invitation and the participant was requested to reflect upon at least one specific substitution project prior to the meeting. The interview guide was structured in three parts covering the main aspects of material substitution projects.

- The first line of questioning was used to establish the development context. Participants were not restricted in the type of material substitution project they had chosen to discuss and hence it was important to control for key characteristics. The start of the interview focused on understanding of the stakeholders involved, their motivations, and the main challenges identified at the project's outset. This included discussion about the extent of market pull versus technology push for the substitution, the intended scale (mass-produced or custom-manufactured) and overall development timeline for the substitution project.
- The second part of the interview guide focused on the development process. The questioning explored the tasks undertaken, their sequence, and planned or encountered iterations during development. The semi-structured approach allowed the participants to explain how technological knowledge was gathered and utilised in relation to their business practice and existing products. This section constituted the greatest portion of the interview allowing participants to talk freely about the aspects, events or situations that caused the most progress or hindrance to the substitution.
- The final stage of the interview reflected on barriers and enablers discussed in the previous section and asked the participant to form an overall qualitative assessment of the project success. The assessment included comparison of cost, function and quality of the final product in relation to the existing product before substitution. Particular focused was spent on comparing the barriers identified at the initiation of the project versus the obstacles encountered throughout development.

Five interviews were conducted using internet conferencing software during the third quarter of 2020. All interviews were recorded and had durations ranging from 45 to 75 minutes. Participants were encouraged to provide relevant data on the project to enhance the qualitative data

Table 4.1: Interview guide used to guie the discussion through the three major topic areas (Context, Process and Outcome)

Development Context	**Development Process**	**Development Outcome**
- Background/motivation for project	-Development activities (design/analysis/test activities to realise development)	- Comparison of initially identified barriers to the substitution and actual barriers after completing project
- Development structure/ stakeholders involved	- Design stage gates, iterations, early/late analysis and test results, model structure, customer involvement	- Assessment of improvement of material substitution
- Development novelty/ Familiarity of stakeholders with existing and substitute material	- Encountered development challenges (design changes/ manufacturing processes/customer requirement updates..)	
- Development timeline		

provided during the interview [56] but it was not mandatory. Table 4.2 provides an overview of the demographic information for the sample of cases.

Transcriptions of all interviews were made for coded analysis. The initial coding structure was based on the interview guide but was refined during the analysis process, which involved multiple iterations through the transcriptions. The final coding structure is presented in Table 4.3.

Table 4.2: Demographic information about organisation, industry and interview participants for each case study

Case	Company	Employees	Industry	Interviewee
C1	Company A	1000+	Mechanical Hardware	Senior Design Engineer
C2	Company B	100-500	Construction	Chief Technical Officer
C3	Company C	100-500	Automotive	Senior Process Engineer and Lead Design Engineer
C4	Company D	100-500	Construction	Structural Engineer
C5	Company E	100-500	Construction	Chief Quality Officer

Table 4.3: Coding structure used to analysis interview transcripts

Node	Subnode
1. Context	1.1 Drivers 1.2 Novelty 1.3 Production Scale 1.4 Stakeholders 1.5 Timeline
2. Process	2.1 Barriers 2.2 Enablers 2.3 Development Activities 2.4 Standards
3. Outcome	3.1 Expected versus actual barriers 3.2 Substitution improvement
4. Participant	4.1 Experience

4.3 Paper II: Establishing Reliability of Bolted Aluminium Connections for Battery Systems

The second paper in the thesis steps down from a high-level strategy perspective and focuses on a specific practical aspect, the nuts and bolts of using aluminium busbars in battery systems. In doing so, the focus turns from analysing technological capabilities in past projects to addressing a specific technical limitation. The paper moves from how to substitute aluminium in a development context, to what specifically can aid aluminium substitution development.

4.3.1 Objective

Bolted connections are a fundamental and versatile connection method for the assembly of battery systems. Currently, existing literature on the reliability of bolted aluminium connections has been performed for high power AC transmission applications [57]. The performance of connections with applicable dimensions and operating conditions for DC battery systems has not yet been established. Unfortunately, existing results from high power AC testing is insufficient to predict the long term performance of design configurations suited for DC battery systems. The important parameters impacting electrical resistance degradation and corrosion mechanisms for aluminium connections have been established but as the influencing parameters are numerous and non-linear their predictive reliability is limited. As such, experimental data is needed to establish the long term performance of aluminium bolted connections dimensioned for battery systems.

Bolted connections for battery systems differ from previously tested configurations as they transfer less current, use smaller conductors, and the connection is ideally formed with only one bolt to reduce size, weight and cost. Unfortunately, a single bolted connection removes redundancy and does not offer parallel current paths that reduce resistance. Therefore, determining the reliability of single bolted connections is critical for using aluminium connectors in battery systems.

The following major steps were undertaken to establish the methodology to test a bolted aluminium connection suitable for battery systems:

- Define materials (§4.3.2) and contact surface properties (§4.3.4)
- Define connection configuration including bolt, washer and tightening torque (§4.3.3)
- Define accelerated environmental (§4.3.5) and operational conditions (§4.3.6) capable of indicating long term performance.

4.3.2 Materials

Three alloys were selected for investigation:

Table 4.4: Electrical and mechanical material properties

Material	Conductivity [% ICAS]	Yield Strength (0.2%) [MPa]	Hardness
AA1070 H0	62.7	27	19 Brinell
AA6101 H19	55.2	192	74 Vickers
Cu-ETP	100	320	103 Vickers

1. AA1070: A high conductivity, low strength aluminium alloy in annealed (H0) condition. The AA1000 series aluminium is high purity aluminium without alloying elements and was chosen as it offers the best conductivity available for aluminium.
2. AA6101: A slightly lower conductivity but higher strength aluminium alloy in strain hardened (H19) condition. AA6101 compromises slightly conductivity due to the alloying elements. This alloy was chosen as the best compromise in conductivity for greatest gain in strength.
3. ETP Cu: A high conductivity grade copper alloy (Electrolytic Tough Pitch Copper (ETP)) was chosen as an industry standard comparison to the aluminium alloys performance.

The electrical and mechanical material properties for all three alloys is provided in Table 4.4 . The chosen aluminium alloys were selected for their high conductivity and provided an envelope of the possible structural strength for high conductivity aluminium alloys. Table 4.4 shows that the aluminium's bulk and surface properties are below that of copper.

4.3.3 Connection method

The bolted connection was formed by connecting two 100 mm long busbars with a bolt, nut and washers. The busbars were cut to 25 mm width from 3 mm plate. The resulting 75 mm^2 cross section provides a current capacity of 100 A typical for battery systems. A thickness of 3 mm was considered prototypical for battery busbars by which the current capacity can be easily increased or decreased by adjusting the busbar width. An illustration of the bolted connection was shown previously in Figure 2.3.

The connection's bolt, washers and tightening torque are key parameters in determining the connections reliability [31, 58]. Ideally, aluminium bolts would be used to bolt aluminium busbars therefore avoiding mismatching thermal expansion stresses (which would occur between steel bolts and aluminium). However, the more expensive aluminium bolts would reduce the cost saving advantage of introducing aluminium busbars (and introduce complexity in a system using steel bolts in all other locations). Therefore in this study, the cheaper and more widely available A4 steel bolts were considered as baseline. A4 stainless steel bolts were chosen as they would provide good corrosion resistance against the accelerated corrosive environment conditions to be tested.

In any case (aluminium or steel bolts), spring washers are needed to compensate for relaxation of the aluminium busbar over time. For this study, Belleville spring washers were used and

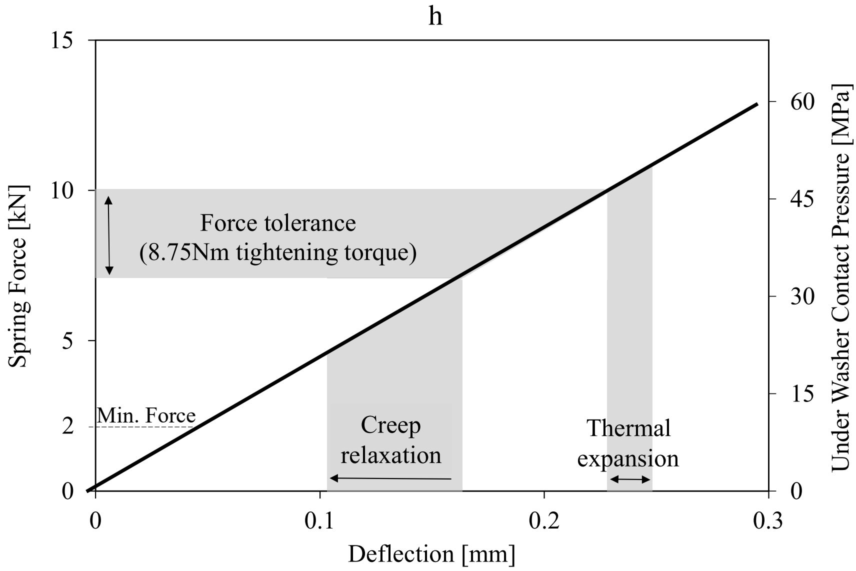

Figure 4.2: Calculated spring washer force from assembly tightening torque with subsequent changes due to creep and thermal expansion operational conditions

sized to accommodate both the thermal expansion mismatch of the bolts and the potential creep relaxation of aluminium. Therefore, the use of steel bolts was compensated and aluminium bolts were unnecessary.

The spring washers were sized to accommodate potential creep relaxation, thermal expansion and provide the necessary force to achieve a low resistance. The creep relaxation and thermal expansion set the required working distance of the spring. Considering the 3 mm busbar thickness and a maximum creep of 1%, the required spring expansion was 0.06 mm (2 x 3 mm x 0.01). Opposingly, the required spring compression under thermal expansion would be 0.012 mm for a conservative 150 °C temperature rise (6 mm x 150 C x (2.3 - 1)x10^{-5} mm / mm C). The spring therefore need to maintain the necessary force over a working length of $\geq$ 0.072 mm.

Having established the spring working length, the second aspect to determine is the necessary clamping force. A high clamping force is desirable to ensure a low resistance connection between the busbars. However, the applied force must be balanced against the strength of the busbar material.

Existing literature on the relationship between contact force and resistance indicated a contact pressure of 9 MPa would achieve the minimum resistance between aluminium contacts [24–27, 59]. A higher contact pressure than 9 MPa does not typically reduce resistance but lowering the pressure can rapidly increase the resistance. It is therefore important the spring can accommodate for creep relaxation while also preventing the stress from increasing significantly (which would accelerate creep relaxation). Translating a 9 MPa contact pressure to a force based on the washer area (215 mm^2) resulted in a minimum clamping force of 2 kN. The spring washer to be selected therefore needed to maintain a minimum force of 2 kN under all conditions.

Two A4 stainless steel DIN6796 spring washers were chosen to provide the clamping force. Two A4 DIN6796 washers require a minimum force of 8.5 kN to flatten. The minimum compression distance of the spring is 0.2 mm and would provide more than 2 kN after 0.05 mm compression. This would give a minimum working length of 0.15 mm which was two times the budgeted 0.072 mm. Spring washers were only used under the bolt head and not on both sides of the busbar, as the spring working length was sufficient. And having no washers on the nut side is representative of situations where washers cannot be mounted on both sides of the busbar (e.g. threaded busbar interfaces or captive nuts).

Figure 4.2 shows the relationship between force and displacement for the two A4 DIN6796 spring washers described above. A tightening torque of 8.75 Nm was chosen to provide a force through the bolt of 7 kN to 10 kN (considering the friction uncertainty). The force in the spring will then increase or decrease based on its relative displacement under creep and thermal expansion. The figure shows the minimum contact force is maintained in all situations. On the right hand side of the figure, the equivalent stress under the washer is shown. The stress can exceed 45 MPa in worst case indicating the higher strength of AA6101 H19 will provide benefits in preventing creep and withstanding the higher contact pressures.

In contrast, the copper configuration did not use spring washers sized to maintain a minimum force or working distance. Instead, a split lock washer and standard flat washer was used as an example of standard industry practice for copper busbars. A tightening torque of 10 Nm was applied. This configuration was chosen as a representative baseline to compare the performance of aluminium to the standard practice of copper busbars.

4.3.4 Contact surface properties

The final aspect of the contact configuration is the contact surface properties. Modifying aluminium's surface properties can improve the resistances long term reliability. Contact surface properties are critical to mitigate fretting failure of electrical contacts as discussed in §2.3. In this study, two effective surface preparations for aluminium were investigated: (1) brushing with the use of lubricant and (2) electroless nickel platting. These two preparations were chosen as they both have shown good performance in power distribution applications yet differ in cost and assembly implications.

Abrading aluminium's surface with a lubricant can remove its non conductive oxide layer. It also can increase the surface roughness (i.e. create larger asperities) allowing it to pierce through the oxide on the interfacing surface. Both of these factors allow larger areas of metal to metal contact to be formed [31]. However, removing non-conductive oxide from the surface and increasing the surface roughness only provides an advantage up until a point. In fact, generating non-conductive oxide particles between the surfaces or a non-planar surface that only touch in a few location can reduce the real metal to metal contact area. Choosing a suitable abrasion technique is therefore important to ensuring a low and repeatable resistance. In this study, a brushing abrasion method was chosen having been shown to be the most effective technique for wrought aluminium [27].

In addition, a contact lubricant was applied to the surface during brushing. Aluminium oxide forms near instantaneously on an exposed aluminium surface so to allow time for assembly the lubrication was applied prior to brushing [27]. Some proponents argue that applying lubricant before brushing can trap oxide particles in the lubricant and reduce the cleanliness of the process, but in this study we followed the research consequence of using Pentetrox A-13 and applying before abrasion [25, 29]. Pentetrox A-13 was applied to both contact interfaces. Brushing was performed in one general direction with a steel brush which had 5 rows of 50 mm long, 0.33 mm diamater steel wires.

The alternative surface preparation method was nickel plating. Nickel has good conductivity and does not oxidise rapidly[60]. It also has suitable chemical compatibility with aluminium so will not diffuse into brittle intermetallic compounds with aluminium [61]. Unfortunately, nickel is a more expensive metal and requires an external process prior to assembly. This can reduce the cost advantage of aluminium as well as complicate repair. But conversely to brushing, a plated surface is less complicated to assemble and does not introduce contamination risks.

The nickel coating was applied in a two step process. First an electroless nickel-phosphorus layer was applied then followed a nickel sulfamate layer. The respective layer thickness were in average less than $5\,\mu m$ and $10\,\mu m$. In similarity to brushed interfaces, an electrical contact lubricant was applied prior to assembly to reduce the suseptability to fretting failure [30]. The contact lubricant was NyoGel 760.

Having now described the materials, surface preparations and connection methods in the previous three sections, the following two sections describe the test conditions. The test conditions were defined to highly accelerate the electrical connection's lifetime performance. The test conditions are split into two sections. The first defines the environmental conditions, and the second the operating conditions.

4.3.5 Environmental conditions

Defining a highly accelerated test environment requires first defining the nominal environmental conditions. What environmental conditions would a bolted aluminium connection experience within a battery system over its lifetime? While answering such a question requires consideration of specific battery system design details and its application, several general considerations can still be made. Usually, bolted connections in a battery system will be housed within an enclosure. An enclosure protects uninsulated conductors from foreign objects and unintentional contact and prevents direct exposure to outdoor conditions. However, such enclosures are not typically hermetically sealed [62], and external bolted connections may be necessary to connect battery modules to external system components. Therefore, it can be assumed that bolted battery connections are not exposed directly to outdoor conditions. However, condensation is possible given the temperature and pressure fluctuations that occur over seasonal or geographical variations.

Then, in addition to condensation, it is important to consider the presence of corrosive accelerants. Measurements in various environments have shown that corrosive gases such as SO2, NO2, H2S, and Cl2 are present in most environments that a battery system would operate [63]. Henriksen's [63] measurements show that such gases could not be excluded even for well-controlled indoor environments. Therefore, the nominal environmental conditions for a battery system are likely benign, but a low frequency of condensation is likely to occur in the presence of corrosive accelerants.

ISO standard 9223 provides classifications for the corrosivity of different environments. The above description would place a battery system between a C2 and C3 environment. A C2 environment is an unheated space with varying temperatures and low-frequency condensation. A C3 environment has moderate condensation and corrosive accelerants. As it is impossible to position most battery systems into one applicable classification, three corrosive environments were tested. The three environments were: (A) no environmental exposure, (B) C2 level exposure and (C) C3 level exposure. The three testing levels explored the corrosive environment's importance and encompassed variations across different battery system applications.

The next question was how to accelerate the long-term effects of C2 and C3 environments for a battery system application. Carlson et al. [64] have assessed various corrosion testing standards and provided guidelines for accelerated tests. They identified a combination of salt mist exposure and humid thermal cycles as the most representative accelerated corrosion test for electrical devices, automotive and marine applications. Such a test regime could then also be combined with exposure to corrosive accelerants to achieve a more aggressive environment. Ideally, the corrosive accelerants would be combined in a mixed-flowing gas test such as the Battelle test. However, the test equipment required to conduct a Battelle test is prohibitive. So instead, a static exposure test developed by Vogel [65, 66] was conducted. Vogel's "Fast hydrogen sulphide (H2S) for contacts and connections" exposes the test samples to a concentration of H2S inside an autoclave. The test is specifically developed to detect vulnerabilities in electrical connections with H2S identified as the most critical corrosion accelerant. The temperature inside the autoclave is 25°C with 75% relative humidity. 1000 ppm of H2S is added to the autoclave and allowed to decay to 0 ppm over 6 hours. The application of H2S is then repeated each day for a total of three days.

The sequence of test exposures for both the moderate (B) and high (C) level corrosion environments is shown in Fig 4.3. Each test sequence was performed over four weeks, and the specific conditions for each exposure are stated in Table 4.5. The humidity exposure was performed in a Heraeus Votsch HC 0057 humidity chamber, the salt mist exposure was performed in an Ascott CC1000t salt mist chamber, and the H2S test was conducted in a custom autoclave. Resistance measurements were taken over each contact once per week using a RNB 320-KD30005D power supply at 5A and Fluke 289 multimeter. The location for probe measurements were marked with a centre punch 5 mm from the contact overlap therefore providing a repeatable position. Measurements were taken in both directions, and an average was reported.

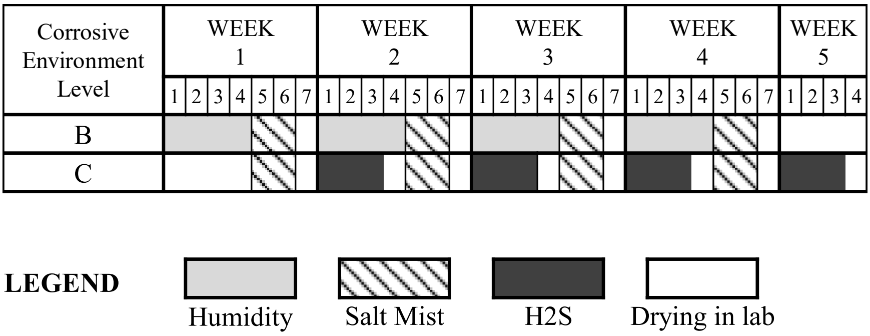

Figure 4.3: Sequence of exposure to corrosive environments for accelerated corrosion levels B and C

Table 4.5: Procedure for each accelerated corrosion environment

ID	Procedure Each Week
A	No accelerated corrosion environment
B	75% relative humidity (2 hrs per day for 4 days) Salt mist chamber, 35 °C 5% NaCl (2 hrs per day for 2 days) Drying, <50 % relative humidity (1 day)
C	Salt mist chamber, 35 °C 5% NaCl (2 hrs per day for 2 days) Drying, <50 % relative humidity (1 day) 1000 ppm H2S at 75% relative humidity (3 days) Drying, <50% relative humidity, (1 day)

4.3.6 Operating conditions

Bolted connections in battery systems need to withstand repeated charging and discharging cycles. These high current levels, followed by periods without any current transfer, will cause heating and cooling of the busbar and contact. The resulting temperature change can cause motion in the contact interface that can degrade the contact, as discussed earlier on fretting failure in §2.3. Determining the specific number of cycles and temperature variations a bolted connection must tolerate would require considering design and application specifics. However, several general considerations can still be made. Typically power connections are limited to a 45 °C temperature rise over a maximum ambient temperature of 45 °C [59]. A maximum temperature of 90 °C provides a margin for insulating materials that cannot tolerate temperatures above 100 °C and lowers the risk of igniting foreign objects. Li-ion battery systems are likely to have lower maximum operating temperatures than 90 °C. Cell temperature control is critical to the storage efficiency and long-term performance [67]. Several battery manufacturers specify a maximum

Table 4.6: Definition of three current levels for thermal cycling

Level	Heating	Dwell	Cooling
1	450 A (330 s)	333 A (600 s)	0 A (700 s)
2	450 A (630 s)	393 A (600 s)	0 A (700 s)
3	500 A (600 s)	435 A (600 s)	0 A (700 s)

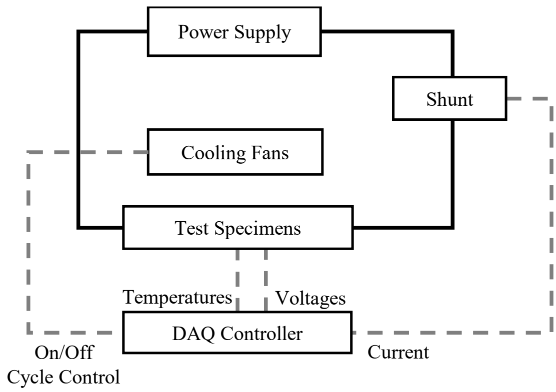

Figure 4.4: Current cycling test setup schematic

60C operating temperature for the cell. Therefore, a busbar connected directly to the cell should ideally have a lower temperature than 60C to act as a heat sink rather than a heat source to the cell. However, downsteam conductors may have higher operations temperatures and external failures may also result in higher temperatures.

The International Electrotechnical Commission (IEC) has issued a test standard (IEC61238 [68]) for aluminium, copper and bimetallic (Al/Cu) connectors power cables rated up to 1 kV. The philosophy of the electrical test is to thermally cycle the contacts at a temperature above the temperature variations that will occur during normal operation. The standard consolidates several national test standards for aluminium contacts. Contacts which have passed the test have been used in the field for decades, providing an empirical basis for the methodology and criteria.

The IEC61238-1-1 test specifies 1000 heat cycles with an 85 °C temperature rise. As the purpose of this study on bolted connections for battery systems was not to qualify a connection for a specific application but to assess and compare several configurations, the test scope was expanded from the nominal IEC61238 criteria. The samples were tested with three duty levels. The initial baseline duty cycle targeted an approximate 70 °C temperature rise, the second level 95 °C and the final 120 °C. The duty cycle for each level is shown in Table 4.6.

All samples were connected in series to a time-controlled Agilent 6681A DC power supply. Cooling fans were programmed to turn on and off in unison with the cooling and heating cycle. The temperature was measured on each busbar chain using a type T thermocouple. Voltage pick-up lines were attached permanently to each contact at a distance of 5 mm from the overlap. An Agilent 34970A multimeter with a multiplexer was used to scan all voltage tracks five times within 30 s. A schematic of the current cycling setup is shown in Figure 4.4. Four-point resistance measurements were performed at 100 A in both polarities, and the average resistance was reported. Thermal cycling was performed continuously and stopped regularly to perform resistance measurements. The average interval between resistance measurements was 78 thermal cycles, and the maximum was 183 thermal cycles.

4.4 Paper III: Evaluating Bimetallic Welds: Hybrid Metal and Extrusion Bonding

The two previous papers investigated (1) past experiences in material substitution product development strategy and (2) reliability evidence for the immediate implementation of aluminium bolted connections. The third paper in this thesis looks to the future by evaluating a new bimetallic joining process with the potential to improve the electrical performance of aluminium and copper connections.

Hybrid Metal Extrusion and Bonding (HYB) is a novel bi-metallic joining process invented by Professor Grong at the Norwegian University of Science and Technology [69]. The process was initially invented for aluminium-aluminium bonding but, in recent years, has been proven successful in bonding bimetallic joints [70]. The third paper in this thesis evaluates the electrical performance of this new process for joining aluminium and copper.

The following sub-chapters describe how the test samples were manufactured (§4.4.1), tested (§4.4.2) and characterised (§4.4.3 & §4.4.4).

4.4.1 Sample manufacturing

The test samples were manufactured from a 3 mm aluminium alloy plate and a 3 mm x 40 mm copper bar. The two metals were offset by 4 mm and joined with the HYB process's filler material, AA6082. The HYB process uses specialised rotating dies to extrude filler material into joint lines continuously. The rotating die is called the HYB PinPoint extruder and uses a rotating pin to pull the filler wire into a set of rotating dies. The wire is pulled by the friction of the rotating die walls that form an extrusion chamber. The extrusion chamber is then closed by a stationary abutment in the extruder housing, which forces the filler material down into the joint.

The PinPoint extruder pin tip for this application had a 7 mm diameter and 12 mm shoulder. The pin tip was positioned adjacent to the copper surface so that the die grooves in the pin machined 3 mm into the aluminium. The copper was on the advancing side of the pin so that the machined aluminium was pulled backwards and mixed with the filler material behind the welding direction. The deposition rate was controlled to fill the joint in one pass. The deposition rate is determined by the filler wire diameter (Ø1.4 mm) and the rotation speed of the pin (350 rpm). The materials were placed on steel backing and 0.1 mm shim underlay under the joint line. An illustration of the pin tip and joint configuration is shown in Figure 4.5.

For a complete description of the HYB process and a detailed analysis of welding parameters, see Sandnes [72].

4.4.2 Thermal ageing

The manufactured welds were inspected with optical and electron microscopy. The weld was examined to assess the interface's mechanical and chemical structure. And the resistance was measured to quantify the interface's electrical performance.

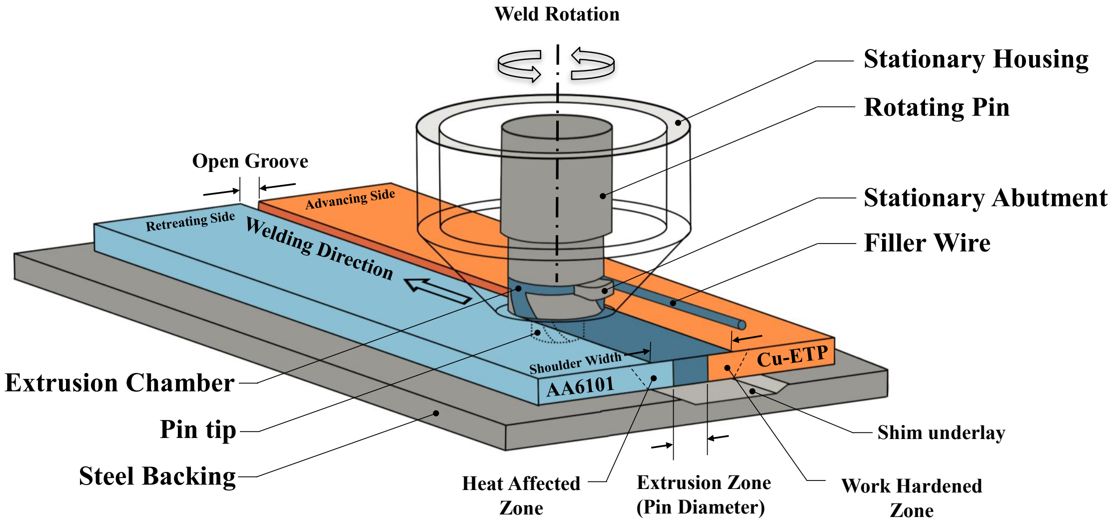

Figure 4.5: Schematic illustration of HYB PinPoint extrduer for butt joining Al-Cu. Prior to the joining operation the two base plates are clamped onto a steel backing with a fixed spacing of 4 mm, where the aluminum plate is placed on the retreating side (RS) and the copper plate on the advancing side (AS) of the joint. *Image source: Fig. 1 © A.Elkjaer et al [71], Creative Commons Attribution 4.0 International Public License*

Once the as-welded configuration was characterised, the crucial question was how the weld would tolerate operating conditions within a battery system. As previously discussed in §2.4, Al-Cu welds are susceptible to degradation at elevated temperatures. Diffusion of Al and Cu across the interface is temperature dependent and can increase the interface resistance. The increased resistance can then cause a negative feedback loop where the higher resistance generates higher temperatures, which increases diffusion and thus increases resistance.

As such, the two key characteristics of an Al-Cu weld are the intermetallic growth rate versus temperature and the weld structure's impact on electrical resistance. A thermal ageing test was conducted to characterise these two characteristics. The test consisted of heating the samples at constant temperature and measuring the intermetallic growth and electrical resistance.

Thermal ageing was performed at three temperatures (200 °C, 250 °C and 350 °C). Three levels were chosen to plot the diffusion rates on an Arrenuis plot and determine the diffusion rate at lower temperatures. The temperature levels were chosen by balancing the two following constraints:

- The elevated temperatures should be as close to the intended operating temperatures to prevent inducing mechanisms that would not occur within the lower operational temperature range
- The temperature should be sufficiently elevated to induce observable changes within 1000 hours of heating to fit with the scope of testing.

Typical operating temperatures for battery system conductors are below 100 °C and the intended life can be more than 10, 20 or even 30 years. Existing literature indicated that intermetallic growth rates would be observable (several microns) within hours at temperatures above 200 °C [36]. The three temperatures (200 °C, 250 °C and 350 °C) were therefore chosen as a range suitable to establish the temperature dependent reaction rate.

Interestingly, the method of heating has been found to impact the intermetallic growth rate. Research by both Braunovic and Alexandrov and Solchenhach et al. showed that self heating by electrical current resulted in faster intermetallic growth rates [36, 73]. Electrical self heating would be the most representative method of heating for an electrical conductor however external heating is performed in most research studies on weld diffusion rates [33–35, 74–77]. In this study external heating in a thermal oven was performed to aid comparison to research on alternative welding methods. After heat treatment, the samples' electrical resistance was measured using a novel four-point resistance measurement technique and the intermetallic thickness was measured using electron microscopy. The thickness measurements were used to establish a diffusion model of intermetallic growth that could prevent growth at the lower operating temperatures.

4.4.3 Electrical resistance measurements

A novel electrical resistance measurement method was used to determine the weld's impact on interface resistance. Existing measurement methods were reviewed and it was discovered that comparing electrical performance across different studies was challenging. Measurement methods in other studies were not provided as a normalised value. The reported resistances are dependent on the specific measurement parameters and the tested sample geometry. Therefore, a direction comparison between the electrical resistance of different welding methods was not possible.

To compare the electrical performance of different welding techniques, a new metric, "specific interface resistivity", was proposed. A new measurement technique was then designed to measure the metric accurately. The metric and measurement technique is equivalent to the approach used in measuring thermal contact resistance [78]. The measurement technique is based on a series of measurements that are extrapolated on both sides of the interface. Extrapolating on both sides of the interface allows the difference across the interface to be determined despite the physical distance across the interface being microscopic. The difference across the interface can then normalised versus the applicable cross-sectional area for comparison.

Implementing the measurement technique required designing a dedicated measurement jig. Figure 4.6 shows a drawing of the measurement jig. The jig base accommodated a 40 mm long test specimen with a 2 mm x 2 mm cross-sectional area. Two supply terminals clamped the test specimen in position and provided a voltage drop over the sample. The test specimen geometry was long and thin to provide a uniform current flow and measurable voltage drop along the specimen length. The voltage drop along the length of the specimen was measured with 17 voltage pickups integrated into a removable top clamp. The top clamp was guided into position with alignment surfaces on the jig base.

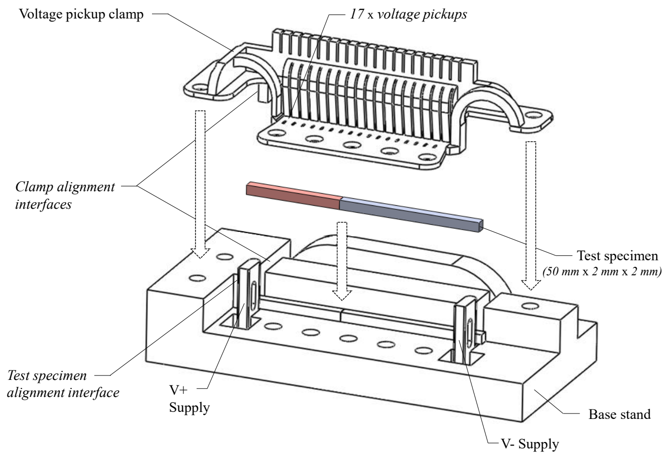

Figure 4.6: Electrical measurement jig for four point measurements, comprised of base stand and clamp with 17 voltage pickups. *Image source: Fig. 2 © A.Elkjaer et al [71], Creative Commons Attribution 4.0 International Public License*

The voltage measurements performed along the length of the sample could then be plotted and extrapolated to the measured location of the interface as shown in Figure 4.7. Plotting the data in this manner allows the increase of voltage across the interface to be directly identified from the graph. The interface voltage drop (V) can then be transformed into a normalised value by dividing by the measurement current (I) and multiplying by the cross-sectional area (A). This increase is defined as the "specific interface resistivity" of the welding method (η), Eq. 4.1.

$$\eta = \frac{VA}{I} \tag{4.1}$$

The metric allows direct comparison between different welding techniques. In a similar manner to how the electrical resistivity of a material is used to determine the resistance of conductors based on length and cross-sectional area; "specific interface resistivity" allows the resistance of an interface to be determined from the cross-sectional area of the interface.

The metric can also be calculated using the data available in published studies, albeit with reduced accuracy compared to the measurement method outlined above. Typically, studies perform one measurement of the weld resistance (R_J) and compare the measured resistance to the theoretical resistance based on the bulk material's resistance. For example, if the measurement is 5 mm on either side of the weld, the measurement will be compared to the theoretical resistance of 5mm aluminium and 5 mm copper. The difference between the theoretical and measured is then attributed to the interface's resistance. Unfortunately the difference is unique

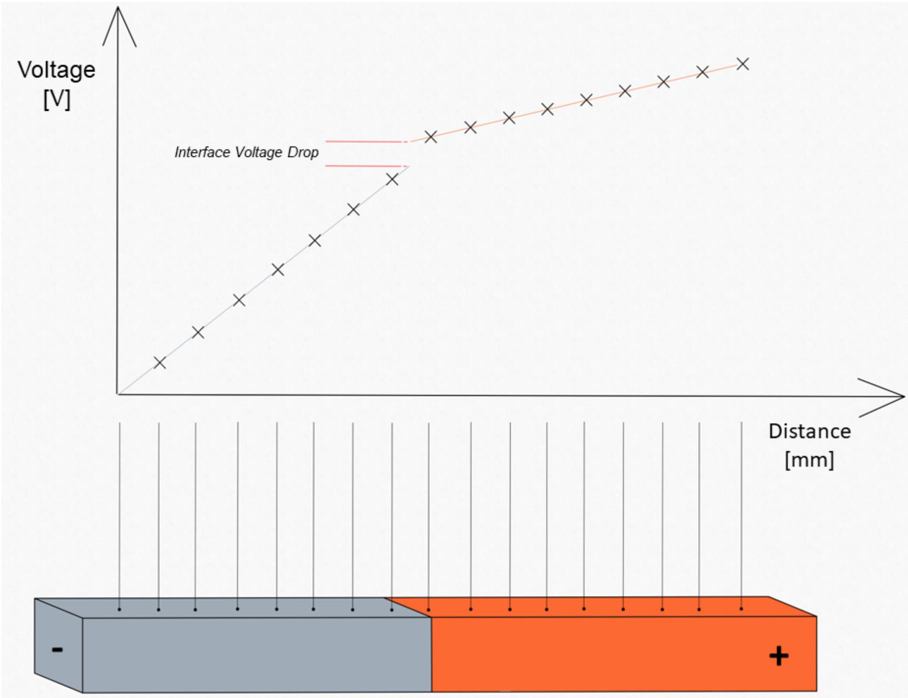

Figure 4.7: Voltage drop over test specimen plotted versus distance. The voltage drop is extrapolated to the interface to determine the interface voltage drop

to the measurement geometry and cannot be compared easily across different welding methods. However, the weld resistance can be transformed into "specific interface resistivity" when the measurement distance from the interface on both sides (x_{Cu} & x_{Al}), cross-sectional area (A) and material resistivities (ρ_{Cu} & ρ_{Al}) are reported. Calculation of "specific interface resistivity" from the specimen geometry and material properties is shown in Eq. 4.2. Unfortunately, this method is less accurate than the extrapolation method shown in Figure 4.7 as the bulk materials are compensated by calculation rather than by measurement (extrapolation) and the single distance measurements have greater uncertainty.

$$\eta = AR_J - (\rho_{Cu}x_{Cu} + \rho_{Al}x_{Al}) \tag{4.2}$$

4.4.4 Microstructure examination

Each sample was inspected using microscopy to observe the intermeatllic compounds present and measure their thickness. In the as welded condition the intermetallic layer was so small that transmission electro microscopy (TEM) was necessary to measure the intermetallic layer thickness. The 200 °C and 250 °C heat treated samples also required TEM inspection, but for the

350 °C heat treated samples the intermetallic growth was sufficient for the layers to be measured using scanning electron microscopy.

4.5 Paper IV: Literature Review on the Integration of Test Activities into the Product Development Process

In addition to the three journal papers that form this thesis, a conference paper was presented at the Conference on Systems Engineering Research. The presented paper was a literature review on the role of test activities in the development process. The literature review analysed research investigating the utilisation of testing within the product development process.

A test is an activity performed on an object, under specified conditions, which is used to evaluate its performance [79]. Test activities will be performed at many different levels during a material substitution innovation. This will range from low level material testing up to entire system validation [80]. Materials are tested to determine their performance and there exist numerous standards for testing of different material properties. This allows the performance of different materials to be compared which aids in their selection. However, once these materials are implemented in the design, the performance is no longer being evaluated against a comparative standard but instead the customer requirements. A significant translation from customer requirements is required to be able to perform testing at the optimum time and location. Defining an appropriate strategy that covers when, what and how to test is a vital component of discovery and verification during product development.

A literature review on testing was considered relevant to material substitutions for 3 reasons:

1. Material substitutions will inevitably involve testing, at a minimum, for low level material characterisation
2. Testing is typically a substantial cost and time commitment during development with it's strategy of key importance to innovation [81]
3. Testing is an effective tool for discovery of unknown factors. Unknown factors of both the existing and substitute material were found to be consequential in Paper 1 therefore emphasises the importance of testing in material substitutions.

4.5.1 Literature review methodology

The literature review was conducted following procedural guidelines by Machi and McEvoy [82]. The literature search was conducted using the SCOPUS peer-reviewed electronic database and limited to the following journal sources; Research in Engineering Design, Journal of Engineering Design, Systems Engineering, Concurrent Engineering, CIRP Journal of Manufacturing Science and Technology, Journal of Mechanical Design. The journals were chosen based on their high reputation with the field of engineering design and product development theory. The fields Title, Abstract and Keywords were searched for any combination of product development AND testing keywords. The list of product development and testing keywords used in the search are shown in Table 4.7.

The resulting literature was then processed according to the inclusion and exclusion criteria listed below. The literature was excluded in three steps. First the criteria was applied considering the articles title, then the abstract and then on critical review of the paper. The number of articles in each stages is shown in Figure 4.8 with 34 articles forming the basis for the literature review.

Table 4.7: Keywords used in literature search. The search must include atleast one product development keyword AND one testing keyword from the list.

Topic	**Keywords**
Product Development	"product development" OR "product design" OR "system development" OR "design and development" OR "system design" OR "design method*" OR "design theory" OR "system engineering” OR "v model" OR "development process" OR "design process" OR "design for" OR "robust design" OR "knowledge based engineering" OR "knowledge management" OR “organi*ational learn” OR “model-based” OR “set*based”
Testing	"test and evaluation" OR "test plan" OR "test definition" OR "test specification" OR "test verification" OR "test validation" OR "test management" OR "verification activities" OR "physical test" OR "virtual test" OR "test activities" OR "testing" OR "set*based test” OR “prototyp*”

Inclusion criteria:

- The engineering design process, new product development practice, system engineering/design, development activities or design approach.
- Test activities or processes were integral to the paper’s research question/thesis.
- Test activities were discussed in relation to the design process (e.g. use of test results contributing to design process/decisions).
- Tests were analysed as a method of verification/validation or source of discovery/ learning/reusable knowledge.

Exclusion criteria:

- “Test” used in reference to testing paper’s hypothesis and not product development test activity. This includes the “testing” of a new design method – if test activities are not relevant to that design method.
- Studies addressing solely software products or construction projects.
- Studies focusing solely on the design improvement of a specific product for the benefit of that specific product – as opposed to development process/design methodology in general.
- “Design methodology” referred to as the methodological design of the study itself (i.e. not product development methodology).
- Virtual prototype, virtual testing, simulation or analysis research not discussed in a context of impact on the design/development process (i.e. research into improving specific modelling technique for a design problem was not included).

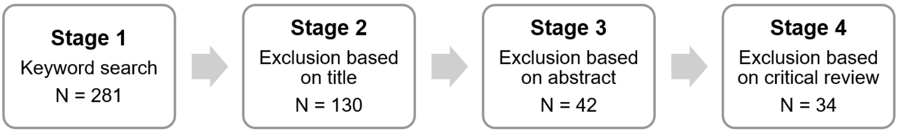

Figure 4.8: Exclusion of the discovered literature was performed in three steps. The figure shows the number of articles in each stage of processing.

Chapter 5

Contributions

"The abundance of aluminium in nature, the purity of its ores, its wonderful lightness and adaptability to numerous purposes, indicate that the goal of the aluminium industry will be reached only when this metal ranks next to iron in its usefulness to mankind. To assist this consummation by furnishing all the reliable information about aluminium, to thus enlighten the general reader, help the workman, instruct the student, assist the experimenter, and in every way to speed the industry on its destined path, is the raison d'etre of this work."

Joseph William Richards, Aluminium (1896) | [83]

5.1 List of publications

This thesis is structured as a collection of academic research papers produced during the doctoral studies. The thesis includes three journal papers (two are published and one under review), an international conference paper and commentary letter. The publications are shown in the tree diagram below showing their relation to the major topic they address. The full titles and references were listed in §1.5. The following sub-chapters provide a brief overview of the main contributions from each paper and the full papers are provided in Part II.

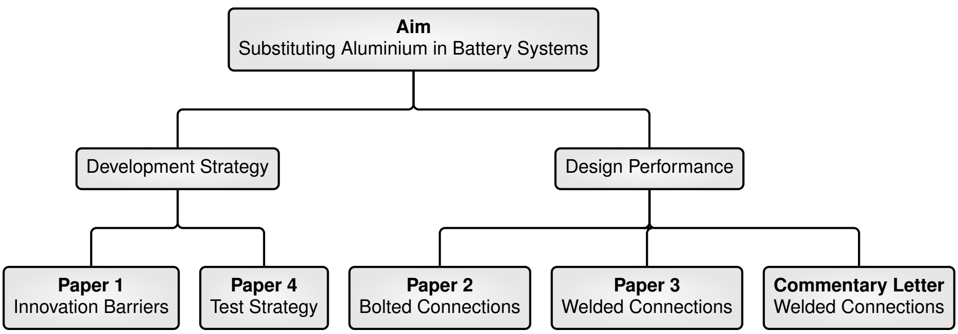

Figure 5.1: Tree diagram showing the publications in this thesis and their association to topic addressed

5.1.1 Authors contributions statements

Author contributions statements are provided in §1.5.1.

5.2 Paper I Contributions

Title	Barriers and Enablers for Material Substitution Innovations: Positioning Exploration and Exploitation Learning Processes
Authors	A. Elkjaer & G.Ringen
Purpose	Investigate technological capabilities needed to facilitate material substitution development projects

The first paper in this thesis provides contributions to engineering management theory. Barriers and enablers faced in material substitution projects were gathered by interviewing engineering professionals. Analysis of the results led to the following contributions:

5.2.1 A Novel Material Substitution Framework

This paper proposes a novel framework for the analysis of material substitution projects. The framework is shown in Figure 5.2 and categorises barriers faced in material substitution projects. The framework is formed by combining the knowledge domains of the existing and substitute material with a Johari-style window [84].

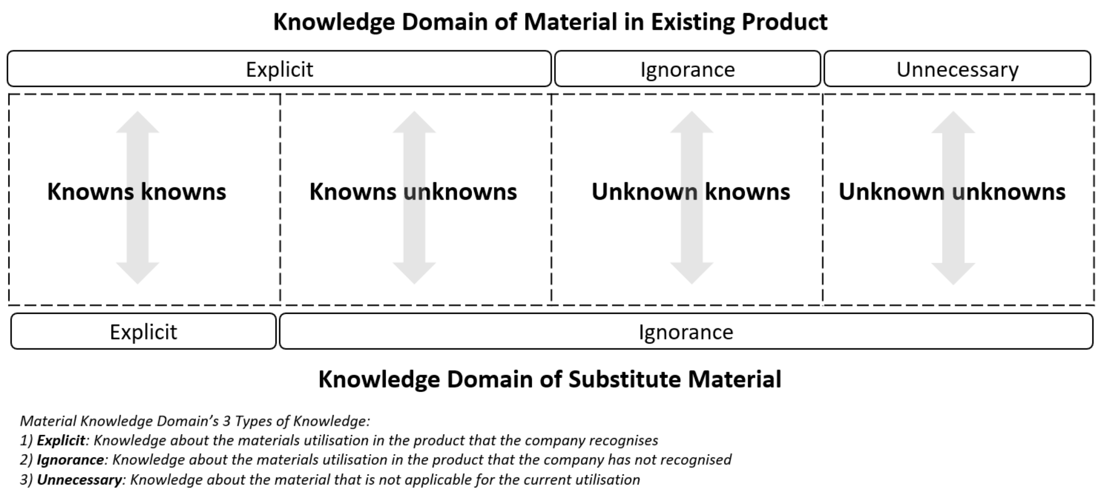

Figure 5.2: Material substitution framework that categorises the barriers to substitution relative to the knowledge of the existing and substitute materials

The framework splits the knowledge domain of both the existing and substitute material into two categories, explicit knowledge and ignorance. Explicit knowledge covers all aspects of the material that is important to the product's success that the company can recognise. In other words, the designer knows an attribute of the material and knows this attribute contributes to the success of the product. The explicit knowledge of the existing material will be greater than that of the substitute material at the start of a development project. Indeed, a development project is initiated because there is some aspect of the new material that we are ignorant of and need to discover. Therefore, two knowledge categories can be formed by comparing the amount of explicit knowledge of the existing material to the substitute material. The first category is known knowns; these are material characteristics that are known for both the existing and substitute material. Substitutions are often initiated from known knowns (e.g. lower material price), or they will be acknowledged limitations that do not prevent substitution (e.g. lower mechanical strength). The second category is then known unknowns; these are the limits in the knowledge of the substitute material that have been identified and must be overcome to realise the product with the substitute material. For example, this could be manufacturing parameters that are unknown for the substitute material.

In contrast to the first half of the framework, which is based on explicit knowledge of the existing material, the second half is derived from attributes that are not recognised in the existing material. Unrecognised attributes in the existing material can be split into two groups when viewed from the perspective of the substitute material. Firstly, there is ignorance about the existing material that will be important to know for the substitute material. These are hidden elements in the existing design that serendipitously work without knowledge of their importance. Learning about the importance of these attributes from the existing material would be possible through a greater understanding of the existing product. This category is called unknown knowns because they would be identifiable in the existing material if a greater understanding of the existing product existed. In contrast, the second category of unrecognised attributes are unknown unknowns. This category is formed by aspects that are unnecessary or unrelated to the performance of the existing material but will impact the success of the substitute material. The defining attribute in this category is that unknown unknowns cannot be identified through a greater understanding of the existing product.

The framework provides a novel description of material substitution development projects. The framework allows the barriers to substitution to be categorised, providing a lens to compare different substitution projects. This perspective can then be used to apply existing engineering management theory to aid material substitution projects.

5.2.2 Managerial implications

When applying the framework to analyse the five case studies presented in the paper, unknown knowns were found to pose the most significant innovation barriers to material substitution. In four of the five cases, interviewees reported that the major barrier faced in the substitution related to an attribute known for the existing material but not identified as a problem for the substitute material at the outset of the development.

Exploiting existing knowledge to overcome defined challenges or experimenting with new possibilities to discover novel solutions are considered conflicting approaches in organisation learning [85]. March's [85] analysis of organisational learning referred to these two approaches as deciding between explorative and exploitive processes.

These two approaches were classically viewed from a broad perspective of innovation cycles. For example, the automotive industry has applied exploitative processes to refine internal combustion engines for over a century. Whereas recently explorative processes have been implemented to develop novel energy storage systems. This paper analyses the combination of explorative and exploitative processes specifically for material substitution. Materials are a fundamental constituent of physical products impacting many development domains. Across all these domains, experience has been accumulated with the existing material. Exploiting this knowledge to reduce development time and cost is critical to successful substitution. However, experimentation and exploration of the substitute material is also needed to learn about the new material.

Balancing exploration and exploitation is a prevailing problem in product development and the presented framework offers a perspective that can be applied specifically for material substitutions. The apparent misconception for material substitutions is to apply excess attention to exploitative processes to tackle acknowledged limitations. Such an approach focuses narrowly on the established benefits and identified limitations of substitution. While a narrow focus allows rapid learning cycles that limit cost and provide observable progress, the findings presented in this paper warn that such an approach is particularly vulnerable to blind spots in material substitution projects. Instead, the framework encourages reflection that the existing design may contain significant latent knowledge which should be discovered. As such, exploration of the substitute material should not only focus on identified weaknesses but attempt to discover entrenched barriers that are latent in the existing material.

5.3 Paper II Contributions

Title	Reliability of Bolted Aluminium Busbars for Battery Systems: Effect of Nickel Coating and Corrosive Environment
Authors	A. Elkjaer, G.Ringen, R.Bjørge, Catalina H. Musinoi Hagen, Sigrid Lædre & Niklas Magnusson
Purpose	Assess the reliability of bolted connections for battery systems.

The second paper in this thesis provides contributions to electrical contact theory. A test was performed to investigate the reliability of bolted aluminium connections dimensioned for battery systems. The following contributions were presented:

5.3.1 Test methodology

A new test methodology for combined environmental and operational testing of bolted aluminium connections was created. The methodology is based on a combination of existing test standards [68] specifically adapted for battery systems. In particular, the methodology utilises accelerated environments that are easier to perform than complicated mixed-flow gas tests, while still representing harsher environments than simple humidity testing.

Current best practice for reliability testing electrical contacts calls for environmental testing [86] however, existing test methodology for the qualification or comparison of aluminium contacts is currently lacking in the literature. Accelerated corrosion testing is limited in its ability to determine long-term performance for specific cases. Rather, corrosion testing can establish degradation mechanisms, identify weaknesses and provide a comparative ranking. The presented test methodology therefore provides a comparative basis for testing of aluminium pressure contact in battery systems.

5.3.2 Performance of bolted aluminium contacts for battery systems

The study provides test data for the reliability of bolted aluminium configurations that are not previously tested. A compact single-bolted connection suited for battery systems was defined and tested in four different configurations. The results showed:

- Nickel-plating aluminium provided a reliable electrical contact that tolerates exposure to corrosive environments and operating conditions that exceed typical design requirements for battery systems. The nickel plating was applied in a two-step process. First, an electroless nickel-phosphorus layer was applied followed by electroplating with nickel sulfamate. The electrical contact did not degrade under repeated exposure to salt mist spray and H2S. The accelerated corrosive environment was designed to identify vulnerabilities in the long-term performance of electrical contact operating in a C3 corrosive environment.

Subsequent thermal cycling of the test samples showed they could withstand significant temperature cycling above applicable design temperatures.

- Lubricated and brushed bolted aluminium contacts are also a viable connection configuration for a battery system. The lubricated and brushed contacts were inferior to nickel-plating contacts with failures in both Al1070 and Al6101 configurations. Investigation of the failures indicated that variability in the initial contact resistance was critical to the contacts' long-term performance. The results showed that obtaining a joint performance factor below 1.5 was essential for stable performance under thermal cycling.

5.4 Paper III Contributions

Title	Electrical and Thermal Stability of Al-Cu Welds: Performance Benchmarking of the Hybrid Metal Extrusion and Bonding Process
Authors	A. Elkjaer, J.A. Sørhaug, G.Ringen, R.Bjørge & Ø. Grong
Purpose	Establish the design envelope of a new Al-Cu welding method and the methodology for comparison to existing processes

The third paper in this thesis provides contributions to bimetallic welding theory. A test was performed to establish the electrical performance of a novel bimetallic welding process. The following contributions were presented.

5.4.1 Specific weld resistivity

A new metric, specific weld resistivity, was proposed to evaluate bimetallic weld resistance. The new metric provides a basis to compare different welding techniques and their degradation. The new metric provides normalisation that is currently lacking in metrics for bimetallic weld resistance. The three most common existing metrics used to characterise bimetallic welds are:

1. Comparison of Measured Weld Conductivity to Theoretical Conductivity
2. Joint Performance Factor
3. Relative Resistance Increase

All three metrics are volumetric resistance measurements that measure the resistance of the interface as well as the bulk materials on both sides. An illustration of the measurements required to calculate all three metrics is shown in Figure 5.3. All three measurement metrics use the volumetric measurement V_j of the joint. V_{Cu} and V_{Al} are additional measurements that are only necessary for joint performance factor. The weakness of all three measurement techniques arises from the measurement V_j.

The most common metric (Comparison to Theoretical Conductivity) compares V_j to the expected theoretical value. The theoretical measurement is calculated by knowing the length of each bulk material being measured. For example, if the voltage measurement is 5 mm from the interface on both sides of the material, the resistance should equal the sum of the voltage drop of 5 mm for both materials. The difference between the measurement and the theoretical value is then attributed to the interface resistance. In this way, the contribution of the interface can be quantified.

Unfortunately, the measurement is highly susceptible to the chosen measurement length and the accuracy to which it is known. It is apparent from this metric that the contribution of the interface can be reduced by increasing the measurement length. A 50%Al - 50%Cu weld that had 90% of the theoretical conductivity with a measurement length of 10 mm would have 95% conductivity over 20 mm despite the interface resistance remaining unchanged in both

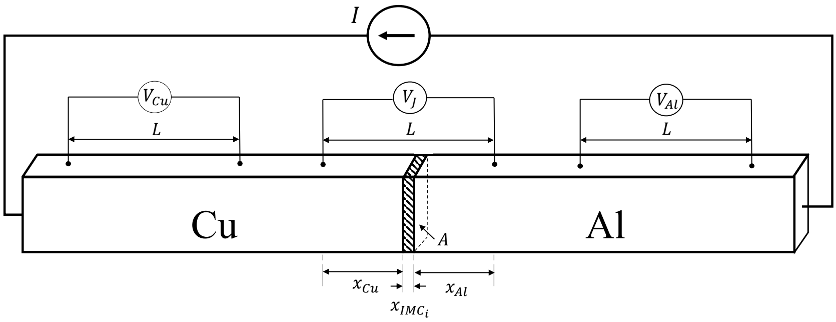

Figure 5.3: Measurement of weld voltage drops (V_j, V_{Cu} & V_{Al}) necessary to calculate common bimetallic weld metrics. *Image source: Fig. 9 © A.Elkjaer et al [71], Creative Commons Attribution 4.0 International Public License*

measurements. Therefore it is not possible to compare even the same welding process using this metric without knowing the measurement length.

It follows from this limitation that measurement length should be minimised. Minimising the measurement length ensures the interface provides the greatest relative contribution in the volumetric measurement,V_j. However, when the measurement length becomes smaller, the accuracy of the bulk material's contribution decreases. The bulk material's contribution must be known to calculate the theoretical conductivity correctly. Should the theoretical calculation be assumed 50% copper and 50% aluminium, but in fact, the measurement was 55 % copper and 45 % aluminium, then the higher conductivity of copper will reduce the resistance and mask the interface resistance.

Another source of inaccuracy in the theoretical calculation is the accuracy of the bulk conductivities. The joint performance factor accounts for this error source by measuring the bulk conductivity of both materials. A measurement is made on both bulk materials over a length equivalent to the joint measurement. The joint performance factor is then calculated as the ratio of the joint measurement versus the two bulk measurements. Unfortunately, the joint performance factor only compensates for the bulk conductivity and is still dependent on the measurement length and accuracy under which it is measured.

Similarly, the metric, relative resistance increase, is dependent on the measurement length. Studies that use this metric simply measure Vj and compare it to subsequent measurements of V_j after the sample has been exposed to different environments (e.g. thermal ageing [34, 36]. In this way, the change in the sample's electrical performance is quantified. But again, the metric is dependent on an arbitrary measurement length. Increasing the measurement length will reduce the apparent resistance increase of the interface. While reducing the length increases the difficulty in achieving repeatable measurements.

All of the above limitations are mitigated by using the presented metric, specific weld resistivity. Specific weld resistivity is not a property of a volume but instead only of area. This allows the metric to capture only the contribution of the interface. Furthermore, normalising the measurement with respect to the area allows the different weld geometries and processes to be compared directly.

5.4.2 Benchmarking of Al-Cu HYB welds

The second contribution in this paper showcases the performance of the Hybrid Metal and Extrusion Bonding process in joining aluminium and copper. The intermetallic growth rate was experimentally determined and compared to similar processes. The results show a slower growth rate than all other processes, indicating that HYB welds can tolerate higher temperatures for longer than all comparable joining processes. Furthermore, the electrical interface resistance of HYB welds is shown to be negligible in the as-welded and artificially aged conditions. The negligible resistance indicates that the interface will not generate heat that would accelerate intermetallic growth. Overall, the slow intermetallic growth and negligible interface resistance, even after significant heat treatment, demonstrates the exciting potential for HYB welding in electrical applications.

5.5 Paper IV Contributions

Title	A Literature Review of the Integration of Test Activities into the Product Development Process
Authors	A. Elkjaer, G.Ringen, & C. Haskins
Purpose	Review research on the utilisation of test activities during product development

The aim of this conference paper was to discover research on the definition and utilisation of testing within the product development process. The research was categorised based on its aim, planning perspective and stage in development the testing was considered. The following contributions were presented.

1. A comprehensive overview of research into test activities during the product development process was presented. The research was organised both with respect to the stage in development and the perspective on testing considered. The overview offers both researchers and practitioners a guide to identify research related to their specific interests.
2. A framework was proposed based on a synthesis of the discovered research. The framework categorised the perspectives on test planning into three groups; test strategy, test objectives and test design. Research into test strategy considered the overall approach to test activities to define why testing should be performed. Research into test objectives considered what specific objectives should be defined for test activities, and test design research assessed how a test activity for a specific objective can be performed in the most optimal manner. The framework provided insight into the role and relationship testing has in the product development process. In doing so, the framework offers assistance in integrating test processes into the development process.

5.6 Commentary Letter Contributions

Title	Correction to Braunovic & Alexandrov's 1994 Article on Intermetallic Compounds at Aluminum-to-Copper Electrical Interfaces
Authors	A. Elkjaer
Purpose	Correct an analysis of intermetallic growth rates from a previously published study

In addition to the scientific papers that form this thesis a short communication commentary letter was also published. The letter comments on Braunovic & Alexandrov's 1994 paper [36] on intermetallic compounds at aluminum-to-copper electrical interfaces. Braunovic & Alexandrov paper is a foundational paper on the welding of aluminium to copper for electrical applications. The paper's results are shown in multiple textbooks [28, 57] and the paper has had an increasing citation rate since publication. However, as part of the work on this thesis an error in their analysis was discovered and commentary letter written to correct the analysis.

Braunovic & Alexandrov's research measured the electrical resistance and intermetallic thickness of heat treated Al-Cu friction welds. The welds were subject to heat treatment from both an external heat source (furnace) and electrical self heating. The heat treatment was used to simulate the thermal exposure that welds would experience during operation in electrical applications. However, the test was accelerated by increasing the temperature so that results could be measured over a rather limited time frame (max 120 hours). This resulted in the heat treatment being performed from 200 °C to 520 °C whereas maximum operational temperatures of conductors are typically below 200 °C. Braunovic & Alexandrov related their results to lower operational temperatures by predicting the intermetallic thicknesses at 100 °C, 150 °C and 200 °C. The predicted intermetallic thicknesses were then plotted over a time period of 1 hour to 10 years.

Braunovic & Alexandrov plot of intermetallic growth rates between 100 °C to 200 °C has been reproduced in textbooks [28, 57] and a research paper [87]. The plot shows intermetallic growth at 100 °C exceeds 1 µm in a few hours under electrical self-heating. The short time frame needed to exceed 1 µm is particularly limiting for use in electrical applications as Braunovic & Alexandrov highlight that 2 µm of intermetallic compounds can greatly reduce the structural integrity of Al-Cu welds [34, 36].

However, an error in Braunovic & Alexandrov prediction of intermetallic growth rates between 100 °C to 200 °C was discovered and in fact the growth rate is approximately 10 times slower than presented. The updated analysis provided in the commentary letter indicates that Al-Cu welds are less vulnerable to limited exposures above 100 °C. Highlighting this error has a meaningful impact on the utilisation of Al-Cu welds in electrical applications. The updated analysis raises the operational window above 100 °C therefore improving fault tolerance and increasing design margin for qualification testing.

Chapter 6

Conclusion

The aim of the thesis was to provide knowledge for the advancement of aluminium conductors in battery systems by investigating the development process for material substitution, and by evaluating electrical connection methods. To achieve this aim, the thesis has presented case study and experimental research into past experiences, current obstacles and the future potential for aluminium conductors.

Looking first to the past, the thesis presents a case study based on interviews with engineering professionals. The interviews investigated previous development projects that have involved a material substitution. Analysing the results led to a framework categorising the barriers faced in material substitution projects. The framework provides a novel perspective to view material substitution projects and reflect upon appropriate strategy. The framework positioned the most challenging aspects of previous substitution projects as arising from ignorance in the existing material. The framework provides a theoretical basis for the formation of such barriers. The defined categories were then assessed with existing theory on exploration and exploitation learning processes to guide development strategy. Deciding when to *explore* the design space or when to optimise (*exploit* current information) is challenging in development projects. In material substitution projects, where a fundamental building block (the material) is exchanged, this thesis emphasises the importance of discovering hidden barriers. This part of the thesis has not explicitly focused on aluminium substitution in battery systems. Rather, the findings are pertinent to material substitutions generally and applicable for the material substitutions that will be necessary for society to transition to more sustainable solutions in many domains.

The second paper in this thesis addressed immediate concerns for introducing aluminium conductors in battery systems. Battery systems are a rapidly growing market, and specific test standards for aluminium connections are yet to be established. This thesis combined battery system design requirements and existing research for bolted connections to define configurations suitable for battery systems. These configurations were tested with a tailored regime to verify performance. The results showed that nickel-plating aluminium conductors achieved robust electrical connections that could withstand environmental and operational conditions above those required for battery systems. The experimental study has provided practicable evidence for introducing bolted aluminium connections in battery systems.

The final step of the thesis looked to the future by benchmarking a novel bimetallic joining process. Interfacing aluminium and copper is a fundamental challenge for introducing aluminium in established copper systems and connecting lithium-ion cell current collectors to external circuits. This thesis presented the first electrical characterisation of the Hybrid Metal Extrusion and Bonding (HYB) process. The results were compared to alternative processes, and a new metric for the electrical resistance of bimetallic welds was proposed. The HYB joints were found to have a negligible interface resistance and slower intermetallic growth rate than all other comparable processes. The findings showcase the exciting potential for the HYB process to expand the design envelope for aluminium and copper connections.

References

[1] Peter Mark Roget. *Thesaurus of English words and phrases, classified so as to facilitate the expression of ideas*. 1853.

[2] Gavin M. Mudd and Simon M. Jowitt. Growing Global Copper Resources, Reserves and Production: Discovery Is Not the Only Control on Supply. *Economic Geology*, 113(6): 1235–1267, 2018.

[3] Ira Joralemon. Joralemon Reviews Copper Situation. *Engineering and Mining Journal*, 117:113, July 1924.

[4] Dana Ashkenazi. How aluminum changed the world: A metallurgical revolution through technological and cultural perspectives. *Technological Forecasting and Social Change*, 143:101–113, 2019.

[5] W H Preece. On electrical conductors. *Minutes of the Proceedings of the Institution of Civil Engineers*, 75(1884):63–78, January 1884. doi: 10.1680/imotp.1884.21616.

[6] Gary P. Tarcy, Halvor Kvande, and Alton Tabereaux. Advancing the industrial aluminum process: 20th century breakthrough inventions and developments. *JOM*, 63(8):101, August 2011. ISSN 1543-1851. doi: 10.1007/s11837-011-0120-4.

[7] W. W. Lewis. Present Status of High Voltage Transmission of Power. *The Journal of the Institute of Electrical Engineers of Japan*, 42(411):754–800, 1922.

[8] Elaine D. Bunten, John L. Donaldson, and Eugene C. McDowell. Hazard assessment of aluminum electrical wiring in residential use. *NASA STI/Recon Technical Report N*, NBSIR 75-677, 1974.

[9] IMF Primary Commodity Prices, December 2021. URL `https://www.imf.org/en/Research/commodity-prices`.

[10] Frank Messner. Material substitution and path dependence: empirical evidence on the substitution of copper for aluminum. *Ecological Economics*, 42(1-2):259–271, 2002.

[11] BloombergNEF. Electric Vehicle Outlook. Technical report, 2021.

[12] Elicia Maine, David Probert, and Mike Ashby. Investing in new materials: a tool for technology managers. *Technovation*, 25(1):15–23, January 2005. ISSN 0166-4972. doi: 10.1016/S0166-4972(03)00070-1.

[13] Jun Jin and Maximilian Von Zedtwitz. Technological capability development in China's mobile phone industry. *Technovation*, 28(6):327–334, 2008.

[14] S. W. Melsom and H. C. Booth. The efficiency of overlapping joints in copper and aluminium busbar conductors. *Journal of the Institution of Electrical Engineers*, 60(312): 889–899, 1922.

[15] EATON. Copper vs. Aluminum Conductor. Technical Report PA202008EN, 2016.

[16] Siemens AG. Siemens white paper: Aluminum versus copper conductors. Application of aluminum conductors in Bus Way systems for more sustainable Data Centers. Technical report, 2014.

[17] Wilson Power Solutions. Aluminium v Copper. Technical report, 2018.

[18] Gene Berdichevsky, Kurt Kelty, J. B. Straubel, and Erik Toomre. The Tesla Roadster Battery System. *Tesla Motors*, 1(5):1–5, 2006.

[19] Pengcheng Zhu, Dominika Gastol, Jean Marshall, Roberto Sommerville, Vannessa Goodship, and Emma Kendrick. A review of current collectors for lithium-ion batteries. *Journal of Power Sources*, 485:229321, 2021. Publisher: Elsevier.

[20] M. F. R. Zwicker, M. Moghadam, W. Zhang, and C. V. Nielsen. Automotive battery pack manufacturing – a review of battery to tab joining. *Journal of Advanced Joining Processes*, 1:100017, March 2020. ISSN 2666-3309. doi: 10.1016/j.jajp.2020.100017.

[21] Gerard Bree, Dan Horstman, and Chee Tong John Low. Light-weighting of battery casing for lithium-ion device energy density improvement. *Journal of Energy Storage*, 68:107852, September 2023. ISSN 2352-152X. doi: 10.1016/j.est.2023.107852.

[22] J.B: Straubel, D Lyons, L Berdichevsky, S Kohn, and R Teixeira. Battery pack and method for protecting batteries, March 2010.

[23] Ian M. Hutchings. Leonardo da Vinci s studies of friction. *Wear*, 360:51–66, 2016.

[24] M. Braunovic. Effect of Current Cycling on Contact Resistance, Force, and Temperature of Bolted Aluminium-to-Aluminium Connectors of High Ampacity. *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, 4(1):57–69, March 1981. ISSN 1558-3082. doi: 10.1109/TCHMT.1981.1135772.

[25] M. Braunovic. Evaluation of Different Types of Contact Aid Components for Aluminum-to-Aluminum Connectors and Conductors. *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, 8(3):313–320, September 1985. ISSN 1558-3082. doi: 10.1109/TCHMT.1985.1136513.

[26] S. Schoft. Joint resistance depending on joint force of high current aluminum joints. In *Proceedings of the 50th IEEE Holm Conference on Electrical Contacts and the 22nd International Conference on Electrical Contacts Electrical Contacts, 2004.*, pages 502–510, September 2004. doi: 10.1109/HOLM.2004.1353163.

[27] R. L. Jackson. Significance of surface preparation for bolted aluminium joints. *IEE Proceedings C (Generation, Transmission and Distribution)*, 128(2):45–54, March 1981. ISSN 2053-7921. doi: 10.1049/ip-c.1981.0007. Publisher: IET Digital Library.

[28] P. G. Slade. *Electrical contacts: principles and applications*. CRC press, 2nd. edition, 2017. ISBN 1-138-07710-0.

[29] Milenko Braunovic. Effect of contact aid compounds on the performance of bolted aluminum-to-aluminum joints under current cycling conditions. *IEEE transactions on components, hybrids, and manufacturing technology*, 9(1):59–70, 1986.

[30] M. Braunovic. Fretting in nickel-coated aluminium conductors. In *Thirty-Sixth IEEE Conference on Electrical Contacts, and the Fifteenth International Conference on Electrical Contacts*, pages 461–471. IEEE, 1990.

[31] Milenko Braunovic. Effect of connection design on the contact resistance of high power overlapping bolted joints. *IEEE transactions on components and packaging technologies*, 25(4):642–650, 2002.

[32] M. Braunovic. Evaluation of different platings for aluminum-to-copper connections. In *Electrical Contacts-1991 Proceedings of the Thirty-Seventh IEEE HOLM Conference on Electrical Contacts*, pages 249–260. IEEE, 1991.

[33] Won-Bae Lee, Kuek-Saeng Bang, and Seung-Boo Jung. Effects of intermetallic compound on the electrical and mechanical properties of friction welded Cu/Al bimetallic joints during annealing. *Journal of Alloys and Compounds*, 390(1-2):212–219, 2005.

[34] M. Abbasi, A. K. Taheri, and M. T. Salehi. Growth rate of intermetallic compounds in Al/Cu bimetal produced by cold roll welding process. *Journal of Alloys and Compounds*, 319(1-2):233–241, 2001.

[35] C.P. Liu, S.J. Chang, Y.F. Liu, and W.S. Chen. Cu-Al interfacial formation and kinetic growth behavior during HTS reliability test. *Journal of Materials Processing Technology*, 267:90–102, 2019.

[36] M. Braunovic and N. Alexandrov. Intermetallic compounds at aluminum-to-copper electrical interfaces: effect of temperature and electric current. *IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part A*, 17(1):78–85, 1994.

[37] David Wield and Robin Roy. R&D and corporate strategies in UK materials-innovating companies. *Technovation*, 15(4):195–210, 1995.

[38] Jan Hendrik Fisch and Jan-Michael Ross. Timing the start of material substitution projects: Creating switching options under volatile material prices. *Journal of Product Innovation Management*, 31(3):567–583, 2014.

[39] Mahmoud M. Farag. *Materials and process selection for engineering design*. CRC Press, 4th ed. edition, 2020. ISBN 978-1-00-300609-1.

[40] David Cebon and Mike Ashby. Data systems for optimal material selection: a structured approach to information engineering allows diverse resources to be exploited fully, and optimal selection of materials can be achieved. *Advanced materials & processes*, 161(6): 51–55, 2003.

[41] Ernest Wilson. The physical properties of certain aluminium alloys, and some notes on aluminium conductors. *Journal of the Institution of Electrical Engineers*, 31(154):321–334, 1902.

[42] Investing.com. Metals Futures Prices. URL https://www.investing.com/commodities/metals.

[43] Everett M. Rogers. *Diffusion of innovations*. Simon and Schuster, 2010.

[44] John C. Fisher and Robert H. Pry. A simple substitution model of technological change. *Technological forecasting and social change*, 3:75–88, 1971. Publisher: Elsevier.

[45] Margaret E. Slade. Recent advances in econometric estimation of materials substitution. *Resources Policy*, 7(2):103–109, 1981. Publisher: Elsevier.

[46] Christopher L. Magee. Towards quantification of the role of materials innovation in overall technological development. *Complexity*, 18(1):10–25, 2012. Publisher: Wiley Online Library.

[47] IRP. Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Technical report, United Nations Environment Programme, Nairobi, Kenya, November 2020. URL https://www.resourcepanel.org/reports/resource-efficiency-and-climate-change.

[48] David C. Wynn and P. John Clarkson. Process models in design and development. *Research in Engineering Design*, 29(2):161–202, 2018.

[49] Karl T. Ulrich and Steven D. Eppinger. *Product design and development*. McGraw-Hill, New York, 5th ed. edition, 2012. ISBN 978-0-07-131681-1.

[50] P. G. Maropoulos and D. Ceglarek. Design verification and validation in product lifecycle. *CIRP Annals*, 59(2):740–759, January 2010. ISSN 0007-8506. doi: 10.1016/j.cirp.2010.05.005.

[51] David C. Wynn and Claudia M. Eckert. Perspectives on iteration in design and development. *Research in Engineering Design*, 28(2):153–184, 2017.

[52] Kossiakoff Alexander, William N. Sweet, Samuel J. Seymour, and Steven M. Biemer. *Systems Engineering Principles and Practice*. John Wiley & Sons, 2nd ed. edition, 2011. ISBN 978-0-470-40548-2.

[53] Robert K. Yin. *Case study research and applications: Design and methods*. Sage publications, 2017.

[54] Norman K. Denzin and Yvonna S. Lincoln. *The SAGE Handbook of Qualitative Research*. SAGE Publications, January 2017. ISBN 978-1-4833-4978-7. Google-Books-ID: k2LgDQAAQBAJ.

[55] Alvin K. Klevorick, Richard C. Levin, Richard R. Nelson, and Sidney G. Winter. On the sources and significance of interindustry differences in technological opportunities. *Research Policy*, 24(2):185–205, March 1995. ISSN 0048-7333. doi: 10.1016/0048-7333(93)00762-I.

[56] Joseph A. Maxwell. *Qualitative research design: An interactive approach*, volume 41. Sage publications, 2012.

[57] M. Braunovic, Valery V. Konchits, and N. K. Myshkin. *Electrical contacts: fundamentals, applications and technology*. CRC press, 2017. ISBN 1-57444-727-0.

[58] Milenko Braunovic and Milutin Marjanov. Thermoelastic ratcheting effect in bolted aluminum-to-aluminum connections. *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, 11(1):54–63, 1988.

[59] Larry Kirkpatrick. *Aluminum Electrical Conductor Handbook*. Aluminium Association, 3rd edition, 1989. ISBN 978-99917-83-07-9.

[60] Norman T. Bond and Frank L. McGeary. Nickel plating for improved electrical contact to aluminum. *IEEE Transactions on Industry Applications*, (3):326–331, 1973.

[61] J. Lefebvre, J. Galand, and R. M. Marsolais. Electrical contacts on nickel-plated aluminum: The state of the art. *IEEE transactions on components, hybrids, and manufacturing technology*, 14(1):176–180, 1991.

[62] Shashank Arora, Weixiang Shen, and Ajay Kapoor. Review of mechanical design and strategic placement technique of a robust battery pack for electric vehicles. *Renewable and Sustainable Energy Reviews*, 60:1319–1331, 2016.

[63] J. Henriksen. *Corrosion of Electronics: A Handbook Based on Experiences from a Nordic Research Project*. S.C. Institute, and Korrosionsinstitutet, 1991.

[64] Bo Carlsson. Accelerated corrosion testing for product qualification. In *First International Symposium on Environmental Testing Engineering*, Royal Military Academy, Brussels, Belgium., 2007.

[65] G Vogel. Korrosion in der Elektronik durch Schadgaseinfluss Welche Schadgas-Tests sind sinnvoll - und warum? Schwachstellen an Komponenten finden, bevor sie verbaut werden. 2012.

[66] G Vogel and S. Ag. Amberg. Corrosive Gas Tests on Electronic Components and Modules in an industrial environment. 2015.

[67] Shuai Ma, Modi Jiang, Peng Tao, Chengyi Song, Jianbo Wu, Jun Wang, Tao Deng, and Wen Shang. Temperature effect and thermal impact in lithium-ion batteries: A review. *Progress in Natural Science: Materials International*, 28(6):653–666, December 2018. ISSN 1002-0071. doi: 10.1016/j.pnsc.2018.11.002.

[68] *IEC 61238-1: Compression and mechanical connectors for power cables*. International Electrotechnical Commission, 2018. URL https://webstore.iec.ch/publication/29515.

[69] Ø Grong, L Sandnes, P Ferro, and F Berto. *Chapter 9 - Hybrid Metal Extrusion & Bonding, in Handbook of Welding: Processes, Control and Simulation (Editors M. d. B. Pereira, F. J. G. da Silva)*. Nova Science Publishers, 2021.

[70] Øystein Grong, Lise Sandnes, and Filippo Berto. A status report on the hybrid metal extrusion & bonding (HYB) process and its applications. *Material Design & Processing Communications*, 1(2), 2019.

[71] Aksel Elkjaer, Jørgen A. Sørhaug, Geir Ringen, Ruben Bjørge, and Øystein Grong. Electrical and thermal stability of Al-Cu welds: Performance benchmarking of the hybrid metal extrusion and bonding process. *Journal of Manufacturing Processes*, 79:626–638, July 2022. ISSN 1526-6125. doi: 10.1016/j.jmapro.2022.04.029.

[72] Lise Sandnes. *On the mechanical integrity of welded joints made by Hybrid Metal Extrusion and Bonding*. PhD thesis, Norwegian University of Science and Technology, Trondheim, 2021.

[73] Tobias Solchenbach, Peter Plapper, Manfred Greger, Jean-Luc Biagi, Jérôme Bour, and Joao A. S. Bomfim. Thermal and electrical aging of laser braze-welded aluminum–copper interconnects. *Translational Materials Research*, 1(1), 2014.

[74] Chih-Yuan Chen and Weng-Sing Hwang. Effect of annealing on the interfacial structure of aluminum-copper joints. *Materials transactions*, pages 0706110009–0706110009, 2007. Publisher: The Japan Institute of Metals and Materials.

[75] Fu-an Hua, Hong-wu Song, Tao Sun, and Jian-ping Li. Inter-diffusion based analytical model for growth kinetics of IMC layers at roll bonded Cu/Al interface during annealing process. *Metals and Materials International*, 26(3):333–345, 2020. Publisher: Springer.

[76] P. Xue, B. L. Xiao, , and Z. Y. Ma. Effect of interfacial microstructure evolution on mechanical properties and fracture behavior of friction stir-welded Al-Cu joints. *Metallurgical and Materials Transactions A*, 46(7):3091–3103, 2015.

[77] L. Pan, P. Li, X. Hao, J. Zhou, and H. Dong. Inhomogeneity of microstructure and mechanical properties in radial direction of aluminum/copper friction welded joints. *Journal of Materials Processing Technology*, 255:308–318, 2018.

[78] Theodore L. Bergman, Theodore L. Bergman, Frank P. Incropera, David P. Dewitt, and Adrienne S. Lavine. *Fundamentals of heat and mass transfer*. John Wiley & Sons, 2011.

[79] IEEE. *IEEE Standard Glossary of Software Engineering Terminology*. The Institute of Electrical and Electronics Engineers 345 East 47th Street, New York, NY 10017, USA, 1990. ISBN ISBN 1-55937467-X.

[80] Patrick DT O'Connor. *Test engineering: a concise guide to cost-effective design, development and manufacture*. Wiley Chichester, 2001.

[81] Stefan H. Thomke. *Experimentation works: The surprising power of business experiments*. Harvard Business Press, 2020.

[82] Lawrence A. Machi and Brenda T. McEvoy. *The literature review: Six steps to success*. Corwin Press, 2016.

[83] Joseph William Richards. *Aluminium: its history, occurrence, properties, metallurgy and applications, including its alloys*. HC Baird & Company, 1890.

[84] Joseph Luft. *Of Human Interaction: The Johari Model*. Mayfield Publishing Co, Palo Alto, Calif, June 1969. ISBN 978-0-87484-198-5.

[85] James G. March. Exploration and Exploitation in Organizational Learning. *Organization Science*, 2(1):71–87, February 1991. ISSN 1047-7039. doi: 10.1287/orsc.2.1.71. Publisher: INFORMS.

[86] *IEC TS 61586: Estimation of the reliability of electrical connectors*. International Electrotechnical Commission, 2017. URL https://webstore.iec.ch/publication/31491.

[87] E. Dalgaard, P. Wanjara, G. Trigo, M. Jahazi, G. Comeau, and J. J. Jonas. Linear friction welding of Al–Cu part 2–interfacial characteristics. *Canadian Metallurgical Quarterly*, 50 (4):360–370, 2011.

Part II

Paper I

Barriers and Enablers for Material Substitution Innovations: Positioning Exploration and Exploitation Learning Processes

A. Elkjaer and G. Ringen.
Business Strategy and the Environment
Submitted 2023

This paper is submitted for publication and is therefore not included.

Paper II

Reliability of Bolted Aluminium Busbars for Battery Systems: Effect of Nickel Coating and Corrosive Environment

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IEEE Transactions on Transportation Electrification
Published 2022

Reliability of Bolted Aluminum Busbars for Battery Systems: Effect of Nickel Coating and Corrosive Environment

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Abstract—**Bolted busbar connections are a simple and versatile connection method used in battery systems. Copper busbars are widely used for such bolted connections however aluminum offers the potential to save weight and cost. To date, the reliability of aluminum connections dimensioned for battery systems and the vulnerability to corrosion accelerants is not established. In this study, bolted aluminum connections were tested under operational and environmental conditions applicable to battery systems. Four bolted configurations (AA1070 and AA6101, with nickel plating or brushed contact surfaces) were exposed to corrosive environments and current-induced thermal cycling. Nickel plating provided a robust contact interface that maintained stable resistance over 6000 cycles across three temperature levels. The nickel plating's electrical performance was unaffected by the corrosive environments, including humidity, salt mist and hydrogen sulfide exposure. The brushed aluminum configurations produced connections with greater contact resistance variation and achieving a joint performance factor <1.5 was critical for long-term reliability. The growing appeal of aluminum in battery systems requires verification methods capable of assessing new contact configurations. Currently, corrosion test environments for evaluating aluminum contacts are lacking in the literature. This study provides insights into the performance of bolted aluminum configurations dimensioned for battery systems and provides methodology for accelerated verification of new configurations.**

Index Terms—**Aluminum, Bolted connection, Contact resistance, Corrosion, Current cycling, Nickel**

I. Introduction

ALUMINUM is an attractive conductor for use in battery systems offering the potential to save cost and weight in comparison to copper conductors. However, maintaining reliable electrical connections with aluminum entails additional challenges compared to copper [1]. Extensive research has been conducted into aluminum's failure mechanisms establishing recommendations for aluminum connections [2]. And industrial experience has led to the formation of standards [3], [4], [5] for their evaluation. That being said, research and industrial experience on aluminum has predominately focused on high voltage power transmission and building cables, with limited testing conducted on the reliability of aluminum connections in low voltage high current DC applications.

Battery systems are a rapidly growing market fuelled by the growth of renewable solutions and the reducing cost of battery technology. Battery system design varies depending on the chosen cell technology, however the general principle involves connecting numerous battery cells in series and parallel to achieve the desired capacity [6]. Busbars are an integral part of battery system design, enabling the connection of numerous cells into modular and scalable systems.

Typical connection methods for aluminum busbars depend on the cell construction. The three common cell forms are cylindrical, pouch and prismatic [7]. The different cell forms pose different geometries and interfacing materials to an aluminum busbar. Existing connection methods for aluminum busbars include wire bonding for cylindrical cells, laser welding for pouch cells and bolted connections for prismatic cells [8].

We have chosen to investigate bolted connections as they are suitable for both prismatic and pouch cells. In addition, bolted connections enable modular, scalable battery systems and are a common interface for standard components [9]. As such, bolted connections are applicable to the design of battery systems using all cell forms.

High-reliability connections are vital to battery systems considering the severe consequences of thermal failures within high energy density systems. The reliability of a bolted aluminum busbar is vulnerable to fretting, in which a build-up of oxide particles can dramatically increase contact resistance. Aluminum connections are more susceptible to fretting than copper due to aluminum's highly insulating oxide, greater thermal expansion relative to typical steel fasteners and lower creep resistance [10]. A variety of fastener configurations, contact lubricants and surface treatments have been tested establishing recommendations for aluminum connections [2]. Whilst this has led to the successful use of aluminum connections in numerous applications, the detailed relationship between all factors under fretting failure remains elusive. Therefore, predicting the reliability of connections is challenging and requires test verification [11].

Following the positive contributions of previous laboratory testing on the reliability of high power AC busbar connections, we have tested aluminum busbar contacts dimensioned for DC battery applications. In particular, to the authors' knowledge, this is the first study in which aluminum busbar connections

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This work was supported by the Research Council of Norway's "Aluminium busbars for marine battery systems" (ES635028) project, "Value" (267768) project and industry partners.

TABLE I: Test configuration's material, surface treatment, preparation and lubrication

ID	Alloy	Surface Treatment	Surface Abrasion	Contact Lubrication
1	AA1070 H0	None	Brushed	Penetrox A-13
2	AA6101 H19	None	Brushed	Penetrox A-13
3	AA1070 H0	Nickel	None	NyoGel 760G
4	AA6101 H19	Nickel	None	NyoGel 760G
0	Cu-ETP	None	None	NyoGel 760G

TABLE II: Electrical and mechanical material properties

Material	Conductivity [% ICAS]	Yield Strength (0.2%) [MPa]	Hardness
AA1070 H0	62.7	27	19 Brinell
AA6101 H19	55.2	192	74 Vickers
Cu-ETP	100	320	103 Vickers

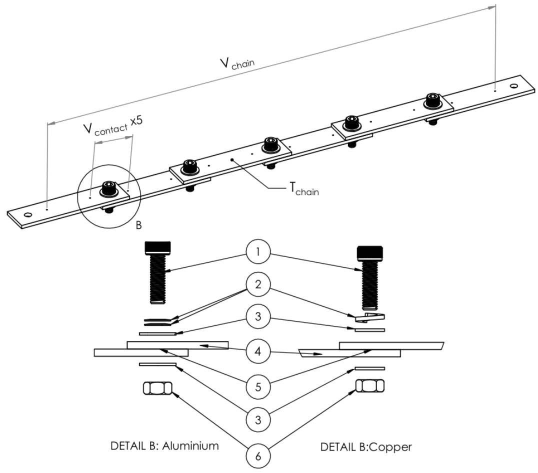
have been current cycled after exposure to a corrosive environment. We find there is a lack of standard tests for assessing aluminum contacts under corrosive environments (such as ASTM B812 [5]) despite recommendations for such practice [11]. Battery systems operate in a range of environments being exposed to varying corrosive environments. Whilst a hermetic enclosure would be preferable from a corrosion perspective, potential requirements for air cooling or variations in external pressure in transport applications may negate such solutions. Hence, assessing degradation from corrosion accelerants is critical for battery system design, yet methods and procedures for their rapid assessment have not been established.

This paper aims to provide insight into the effects of accelerated ageing on the reliability of bolted aluminum DC contacts. We have defined bolted configurations applicable to battery systems, environmentally stressed them through exposure to corrosive environments, then assessed their resistance stability through direct current cycling.

II. Connections Investigated

A bolted connection test specimen is shown in Fig 1. Six identical busbars (3 mm x 25 mm x 100 mm) were connected in series to form a chain of five bolted connections. Five test connections were chosen as the minimum number of test parallels that is still comparable to the number of parallels required for certification tests [3]. The bolted busbars overlapped by 25 mm to form a nominal 625 mm^2 contact area. A jig was used to align the busbars with the nominal contact area before the busbars were bolted together to form a chain.

In total 15 busbar chains (one chain comprising of five bolted connections) were assembled to test 5 different configurations in three different environments (later defined as environment A, B and C). The five different bolted configurations included two aluminum alloys, with two different surface treatments and preparations, as well as one copper configuration for reference, see Table I. The configurations are subsequently referred to by their ID from Table I, i.e. 0-4, followed by A, B or C.



Item No.	Aluminium Configuration	Copper Configuration
1	Bolt M6x16 (A4-80)	Bolt M6x16 (A4-80)
2	Spring washer (DIN6796 A4)	Split lock washer (DIN127 A4)
3	Flat washer OD 18mm (DIN9021 A4)	Flat washer OD 12mm (DIN125 A4)
4	Busbar sample (100mm x 25 mm x 3mm)	Busbar sample (100mm x 25 mm x 3mm)
5	Penetrox A-13	Nyogel 760g
6	Nut M6 (A4)	Nut M6 (A4)

Fig. 1: Test specimen configuration overview (top) 3D view of busbar chain defining voltage and temperature measurement locations. (middle) Exploded view of aluminum and copper configurations (bottom) Bill of materials

A. Material Selection

The properties of all three materials are shown in Table II. AA1070 H0 and AA6101 H19 busbars were chosen to envelop the importance of mechanical properties in the bolted configurations. Previous testing of bolted aluminum connections has focused on AA1000 series conductors for high power applications, with conductor cross-sections around 500 mm^2 [10], [12], [13], [14]. High purity AA1000 series alloys are commonly used, despite their inferior strength to other alloys, as they provide the best electrical conductivity[15]. Strain hardening can be used to increase the strength of AA1000 series alloys. However, the lack of alloying elements results in limited mechanical strength [16]. High strength is important in bolted connections to prevent stress relaxation from reducing the connection integrity [12]. We consider relevant busbar cross-sections for battery applications to be in the range from 50-200 mm^2, with fewer bolts and higher stresses than larger busbars used in high power AC transmission. AA6000 series alloys are also widely used for bolted applications that require higher strength, offering only a limited reduction in conductivity [2]. However, we find limited literature on the long term reliability of AA6000 bolted connections.

B. Contact Surface Properties

Preventing the formation of aluminum oxide between aluminum conductors is critical for reliability. Aluminum oxide is a hard non-conductive compound that forms rapidly on the surface of aluminum [2]. Common commercial practises to prevent the formation of aluminum oxide include plating the aluminum surface with nickel or abrading and lubricating the contact surface [2].

1) Brushing and Lubrication: Despite aluminum oxide forming an insulating layer on aluminum, it is broken under the high contact loads of bolted connections [15]. As such, aluminum can be bolted together to form low resistance contacts with relative ease. However, the real contact area between the contacting surfaces will be a fraction of the nominal contact area, consisting of so-called a-spots where the oxide layer has broken and direct metal-to-metal contact has been established. The number and size of the a-spots depend primarily on contact force and surface roughness [17]. These small areas of aluminum-to-aluminum contact are then at risk of oxidation, which will decrease the conducting area. The reliability of the contact is ultimately determined by the size of the real contact area. The resistance of contacts with small a-spots would increase significantly as their perimeter oxidizes, whereas larger contact areas would be less affected. Small contact areas are also more vulnerable to small relative displacements between the contact surfaces. Such movement in the surfaces can break metal-to-metal contact and introduce oxide particles into the connection.

A reliable aluminum connection should therefore have a large real contact area that is protected from oxidation. A large contact area can be achieved by abrading the contact surface. Abrading contact surfaces removes the oxide layer and increases surface roughness. Increased surface roughness is desirable as larger surface asperities can pierce through the oxide and form larger contact areas [17]. However, surface roughness only provides an advantage up until a point, after which further increasing roughness or creating a non-planar surface would reduce the real contact area. Investigations of abrasion techniques have shown brushing to be an effective technique for the preparation of wrought aluminum [14].

Maintaining a low contact resistance can then be achieved by using a contact lubricant to prevent oxidation. Braunovic [18] established an index ranking several contact lubricants for aluminum where Penetrox A-13 was found most effective. Penetrox A-13 is commercially available, however we discovered a contrast in the application process between research recommendations and industry practice. Jackson [14] has shown that applying lubrication before abrasion reduces the resulting contact resistance. Aluminum oxide forms very rapidly on surfaces so, without a lubricant preventing its formation, the surfaces oxidise again before the contacts are bolted together [14]. Lubricating before brushing minimises the immediate oxidation of the surface; however opponents claim brushing with lubricant will trap oxide particles in the contact area potentially reducing metal to metal contact. Jackson's results also indicated that the importance of preventing immediate oxidation was less significant for coarse abrasion methods.

In this study, we followed the apparent research consensus and that used by Braunovic [18], [19] in applying lubricant before brushing. The Penetrox A-13 contact grease was applied to both contact areas before brushing of both contact areas. Brushing was conducted for approximately 20-30 seconds in one general direction. The steel brush had 5 rows of 0.33 mm diameter and 30 mm long wires, in similarity to the best performing brush reported by Jackson [14].

2) Nickel Coating: Nickel is proven to be a highly effective coating for aluminum contacts [20], [21]. Nickel provides good corrosion resistance and does not diffuse readily into brittle compounds with aluminum [22]. Therefore, nickel can be used to prevent the formation of aluminum oxide and the growth of brittle compounds that can occur between aluminum and copper contacts [21]. However, nickel is more noble than aluminum, so a partial or damaged coating of nickel on aluminum is susceptible to galvanic corrosion.

The samples in this study were prepared with a robust coating of nickel in two layers. The samples were first plated with an electroless nickel-phosphorus layer, followed by electroplating with nickel sulfamate. Measured average layer thicknesses were less than 5 μm and around 10 μm, respectively.

Contact lubricants are also proven to reduce the onset of fretting of nickel contacts [23]. Therefore, NyoGel 760g electrical contact lubricant was applied over the contact area for the nickel-plated test specimens.

C. Fastener Configuration

1) Aluminum Configuration: The combination of bolt, washers and tightening torque is vital to the reliability of aluminum connections [10], [17]. A high clamping force is desirable to maximize the real contact area. However, this must be balanced against the resulting thermal stresses and creep relaxation. A tightening torque of 8.75 Nm was used to achieve sufficient contact force at the interface whilst preventing overstressing the bolt under thermal expansion. Belleville spring washers were then used to maintain the desired contact force under potential displacement of the aluminum.

The target contact force at the interface was estimated based on available literature. The relationship between contact force and resistance has been reported for several aluminum alloys and preparation methods. The studies show that the relationship between contact pressure and resistance follows an exponential decay relationship, where a minimum pressure is required to achieve a low resistance, after which further increase of pressure has limited effect on contact resistance. For brushed EC(1350) aluminum busbars, the minimum clamping pressure has been found to require: 2 MPa [19], 3 MPa [24], 6 MPa[14] and also up to 27 MPa [25]. Comparably, Kirkpatrick's Aluminum Conductor Handbook [15] states a practical design range of 5 to 8 MPa for AA1350 and suggests higher average pressures may be used for AA6101. We discovered less research available on the appropriate contact force for the 6000s aluminum. However, a contact pressure of 3 MPa [24] achieved the minimum resistance asymptote for machined AA6060 and a contact pressure of $\sim$8 MPa [1] for AA6351-T6 [13]. Based on the available literature, a

[1]Resistance was reported versus contact force rather than contact pressure. An 8 MPa pressure was therefore estimated based on required 6kN force and 12.7 mm bolt used. The area was not specified so estimated from the provided schematic and bolt dimensions.

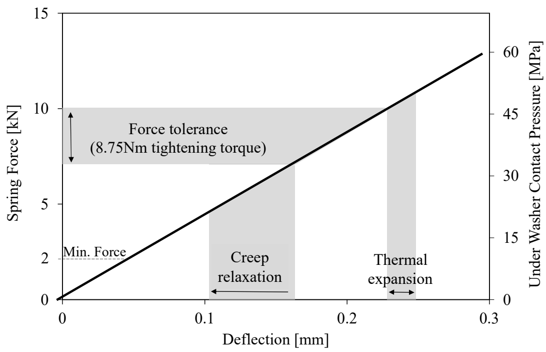


Fig. 2: Calculated spring washer force from assembly tightening torque with subsequent changes due to creep and thermal expansion operational conditions

minimum contact pressure of 9 MPa was considered necessary to ensure connections would reach the minimum contact resistance asymptote. A 9 MPa contact pressure then translates to a contact of 2 kN considering an under-head washer area of 215 mm^2 or a contact force of 5.5 kN considering the total overlap area of 25 mm x 25 mm.

The chosen spring configuration was sized to maintain the required contact force over the working length. Two A4 stainless steel DIN6796 spring washers in series were calculated to require a minimum force of 8.5 kN to flatten. The minimum force being based on the spring's minimum working length tolerance of 0.2 mm. Therefore, two springs in series ensure the springs could provide a greater than 5.5 kN clamping force in the worst case. Spring washers were not used in parallel (on the nut side) as the spring working length of 0.2 mm was considered sufficient to accommodate creep. Although creep failure was not the focus of the subsequent testing, the bolted connection design was considered to accommodate 1% creep in worst case, which would be 0.06 mm. Fig 2 shows the calculated loss of contact force from 1% strain demonstrating that a 5 kN contact force would be maintained by the spring washers. In addition, by not using spring washers on the nut side, the configuration was representative of configurations where washers cannot be placed on the nut side, for example, busbars with captive nuts or threaded insert components.

Fig 2 shows the calculated maximum force applied with a tightening torque of 8.75 Nm, including tolerances for variation in bolt friction and increase from thermal expansion. The right-hand side y-axis shows the equivalent pressure under the washer (which is higher than the nominal contact overlap pressure (25 mm x 25 mm)). The calculated stresses indicate that the higher mechanical strength of AA6101 H19 will be important to maintaining contact force and the AA1070 H0 is susceptible to creep relaxation greater than 1%.

2) Copper Configuration: The copper configuration did not use Belleville and oversized washers, as used in the aluminum configurations. The purpose of the copper configuration was to provide a reference for the initial contact resistance. The copper configuration was not included in the subsequent thermal cycling of the aluminum configurations. The copper configuration was based on the authors' experience of standard industry practice for copper busbars. The configuration used a split lock washer, a standard flat washer and NyoGel 760g, as shown in Fig 1. A tightening torque of 10 Nm was used for the copper configurations.

III. Experiment Methodology

In this study, we chose to test the reliability of bolted aluminum connections under two sequential tests. First, the samples were exposed to a corrosive environment followed by current-induced thermal cycling.

A. Environmental Exposure

The samples were exposed to a corrosive environment to accelerate the naturally occurring corrosion processes. The aged samples were then thermally cycled by direct current to establish operational performance.

It is difficult to define the correct environmental conditions for a battery system, as we envisage that the intended design environment is benign, yet exposure to changing atmospheric conditions cannot be excluded. We consider battery systems as operating within enclosures and not exposed to outdoor environments. However, we consider that most battery systems have the potential to be exposed to corrosive conditions. For example, battery systems for transport applications can operate in a range of changing environments. Car batteries may not be hermetically sealed to mitigate the structural demands of changing pressures and temperatures that occur when driving over elevated terrain [26]. As such, changes in humidity may lead to condensation on cold metallic busbar surfaces. Also, considering operation in coastal environments, contaminants from road salts, and other urban pollutants, the combination of high relative humidity and corrosion accelerants is difficult to exclude.

Considering the difficulty of defining the accurate level of corrosivity for the specific application of busbars [27], [28], we chose to test three corrosivity levels. The three levels were defined to cover: (A) no accelerated ageing (B) accelerated ageing in a moderate corrosive environment and (C) accelerated ageing in a severe corrosive environment for a battery system. The three levels were chosen to envelop the worst-case operating environment for a battery system whilst still providing comparison to more favourable conditions.

The ISO 9223 standard is a well-established classification for the corrosivity of different environments [29]. We consider the worst case environment for aluminum busbars in a battery system to be between categories C2 and C3, representing low and moderate corrosion conditions, respectively. The C2 environment represents an unheated space with varying temperatures and a low frequency of condensation and pollution, whereas the C3 represents a moderate frequency of condensation and pollutants.

Carlsson et al. [30] have conducted a review of several corrosion test standards and provided guidelines for selecting accelerated corrosion test methods. The suitability of different corrosion test methods was reviewed with respect to different

TABLE III: Procedure for each accelerated corrosion environment

ID	Procedure Each Week
A	No accelerated corrosion environment
B	75% relative humidity (2 hrs per day for 4 days) Salt mist chamber, 35 °C 5% NaCl (2 hrs per day for 2 days) Drying, <50 % relative humidity (1 day)
C	Salt mist chamber, 35 °C 5% NaCl (2 hrs per day for 2 days) Drying, <50 % relative humidity (1 day) 1000 ppm H2S at 75% relative humidity (3 days) Drying, <50% relative humidity, (1 day)

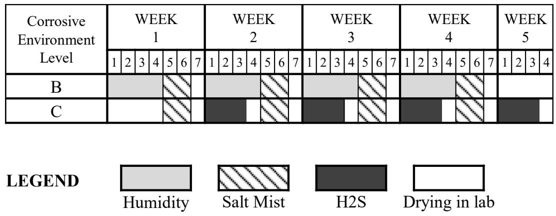


Fig. 3: Sequence of exposure to corrosive environments for accelerated corrosion levels B and C

applications and operating environments. The preferred test method for most fields of application, including automotive, marine and electric devices, was cyclic variation of humidity with steps of salt spraying. In addition, for electric devices, Carlsson et al. recommended additional exposure to air pollutants. Therefore, we defined two test sequences in which one would be exposed to humidity and salt spray, and a second which would include an additional air pollutant.

Ideally, the second test sequence would include a mixture of air pollutants that matches the air pollutants of the intended operating environment. Henriksen [31] measured the pollutant concentrations in a range of applicable environments for battery systems including a car cabin, seashore and industry facilities. Henriksen's measurements show that corrosion accelerants such as SO2, NO2, H2S and Cl2 are present in the air in most environments and applicable even for a battery system operating within a well-controlled indoor environment such as an "Instrumental room". However, testing multiple pollutants requires a mixed flowing gas test, such as the Battelle test [31], that are complicated to perform. Therefore we chose to use a test developed by Vogel [32], [33] for weatherproof industrial environments called the "Fast hydrogen sulphide (H2S) for contacts and connections". The test is designed to quickly indicate vulnerabilities of a component, employing 75%RH and 25 °C with H2S. H2S is added at 1000 ppm to an autoclave containing the test components, and allowed to decay to 0 ppm over 6 hours. The cycle is then repeated over the next two days. The test corresponds to a test of approximately 10-100 ppm H2S over 1-2 days.

The three corrosive test methods (A, B and C) defined for this study are shown in Table III and the test procedure visualized in Fig 3. A Heraeus Votsch HC 0057 humidity chamber was used to expose the B sequences samples to 75% relative humidity at 25 °C for two hours each day. An Ascott CC1000t salt mist chamber was used to expose both B and C sequence samples to a 5% NaCl concentration salt mist at a temperature of 35 °C for two hours each day. A custom autoclave was used to expose the samples to H2S.

Four point resistance measurements were performed each week for each busbar chain, see Vchain in Fig. 1. Measurements were taken in both directions, and an average reported, using a RNB 320-KD30005D power supply at 5A and Fluke 289 multimeter.

B. Current Cycling

As previously mentioned, relative motion in the contact interface generates oxide particles that have high electrical resistivity. Aluminum oxide particles are hard hence under continued relative motion these particles facilitate the generation of more oxide particles. As oxide particles build up in the contact interface, the electrical resistance increases, generating more heat and more displacement. The extent and rate of fretting of aluminum contacts depend on multiple factors for a given configuration (contact conditions, environmental conditions and material properties) [34].

Thermal cycling is the most severe mechanism to induce fretting in aluminum bolted connections [34]. The thermal expansion of aluminum causes displacement in the contact area that generates the abrasive and poorly conducting oxide particles. External vibration may also be a source of relative motion between contacts but is often prevented by the high clamping forces of bolted connections [34]. We chose therefore to test the reliability of aluminum configurations using a current cycling procedure.

The procedure was based on the standard test method from IEC61238-1-1, Electrical Test [3]. The philosophy of the standard is to cycle the busbar above its maximum design temperature and show that a sufficient number of cycles can be completed with stable resistance. In other words, achieve sufficient cycles at an elevated temperature, to show that the contact will work within the design temperature range during its lifetime. However, the challenge is determining how many cycles and what temperature will represent the design temperature range during the contacts' lifetime.

IEC61238 is used to prove the suitability of aluminum, copper and bimetallic (Al/Cu) connectors for power cables rated up to 1 kV. The international standard is an amalgamation of several national standards that have been used to verify the performance of aluminum contacts over decades. The standard therefore provides an established methodology and criteria suitable for the assessment of aluminum contacts.

IEC61238 considers a maximum continuous operating temperature of 90 °C. We consider this a more stringent requirement than applicable for battery systems as lower temperatures improve efficiency and prevent cell degradation [35]. A maximum temperature around 60 °C is quoted by several battery cell manufacturers and the busbar can play an important role in the thermal management of the cell. Therefore, it is desirable that the busbar has a lower temperature than 60

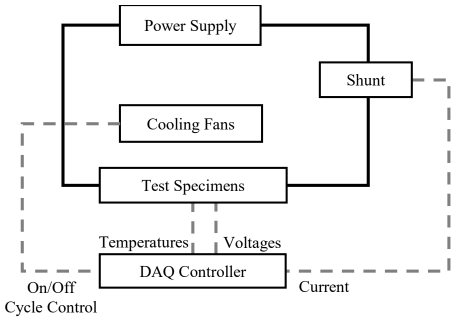


Fig. 4: Current cycling test setup schematic

°C to act as a heat sink for the cell. Downstream busbars may have negligible influence on cell temperatures, however, lower operating temperatures provide better efficiency. We therefore consider the 90 °C maximum design requirement for IEC61238 to exceed the design requirement of a battery system. As such, the IEC61238 criteria of 1000 heat cycles with nominal 85 °C temperature rise serves as a suitable indicator of long-term performance.

We chose to use a current cycling procedure with three increasing duty cycle levels. We defined an initial level of 800 cycles to establish a baseline performance. We then increased the current to an intermediate level for 4000 cycles. Finally, a third level was applied for 1200 cycles to aggravate failure before stopping the test. A staggered cycling level was used to reduce the risk of premature failure and compare performance between the different configurations. The duty cycle for each level is shown in Table IV.

A schematic of the current cycling setup is shown in Fig. 4. Voltage measurements were made over individual contacts as illustrated by Vcontact in Fig. 1. Voltage and temperature measurements were made with an Agilent 34970A. The current duty cycle was programmed into an Agilent 6681A DC power supply. A controller was used to switch cooling fans on and off in unison with the commanded current cycle.

The cycling was stopped to perform four-point resistance measurements at room temperature at least three times a week. The average number of cycles between measurements was 78, with a maximum interval of 183 cycles. A multiplexer was used to measure each contact five times in both current directions and the average resistance is reported. The measurement current was 100 A and all measurement taken within 1 minute to prevent self-heating. Resistance measurements were compensated for variations in room temperature using the busbar chain temperature measurements. Each busbar chain had one temperature sensor as illustrated by Tchain in Fig. 1

IV. Results

A. Assembly resistance measurements

The initial contact resistance for each configuration was measured after assembly. The range and average contact resistances, transformed into joint performance factor, are shown in Fig 5. Each configuration is based on 15 contacts

TABLE IV: Definition of three current levels for thermal cycling

Level	Heating	Dwell	Cooling
1	450A (330s)	333A (600s)	0A (700s)
2	450A (630s)	393A (600s)	0A (700s)
3	500A (600s)	435A (600s)	0A (700s)

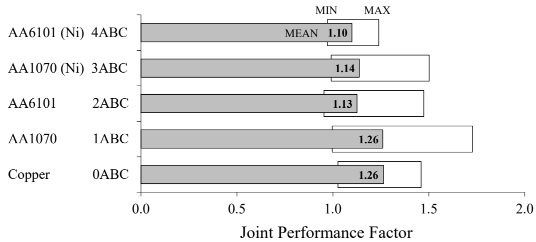


Fig. 5: Initial joint performance factors measured after assembly showing averages over the 15 contacts for each configuration

corresponding to three busbar chains. The contact resistance measurements have been transformed into joint performance factors for comparison. The joint performance factor is a metric to evaluate the performance of electrical contacts [36]. The joint performance factor, k, is calculated from the ratio of contact resistance, R_c, divided by an equivalent length of the nominal conductor, R_{eqv}, eq. 1. The equivalent resistance, R_{eqv}, is calculated from the conductor's nominal cross-sectional area, A, material resistivity, ρ and contact length, L. As the measured resistance, R_m, was made over a length of 35 mm, while the contact overlap was only 25 mm, a reference resistance, R_l, is subtracted from the measurement, therefore removing the contribution of the extra 10 mm bulk resistance.

A low joint performance factor is desirable as the joint is dissipating less energy compared to the nominal conductor cross-section. Fig 5 shows AA6101 achieved lower joint performance factors than AA1070. Nickel coating reduced both the magnitude and variation of the joint performance factor for both AA6101 and AA1070.

$$k = \frac{R_c}{R_{eqv}} = \frac{R_m - R_l}{\frac{\rho L}{A}} \tag{1}$$

B. Environmental Exposure

1) Visual Observations: Fig. 6 shows photos of the corrosion for each configuration after exposure to B and C corrosion environments. Photos of the B samples before corrosion are shown for direct comparison. The sample group A were not exposed to a corrosive environment.

The visual appearance of copper after B level exposure had become dull from the accelerated oxidation. Near the contact location, the excess contact lubricant had prevented oxidation of the external surface demonstrating the protection provided by the lubricant. The copper C level exposure samples were significantly darker which is in line with the formation of copper sulphide [2].

Visually there was no significant difference in corrosion between bare AA1070 and AA6101 samples. Both had the appearance of pitting on all surfaces which produced a rougher surface.

The nickel sulphate coating looked similar for both AA1070 and AA6101. No corrosion was observed from B level exposure with a smooth surface maintained on all samples. C level exposure showed corrosion products on all samples at several locations.

2) Resistance Measurements After Environmental Exposure: Fig. 7 shows the total chain resistances measured before and after the corrosion exposure. The busbar chain resistances were stable with 0B (Cu) and 2B (AA6101 brushed) showing the greatest change. Measurement of individual contact resistances showed the 5% increase in total chain resistance of 0B was due to one contact resistance measurement increasing from 10.1 $\mu\Omega$ to 13.9 $\mu\Omega$. Measurement of individual contacts for 2B showed the reported 4% increase was uniform across all contacts with an average increase of 1.7 $\mu\Omega$ per contact. The decrease in resistance for all nickel-plated samples occurred after the first week of testing indicating the real contact area improved after mechanical settling of the contact.

C. Current Cycling

1) Temperatures: The current cycling was performed at three levels, as specified in Table IV, resulting in three temperature levels during cycling. Temperature measurements were made at the center of each busbar chain. The delta temperature was calculated for each cycle by processing the maximum and minimum measured temperature time signal. All busbars were cooled to the ambient room temperature within the 700 seconds cooling time, however the ambient room temperature varied from 16 ^oC to 22 ^oC over the 6-month test duration. The average delta temperature for each level is shown in Table V. Each configuration is labelled with the configuration number and corrosion sequence letter reported in Tables I and III. To determine maximum cycle temperatures, the ambient room temperature should be added to the values in Table V.

The resistance of each chain varied slightly due to the differences in bulk resistivity and contact resistance, see total chain resistances in Fig. 7. The same temperature was therefore not achieved for each configuration. However, the temperature differences were limited and less than the relative increases for each level.

At the highest current level, the Nyogel 760g lubricant temperature, used on the nickel coated samples, was at its rated temperature limit (135 °C) yet no degradation was observed. The operational temperature range for Penetrox A-13 was not defined in the datasheet however its properties are specified up to 260 °C. Small areas of excess Penetrox A-13 outside the contact were observed to harden however the observation was not linked to any increase in contact resistance during the test. Individual characterisation of the lubricant properties was not conducted hence assessment of lubricant degradation is limited to the contact resistance measurements.

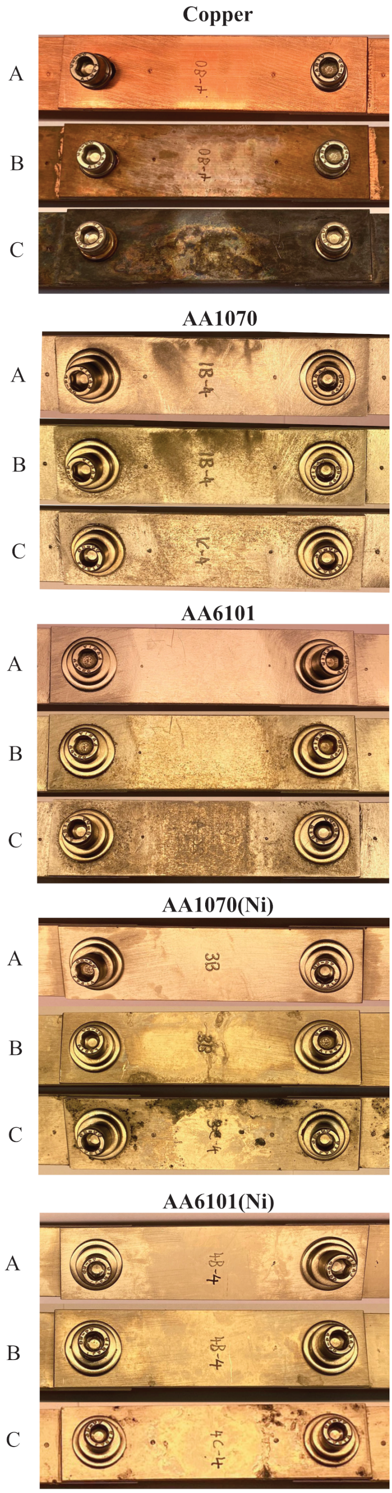


Fig. 6: Photograph of each configuration before corrosion exposure and after B and C level corrosion exposure

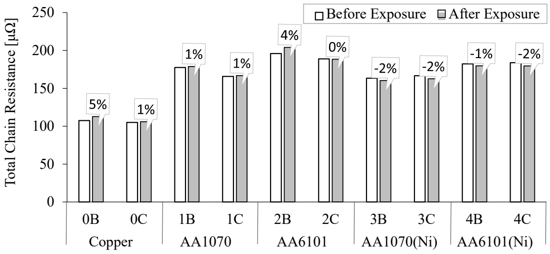


Fig. 7: Busbar chain resistance measurements before and after corrosion exposure

TABLE V: Average temperature increase during current cycling for each busbar chain, listed for each current level duty cycle.

Cycles Performed	800	4800	1200
Current Setting	Level 1	Level 2	Level 3
Config ID	*Average Delta Cycling Temperature [C]*		
1A	65	92	-
1B	69	100*	-
1C	71	99*	-
2A	71	95	131
2B	76	107	144*
2C	74	100	132*
3A	66	91	115
3B	68	92	108
3C	68	94	116
4A	73	97	118
4B	75	100	120
4C	70	96	118

*Complete number of cycles for this level was not achieved

2) Contact Resistances: Fig 8 shows the joint performance factors during the current cycling for each configuration.

No failures occurred in the nickel-coated samples and no degradation in performance from accelerated corrosion environments was detected. The contact resistance was stable in all nickel-plated busbar chains (3A, 3B, 3C, 4A ,4B, 4C) throughout the total 6000 cycles.

A failure was defined as a 100% increase in joint performance factor. Failing contacts are identifiable in Fig 8 by a change in gradient and a rapid degradation was associated with contacts that had doubled in resistance. Failures occurred within all brushed and lubricated AA1070 busbar chains (1A,1B,1C). Busbar chain 1B was the first to fail, reaching a 100% increase in joint performance factor after 1050 cycles. The resistance of several contacts on busbar chain 1C also increased after the current increase at 800 cycles. However, busbar chain 1C reached 4350 cycles before a contact had increased by over 100% and the busbar chain removed from the test setup. Busbar chain 1A had one contact fail after 2450 cycles, however, this contact had a higher starting contact resistance. In this case, the failed contact on chain 1A was removed and cycling continued with the remaining four contacts. The remaining contacts on busbar chain 1A were cycled until the end of current level 2, 4800 cycles, before being removed at the start of current level 3.

Failure occurred on AA6101 samples 2B and 2C after 4800 and 5200 cycles, respectively. Busbar chain 2B had several contacts with slowly increasing resistance over the level 2 cycling, which ultimately failed after increasing to the level 3 current setting, whereas busbar chain 2C had stable resistances through level 2 before a contact failed rapidly at current level 3. No contacts failed on busbar chain 2A over the entire 6000 cycles.

V. Discussion

A. Joint Performance Factor

A joint performance factor, k, greater than 1 indicates that the contact will be dissipating a greater amount of energy per unit length than the nominal cross-section of the busbar. As such, the contact is at risk of being the conductor's hottest location, which may reduce the allowable current for the busbar. Ideally, interface locations of busbars should have a lower temperature than the bulk busbar temperature to avoid a reduction in operational capacity and improve reliability. Therefore, the lowest joint performance factor possible is preferable.

The IEC61238 standard [3] does not specify an absolute limit for joint performance factor but does specify that the contact temperature must be below the temperature of a reference conductor (and that the k factor must not increase by 100% during the test). A joint performance factor above 1 may be acceptable and may not result in a hot spot depending on the busbar thermal design. Schlegel et al. [36] considered a joint performance factor of up to 1.5 to be "rated as technically good" for bolted connections. A joint performance factor higher than 1 may not increase temperatures depending on the conductive and convective cooling of the busbar contact area and spanning length. The current cycling test setup did not include a reference conductor and the short distance (50mm) between bolted connections was not suited to identify temperature increases between the contact and spanning busbar length. Spot checks of temperatures under thermal cycling confirmed a uniform temperature across the busbar chain and between the center of the busbar and contact locations. These measurements could not be used to define the limit for what joint performance factor would cause a temperature increase of the contact. However, one may make an estimate considering the heat dissipating area. The tested joints have a 50% larger heat dissipating area than the busbar itself (considering the sides of the bolt head, nut and busbar overlap). Hence, a 50% higher power dissipation over the length of the joint, corresponding to a joint performance factor of 1.5, results in the same temperature of the joints as the busbar at steady state.

Fig. 5 shows that the joint performance factor was above one for all samples including copper. This shows that the configuration with one bolt and 25 mm x 25 mm overlap has not established sufficient real contact area to equate to the nominal cross-section of 25 mm x 3 mm. It is important to note the influence of bulk resistance when comparing joint performance factors and evaluating contact design. As the joint performance factor is the relationship between the contact

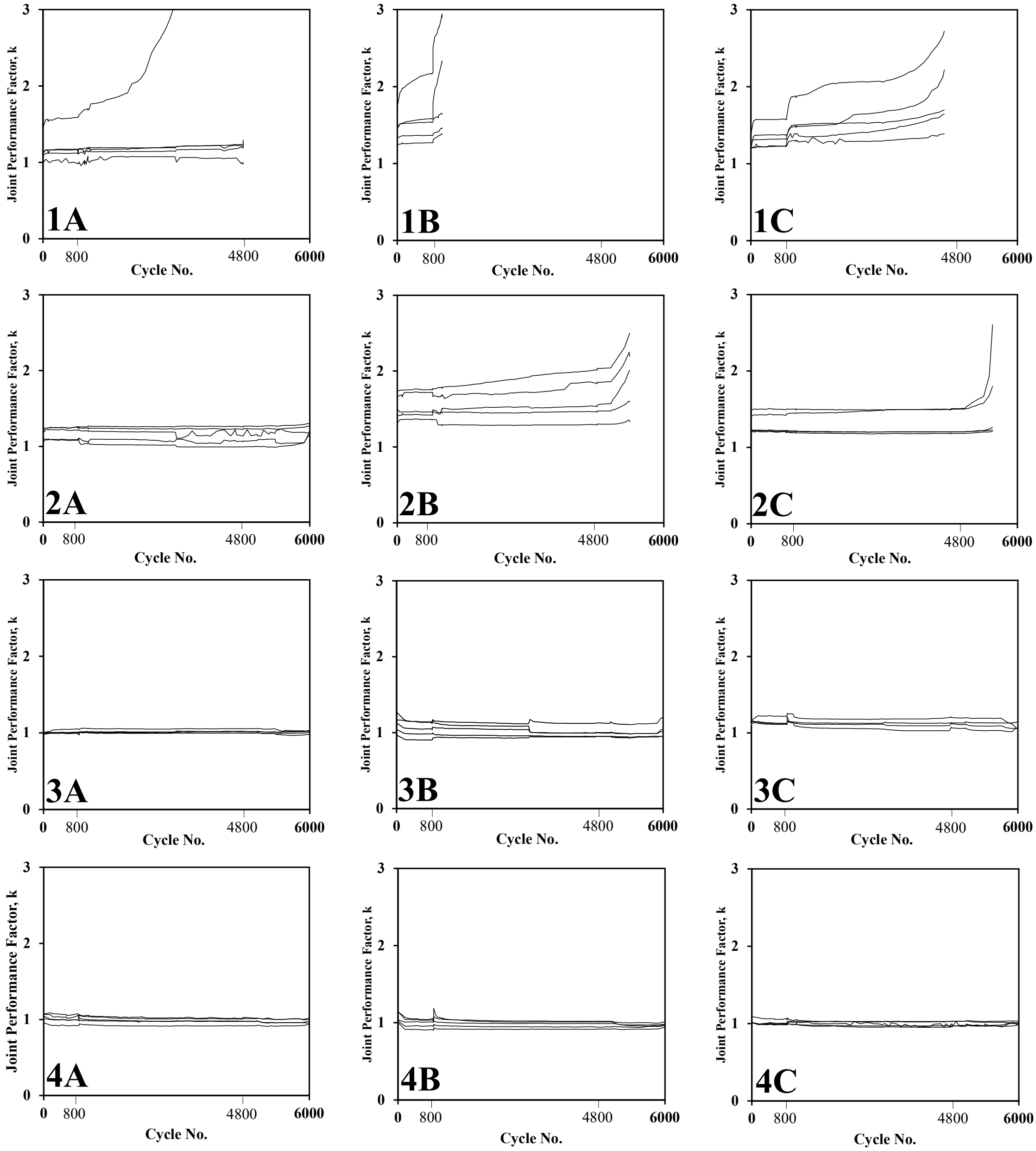


Fig. 8: Joint performance factor under current cycling for each busbar chain.The figures are labelled according to their numerical configuration ID (material and surface properties, see Table I) and alphabetical ID (corrosion exposure procedure, see Table 3). Each figure shows the joint performance factor for the 5 bolted connections on the chain. Cycle number 800 and 4800 are labelled indicating the transitions to increased current levels.

TABLE VI: Calculated composite contact area for each configuration based on the initial resistance measurements

ID		Resistance [$\mu\Omega$]	a_c [mm]	A_c [mm^2]	A_c/A_{c_0}	A_c/A_n
0	Cu	7.3	1.18	4.38	100%	0.70%
1	AA1070	11.5	1.20	4.49	102%	0.72%
2	AA6101	11.7	1.33	5.60	128%	0.90%
3	AA1070(Ni)	10.4	1.32	5.49	125%	0.88%
4	AA6101(Ni)	11.4	1.37	5.90	135%	0.94%

resistance and nominal busbar resistance, both elements must be sized appropriately to avoid a contact hot spot. So although the copper configuration has a higher joint performance factor compared to the aluminum configurations, Fig. 5, it should also be noted that the 3 mm copper configuration has a higher current carrying capability.

It is also interesting to assess the quality of contact through estimation of the metal-to-metal contact area. The real contact area can be estimated by representing the numerous discrete a-spots as a large circular composite area, A_c, with composite electrical resistance R_c [17]. The radius of the contact circle, a_c, for such a cylindrical constriction, is given by:

$$a_c = \rho/2R_c \tag{2}$$

$$A_c = \pi a_c^2 \tag{3}$$

Calculation of the composite area from the average electrical resistances of each configuration is shown in Table VI. The material resistivity, ρ, was previously reported in Table II. The calculated area was similar for the copper and the brushed AA1070 configurations, however AA6101 and nickel-plated configurations showed a $>25\%$ increase relative to the copper contact area, A_{c_0}. It was expected that the greater hardness of AA6101 would result in a smaller real contact area compared to AA1070, and therefore higher contact resistance. In fact, a greater contact area was achieved with AA6101 as the average resistance was similar for AA6101 and AA1070. Schoft's [24] testing of brushed AA1350 and machined AA6060 also showed the minimum resistance achieved with both alloys was similar. This shows in both cases that the penalty in current carrying capacity for AA6101 versus AA1070 is compensated by a higher quality contact. Finally, it is also worth noting that the contact area achieved is $<1\%$ of the nominal (25 mm x 25mm) contact area, A_n, in all configurations. A result typical for bolted connections [17].

The above discussion serves to highlight the importance of matching contact design and current carrying capacity to achieve an acceptable joint performance factor, which is again dependent on the thermal environment and control of the busbars. As such, configurations should not be excluded based on the magnitude of the initial joint performance factor alone. Instead, the joint performance factor should be considered with respect to the thermal design, assembly variability and the resulting stability under operation.

Fig. 5 shows that the nickel coating reduced variability for both AA1070 and AA6101. And AA6101 had a smaller range in resistance measurements than AA1070 in both cases. Therefore, considering balanced resistances and sensitivity to assembly, the AA6101 nickel configuration performed best.

B. Contact Resistance Stability Under Current Cycling and Influence of Corrosion Exposure

The nickel configurations achieved stable performance throughout all testing. The results corroborate the effectiveness of nickel found previously [20], [22], [23], [37], and expand on the reported performance by showing that nickel-plated aluminum contacts resist degradation from pre-exposure to corrosive environments.

At first glance, the results for the lubricated and brushed AA1070 and AA6101 aluminum in Fig. 8 could indicate that environment B was more severe than C, as failure occurred earlier from B environment exposure for both alloys. However, it is also apparent that contacts with higher starting values failed earlier. And given that B samples had higher starting values, it is not possible to separate the two factors. Generally, it appears that contacts with the same starting resistance performed similarly in both B and C environments. Analyzing 1B, 1C, 2B, and 2C, a critical value of 1.5 appears to indicate whether performance will be stable or result in failure. A minimum value of 1.5 is also supported by the one failure in busbar chain 1A, recommendation from Schlegel et al. [36] and the previously mentioned power dissipation prediction.

C. Acceleration Factors For Verification of Aluminum Contacts in Battery Systems

Battery systems are a growing industry with standardization and regulation ongoing. Several regulations for battery systems across different product domains have been created or updated in recent years [38], [39], [40], [41], [42]. Design requirements for battery busbars will vary based on the required connection methods, energy storage, power delivery, operating environment and desired lifetime. The operational conditions of busbar contacts can thus vary, which in turn, induces different failure mechanisms. The authors did not identify an established test standard for the accelerated reliability testing of battery system busbar connections. Therefore, we expect the methodology proposed in this study and the implemented accelerations factors will be of interest to the growing adoption of aluminum conductors. However, it should be noted that the high clamping loads used in this study mitigated the risk of slippage from external vibrations common in transportation battery systems. Therefore, verification of novel aluminum contact designs for battery systems should assess slippage vulnerability and consider inclusion of vibration testing.

Nevertheless, the two fundamental parameters for accelerated testing of fretting failure are the temperature cycling level and the number of cycles. Unfortunately, there are no analytical models or empirical relationships to define acceleration factors for either parameter. Therefore, it is not possible to state the operational design performance (e.g., max operational temperatures and number of cycles) each configuration is rated for based on the completed temperature and number of cycles in a study.

As previously mentioned, standards like IEC61238 [3] and IEC61545 [43] have been established as current cycling benchmark tests based on field testing and operational experience. The standards indicate long term reliability, as connections that have passed such tests have worked successfully in the field. However, the operational experience of aluminum busbars for battery systems has not been gathered yet; hence accelerated test methods suitable for battery systems are not established.

We consider acceleration factors necessary for testing aluminum connections for battery systems could be reduced compared to established standards. For example, the IEC61238 standard [3] is based on test experience and applications of mostly buried or building cables with a maximum operational temperature of 90 °C and a typical lifetime of 30 years. Therefore, a battery system targeting lower operating temperatures and shorter lifetimes before refurbishment may be evaluated with lower acceleration factors. In particular, aluminum's weight and cost advantage over copper is suited to reducing operating temperatures in battery systems, offering increased life and efficiency. As such, a busbar designed to operate with minimal temperature rise over ambient conditions is under dramatic acceleration with cycling temperatures above 100 °C.

The above discussion serves to highlight the positive results reported in this study. In principle, the IEC61238 standard for current cycling specifies 1000 cycles at 85 °C delta temperature. In this study, several configurations have surpassed 5000 cycles at greater than 90 °C delta temperatures, indicating such connections would operate reliably in a battery system.

VI. Conclusion

In this study, bolted aluminum busbars were exposed to corrosive conditions and then thermally cycled to investigate the electrical resistance reliability. The key findings were:

- A combined electroless nickel-phosphorus layer followed by electroplating with nickel sulfamate achieves a robust surface finish. The surface coating prevented fretting failure on bolted aluminum configurations considering dimensions, operational conditions and corrosive environments applicable for battery systems.
- For brushed and lubricated aluminum, achieving a consistent joint performance factor below 1.5 is critical for stable connections under thermal cycling.
- Initial ageing of bolted connections through corrosion exposure has a predominately negligible impact on subsequent resistance stability under thermal cycling. All contacts were assembled with contact greases and maintained stable contact resistance despite corrosion of the external surfaces. An exception was the brushed and lubricated AA6101, which increased resistance from exposure to humidity and salt mist cycling.
- The methodology defined in this study, including detailed corrosive environments and current cycling levels, provide a benchmark to further evaluate aluminum contact designs for battery systems.

References

[1] J. Aronstein, "An updated view of the aluminum contact interface," in *Proceedings of the 50th IEEE Holm Conference on Electrical Contacts and the 22nd International Conference on Electrical Contacts Electrical Contacts, 2004*. IEEE, 2004, pp. 98–103.

[2] P. G. Slade, *Electrical contacts: principles and applications*, 2nd ed. CRC press, 2017.

[3] *IEC 61238-1: Compression and mechanical connectors for power cables*. International Electrotechnical Commission, 2018.

[4] *ANSI C119.4 : Electric Connectors — Connectors for Use between Aluminum-to-Aluminum and Aluminum-to-Copper Conductors Designed for Normal Operation at or Below 93°C and Copper-to-Copper Conductors Designed for Normal Operation at or Below 100°C*. National Electrical Manufacturers Association (NEMA), 2016.

[5] *ASTM B812 - 18: Test Method for Resistance to Environmental Degradation of Electrical Pressure Connections Involving Aluminum and Intended for Residential Applications*. ASTM International, 2018.

[6] M. F. R. Zwicker, M. Moghadam, W. Zhang, and C. V. Nielsen, "Automotive battery pack manufacturing – a review of battery to tab joining," *Journal of Advanced Joining Processes*, vol. 1, pp. 2666–3309, Mar. 2020.

[7] J. Becker, T. Nemeth, R. Wegmann, and D. U. Sauer, "Dimensioning and optimization of hybrid li-ion battery systems for EVs," *World Electric Vehicle Journal*, vol. 9, no. 2, p. 19, 2018.

[8] A. Das, D. Li, D. Williams, and D. Greenwood, "Joining technologies for automotive battery systems manufacturing," *World Electric Vehicle Journal*, vol. 9, no. 2, p. 22, 2018.

[9] T. Solchenbach, P. Plapper, and W. Cai, "Electrical performance of laser braze-welded aluminum–copper interconnects," *Journal of Manufacturing Processes*, vol. 16, no. 2, pp. 183–189, 2014.

[10] M. Braunovic and M. Marjanov, "Thermoelastic ratcheting effect in bolted aluminum-to-aluminum connections," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol. 11, no. 1, pp. 54–63, 1988.

[11] *IEC TS 61586: Estimation of the reliability of electrical connectors*. International Electrotechnical Commission, 2017.

[12] M. Braunovic, "Effect of different types of mechanical-contact devices on the performance of bolted aluminum-to-aluminum joints under current cycling and stress relaxation conditions," *Electrical Contacts*, p. 133, 1986.

[13] ——, "Effect of current cycling on contact resistance, force, and temperature of bolted aluminium-to-aluminium connectors of high ampacity," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol. 4, no. 1, pp. 57–69, 1981.

[14] R. L. Jackson, "Significance of surface preparation for bolted aluminium joints," *IEE Proceedings C-Generation, Transmission and Distribution*, vol. 128, no. 2, pp. 45–54, 1981.

[15] L. Kirkpatrick, *Aluminum Electrical Conductor Handbook*, 3rd ed. Aluminium Association, 1989.

[16] J. G. Kaufman, *Introduction to Aluminum Alloys and Tempers*. Materials Park, OH: ASM International, 2000.

[17] M. Braunovic, "Effect of connection design on the contact resistance of high power overlapping bolted joints," *IEEE transactions on components and packaging technologies*, vol. 25, no. 4, pp. 642–650, 2002.

[18] ——, "Effect of contact aid compounds on the performance of bolted aluminum-to-aluminum joints under current cycling conditions," *IEEE transactions on components, hybrids, and manufacturing technology*, vol. 9, no. 1, pp. 59–70, 1986.

[19] ——, "Evalutation of Different Types of Contact Aid Components for Aluminum-to-Aluminum Connectors and Conductors," *IEEE transactions on components, hybrids, and manufacturing technology*, vol. 8, no. 3, pp. 313–320, 1985.

[20] N. T. Bond and F. L. McGeary, "Nickel plating for improved electrical contact to aluminum," *IEEE Transactions on Industry Applications*, no. 3, pp. 326–331, 1973.

[21] M. Braunovic, "Evaluation of different platings for aluminum-to-copper connections," in *Electrical Contacts-1991 Proceedings of the Thirty-Seventh IEEE HOLM Conference on Electrical Contacts*. IEEE, 1991, pp. 249–260.

[22] J. Lefebvre, J. Galand, and R. M. Marsolais, "Electrical contacts on nickel-plated aluminum: The state of the art," *IEEE transactions on components, hybrids, and manufacturing technology*, vol. 14, no. 1, pp. 176–180, 1991.

[23] M. Braunovic, "Fretting in nickel-coated aluminium conductors," in *Thirty-Sixth IEEE Conference on Electrical Contacts, and the Fifteenth*

International Conference on Electrical Contacts. IEEE, 1990, pp. 461–471.

[24] S. Schoft, "Joint resistance depending on joint force of high current aluminum joints," in *Proceedings of the 50th IEEE Holm Conference on Electrical Contacts and the 22nd International Conference on Electrical Contacts Electrical Contacts, 2004.* IEEE, 2004, pp. 502–510.

[25] S. W. Melsom and H. C. Booth, "The efficiency of overlapping joints in copper and aluminium busbar conductors," *Journal of the Institution of Electrical Engineers*, vol. 60, no. 312, pp. 889–899, 1922.

[26] S. Arora, W. Shen, and A. Kapoor, "Review of mechanical design and strategic placement technique of a robust battery pack for electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1319–1331, 2016.

[27] B. Carlsson, G. Engstrøm, A.-L. H. Leijre, M. Johansson, R. Johnsen, R. Lahtinen, and M. Strøm, "Guideline for selection of accelerated corrosion test for product qualification (nt tr 597)," Nordic Innovation Centre, Tech. Rep., 2006.

[28] D. E. Klinesmith, R. H. McCuen, and P. Albrecht, "Effect of environmental conditions on corrosion rates," *Journal of Materials in Civil Engineering*, vol. 19, no. 2, pp. 121–129, 2007.

[29] I. 9223, "Corrosion of metals and alloys - corrosivity of atmospheres - classification." 1992.

[30] B. Carlsson, "Accelerated corrosion testing for product qualification," in *First International Symposium on Environmental Testing Engineering*, Royal Military Academy, Brussels, Belgium., 2007.

[31] J. Henriksen, *Corrosion of Electronics: A Handbook Based on Experiences from a Nordic Research Project*. S.C. Institute, and Korrosionsinstitutet, 1991.

[32] G. Vogel, "Korrosion in der Elektronik durch Schadgaseinfluss Welche Schadgas-Tests sind sinnvoll - und warum? Schwachstellen an Komponenten finden, bevor sie verbaut werden." 2012.

[33] G. Vogel and S. A. Amberg, "Corrosive Gas Tests on Electronic Components and Modules in an industrial environment," 2015.

[34] M. Braunovic, V. V. Konchits, and N. K. Myshkin, *Electrical contacts: fundamentals, applications and technology*. CRC press, 2017.

[35] S. Ma, M. Jiang, P. Tao, C. Song, J. Wu, J. Wang, T. Deng, and W. Shang, "Temperature effect and thermal impact in lithium-ion batteries: A review," *Progress in Natural Science: Materials International*, vol. 28, no. 6, pp. 653–666, Dec. 2018.

[36] S. Schlegel, S. Grossmann, M. Lakner, and T. Schoenemann, "Investigations on material structural changes on electrical joints at high contact temperature," in *26th International Conference on Electrical Contacts (ICEC 2012)*. Beijing, China: IET, 2012, pp. 7–11.

[37] C. T. Dervos, J. Novakovic, and P. Vassiliou, "Electroless Ni-B and Ni-P coatings with high-fretting resistance for electrical contact applications," in *Proceedings of the 50th IEEE Holm Conference on Electrical Contacts and the 22nd International Conference on Electrical Contacts Electrical Contacts, 2004.* IEEE, 2004, pp. 281–288.

[38] *GB 38031-2020 Electric vehicles traction battery safety requirements*. Guo Biao National Standard of the People's Republic of China, 2020.

[39] *FMVSS 305: Electric-Powered Vehicles, Electrolyte Spillage and Electrical Shock Protection*. Federal Motor Vehicle Safety Standards, 2019.

[40] *UN 3481: Lithium ion batteries contained in equipment or packed with equipment*. UN Recommendations on the Transport of Dangerous Goods - Model Regulations, 2019.

[41] *DNVGL-CP-0418: Electrical Energy Storage*. DNV Maritime Class Programmes, 2020.

[42] H. Huo, Y. Xing, M. Pecht, B. J. Züger, N. Khare, and A. Vezzini, "Safety Requirements for Transportation of Lithium Batteries," *Energies*, vol. 10, no. 793, 2017.

[43] *IEC 61545: Connecting devices - Devices for the connection of aluminium conductors in clamping units of any material and copper conductors in aluminium bodied clamping units*. International Electrotechnical Commission, 1996.

Paper III

Electrical and Thermal Stability of Al-Cu welds: Performance Benchmarking of the Hybrid Metal Extrusion and Bonding Process

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Journal of Manufacturing Processes
Published 2022

Journal of Manufacturing Processes 79 (2022) 626–638

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Electrical and thermal stability of Al-Cu welds: Performance benchmarking of the hybrid metal extrusion and bonding process☆

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ARTICLE INFO

Keywords:
Aluminum
Copper
Intermetallic growth rate
Electrical resistance
Hybrid metal extrusion and bonding

ABSTRACT

Advances in joining processes for aluminum and copper are sought after to facilitate the greater adoption of aluminum in electrical applications. Aluminum's chemical affinity to copper causes the joining and lifetime of Al-Cu welds to be vulnerable to the formation of various intermetallic compounds. Intermetallic compounds and the resulting weld structure are known to reduce the structural integrity and increase the electrical resistance of Al-Cu welds. In this study we evaluate the novel joining process, Hybrid Metal Extrusion and Bonding, for butt welding aluminum and copper. The weld structure was examined using scanning and transmission electron microscopy, and the weld resistance was measured using four-point measurements forecast to the weld interface. Energy dispersive spectroscopy and electron diffraction zone axis patterns were analysed to identify intermetallic compounds. Weld samples were examined pre and post heat treatment at 200 °C, 250 °C and 350 °C for total durations of over 1000 h. The results are compared to existing Al-Cu joining processes, and a new metric, weld interface resistivity, is proposed to compare the electrical properties of bimetallic welds. The Hybrid Metal Extrusion and Bonding process was found to form a thin, consistent and straight intermetallic layer with negligible impact on electrical resistance in the as-welded condition. Artificial ageing of samples by heat treatment established the overall growth rate of intermetallic compounds. The growth rate was used to evaluate the weld's operational lifetime versus temperature. The intermetallic growth rate of Hybrid Metal Extrusion and Bonding was quantified at 200 °C and compared to alternative processes. The Hybrid Metal Extrusion and Bonding process showed a significant performance advantage requiring the longest time to reach 2 μm thickness. Furthermore, the growth of intermetallic compounds did not increase the electrical resistance of the weld interface. The negligible impact on electrical resistance and slow intermetallic growth are promising results of the potential functional performance. This study is the first characterisation of the Hybrid Metal Extrusion and Bonding process for electrical applications showcasing its exciting potential for the joining of aluminum and copper.

1. Introduction

The world's energy diet is changing with increasing consumption of electricity. "Electrification of end uses" is explicit policy for reducing greenhouse gases across the globe [1], and an increasing dependency on electricity is fostering interest in joining two of the best electrical conductors, namely copper and aluminum [2,3]. Copper is ubiquitous in electrical applications due to its good conductance and ease in forming reliable connections. Aluminum, on the other hand, has less favourable connection properties, but offers greater conductivity per unit mass than copper. Hence, aluminum conductors are preferable for lightweight applications in which mass savings compensate for more complex connection methods.

Historically, such lightweight applications using aluminum have been predominantly limited to high voltage power transmission [4,5]. Recently, aluminum conductors have become more desirable with the

☆ This work was supported by the Research Council of Norway's "Aluminium bus bars for marine battery systems" (ES635028), "Value" (267768), the "In-SANE" (301176), NorFab (295864) and the NORTEM (197405) projects.

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https://doi.org/10.1016/j.jmapro.2022.04.029
Received 1 December 2021; Received in revised form 18 April 2022; Accepted 22 April 2022
Available online 19 May 2022

growing demand for electric transportation. Aluminum conductors are suited for electric vehicles as weight-saving is essential, and aluminum is often inherent in the electrical design, as aluminum is used as a current collector in popular battery cell technologies [6]. Therefore, aluminum is already present in the electric circuit, and its wider use for connecting battery cells into larger networks and downstream components is beneficial.

Aluminum is a more abundant metal than copper on Earth, resulting in a lower and more stable price [4]. However, the greater difficulty in forming reliable electrical connections inhibits wider adoption. Aluminum's rapidly forming and highly insulating oxide layer, combined with lower strength and greater thermal expansion than copper, complicates contact design [7]. In particular, mechanical compression contacts (e.g. bolted or crimped connections) of aluminum interfaces are susceptible to fretting failure [8]. Fretting of aluminum contacts may cause dramatic increases in resistance as insulating aluminum-oxide particles build up between the contacting interfaces. One method to prevent a fretting failure would be to weld connections, as a welded connection removes the possibility for oxide particles forming between the contact interfaces [7]. A copper compatible welding method would therefore enable aluminum to be utilised more in electrical applications and interface to a wider range of existing components.

Unfortunately, traditional fusion welding is not suited for joining aluminum and copper as the required melting temperatures promote the formation of brittle intermetallic compounds [9]. Instead, lower heat input processes are utilised to reduce the formation of intermetallic compounds while still achieving bonding [9]. Generally, investigations of Al-Cu joints have shown that welds with an intermetallic thickness above 2 μm have significantly degraded structural integrity [10,11]. Low heat input processes, such as friction welding [12–14], cold rolling [11,15–18] and ultrasonic welding [19–21], can join aluminum and copper with intermetallic thicknesses below 2 μm. However, the weld interface may be a source of electrical resistance, provoking a hot spot under operation [12]. High operating temperatures are detrimental to Al-Cu conductors as they accelerate solid-state diffusion, promoting the formation of intermetallic compounds over time. An ideal Al-Cu joining process should form a structural bond with minimal intermetallic compounds, low electrical resistance and a slow diffusion rate, therefore maximising the conductor's operational performance.

In this study, we investigate the performance of Hybrid Metal Extrusion and Bonding (HYB) for joining aluminum and copper. Hybrid Metal Extrusion and Bonding (HYB) is a novel joining process capable of welding along joint lines [22]. The results in this paper provide the first characterisation of the HYB process for electrical applications. The results show that the HYB process forms a thin intermetallic layer with negligible impact on electrical resistance. Artificially ageing the HYB welds by heat treatment caused continued diffusion with the formation of AlCu, Al_2Cu and Al_4Cu_9 in three distinct layers. The intermetallic growth rate was slower than alternative processes, and the intermetallic layers did not increase the electrical resistance. The results indicate that the HYB process is well-suited for joining Al and Cu, providing reliable operation at high temperatures.

2. Methodology

2.1. Manufacturing test specimens

Hybrid Metal Extrusion and Bonding (HYB) is a joining process that uses continuous extrusion of filler material to join offset interfaces [22]. The following section provides an overview of the setup and welding parameters used to manufacture the test specimens in this study. For a complete description of the HYB process and detailed analysis of welding parameters, see Grong et al. [23] and Sandnes [24].

Fig. 1 shows a schematic drawing of the experimental set-up during Al-Cu butt welding. Included in the sketch is the HYB PinPoint extruder with its main tool parts. The extruder is built around a rotating pin with a set of moving dies through which the aluminum is allowed to flow. The pin rotates at a constant speed so that the inner extrusion chamber with its three moving walls will drag the aluminum filler wire (FW) both into and through the extruder, due to the imposed friction grip. At the same time, it is kept in place inside the chamber by the stationary housing constituting the fourth wall.

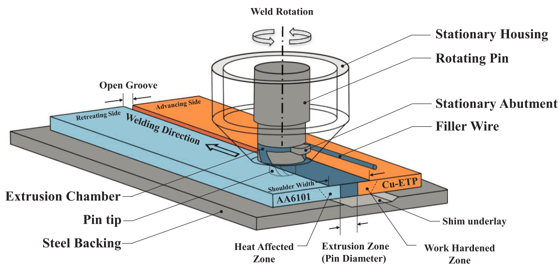

Fig. 1. Schematic illustration of HYB PinPoint extrduer for butt joining Al-Cu. Prior to the joining operation the two base plates are clamped onto a steel backing with a fixed spacing of 4 mm, where the aluminum plate is placed on the retreating side (RS) and the copper plate on the advancing side (AS) of the joint.

Prior to the butt welding operation, the two base plates are first mounted in a fixture with a fixed spacing of 4 mm. The plates rest on a steel backing. During welding, the HYB PinPoint extruder slides along the joint line at a constant travel speed. At the same time the rotating pin tip (7 mm) with its moving dies is submerged into the groove between the plates to be joined. Because the moving dies extend into the groove, the aluminum will start to flow through them as soon as the filler wire (FW) hits the abutment, and the pressure build-up will become sufficiently large to initiate extrusion. The pin tip is positioned to only touch the copper base metal (Cu-BM) groove wall without actually machining it. In contrast, the aluminum base metal (Al-BM) on the retreating side (RS) of the joint will be dragged along with the rotating pin shoulder (12 mm) and deposited in the groove behind, where bonding with the filler metal (FM) occurs inside the extrusion zone (EZ). By proper pre-setting of the two main process parameters controlling the FM deposition rate (i.e. the FW diameter and the drive spindle rotational speed), the entire groove cross sectional area can be filled in one pass. The welding parameters are listed in Table 1.

The samples were manufactured from a 3 mm rolled AA6101 H19 plate and a 3 mm ETP-Cu bar, using an Ø1.4 mm AA6082 filler wire. The welds in this study were the first time the HYB process had been used to join aluminum and copper in a butt weld configuration. Previously, the HYB process has been used to join aluminum and copper in a state-of-the-art four material (Al-Cu-Ti-Fe) weld [25]. Characterisation of the Al-Cu interface in this weld indicated that having copper on the retreating side increased the likelihood of gaps and deformations occurring [25]. Similarly, Galvao et al. reported that friction-stir butt welds of aluminum and copper generally perform better with copper on the advancing side [3]. Therefore, the welds in this study were performed with copper on the advancing side and aluminum on the retreating side. In addition, two 0.1 mm steel shims were used as an underlay for the weld, having been found to aid the weld formation.

Table 1
Welding parameters used for HYB butt joining Al-Cu.

Open groove (mm)	Pin rotation (RPM)	Welding speed (mm/s)	Wire feed rate(mm/s)	Gross heat input(kJ/mm)
4	350	12	125	0.16

2.2. Test specimen characterisation

The 3 mm thick welded plate was subsequently cut into 2 mm wide strips, with a length of 50 mm (20 mm copper and 30 mm aluminum). Hardness measurements were performed across the weld interface using an HM-220 Mitutoyo Micro-Vickers hardness testing machine. Hardness tests were repeated three times at the same location by grinding the cross-section interface after each repetition. Measurements were performed with 0.5 mm spacing and 1 kgf test load.

One cross-section was ground, polished and leached with an alkaline solution of 1 g NaOH per 100 ml H2O for examination in an Alicona Confocal microscope.

The height of specimens for heat treatment and electrical resistance measurements was reduced from the initial plate thickness of 3 mm to 2 mm. A nominal 0.75 mm was removed from the top and 0.25 mm from the bottom to achieve a planar interface for electrical characterisation.

The specimens were heat-treated at 200 °C and 250 °C in a Heraeus T 5042 EK drying cabinet and at 350 °C in an ESAB PK 410 drying cabinet. Individual specimens were removed at three time intervals with the longest exposure exceeding 1000 h for each temperature.

2.2.1. Electrical characterisation

A custom measurement jig was used to measure the resistance of the test specimens. The jig, illustrated in Fig. 2, provided consistent voltage pickups with 2 mm spacing over a total length of 32 mm. Four-point electrical resistance measurements were performed for each voltage pickup location using a 3 A measurement current. The voltage drop over the complete specimen was monitored for 30 min before starting measurements along the specimen length. The monitoring was performed to confirm negligible self-heating of the specimen and stable performance of the measurement equipment. Measurements were performed with a PeakTech 6135 power supply and Fluke 8864A precision multimeter.

2.2.2. Microstructural characterisation

After measuring the electrical resistance, the sample's microstructure was examined using electron microscopy. A FEI Apreo field emission scanning electron microscope (SEM) operated at acceleration voltages in the range of 10–20 kV, was used to inspect the samples heat-treated at 250 °C and 350 °C. The SEM samples were ground using SiC papers down to a grit size of 2000 and polished using cloths with 3 μm and 1 μm diamond abrasives. Backscattered electron imaging (BSE) and SEM X-ray energy dispersive spectroscopy (EDS) using an Oxford Xmax 80 SDD EDX detector were used to reveal the formation of intermetallic phase layers.

FEI Helios G2 and G4 dual-beam focused ion beam (FIB)-SEMs were used to prepare lamellae from polished joint cross-sections of a non-heat treated, and from joints heat-treated at 200 °C and 250 °C. The lamellae were then inspected using a JEOL JEM 2100 for transmission electron microscopy (TEM), and a JEOL JEM 2100F and a JEOL double corrected JEM-ARM200CF integrated with CEOS spherical aberration correctors for scanning TEM (STEM) imaging, and using an Oxford X-Max 80 SDD EDX and Centurio EDS detector for STEM-EDS. The intermetallic layer thickness was determined by comparing annular dark field (ADF) STEM images with bright field (BF) TEM images and EDS maps. The EDS maps were analysed and visualised using the python library hyperspy [26]. Twenty intermetallic phase (IMP) thickness measurements were done on each sample. Electron diffraction zone axis patterns and precession electron diffraction patterns were acquired to assess possible phases in the observed layers.

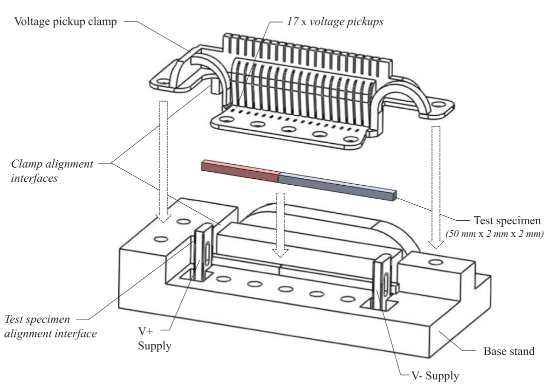

Fig. 2. Electrical measurement jig for four point measurements, comprised of base stand and clamp with 17 voltage pickups.

3. Results

The results are reported in three subsections. In the first section, the initial weld structure (before heat-treatment) is described. Then the results of the heat-treated samples are presented in the second and third sections. The second section presents the electrical performance and the third section presents the microscopy results.

3.1. Initial weld structure

In Fig. 3(a), the Vickers hardness across the interface centreline is plotted with reference to a cross-sectional optical macrograph. The weld cross-section is the original 3 mm plate thickness and was not ground down for heat treatment and electrical resistance measurement. The sample was leached before imaging to contrast the AA6101 base material and the AA6082 filler material. A wide and thin layer of filler material is visible on the top of the weld. The filler material is compressed towards the copper interface before deflecting against the steel underlay at the bottom and spreading further out. The labelled extrusion zone (EZ), consisting of a mix of filler metal and thermomechanically treated aluminum base metal, corresponds to the pin tip diameter of 7 mm.

The hardness measurements show that the base materials properties have been altered outside of the extrusion zone. On the copper side, work hardening has increased the hardness from nominally 108 Hv up to 116 Hv over 2.5 mm. On the aluminum side, a heat affected zone has reduced the hardness from its nominal value of 74 Hv. Inside the extrusion zone, the aluminum hardness averaged 70 Hv over the first 2 mm from the copper interface, before reducing further to 53 Hv. The hardness increased over the remaining extrusion zone but did not recover to the nominal value until outside the heat affect zone.

Fig. 3(b) & (c) shows optical micrographs of the weld interface with increasing magnification. Both images are from the centre of the weld cross-section and show no transfer of material across the interface or mechanical interlocking. A straight interface has been achieved, and intermetallic compounds are not observable under maximum magnification.

Fig. 4a) shows a BF-TEM image of the weld interface in which a continuous intermetallic layer is observable. Diffraction pattern analysis indicates the presence of mainly Al_2Cu and Al_4Cu_9. The average thickness of the intermetallic layer was (0.19 ± 0.01) μm. Fig. 4b) shows an ADF-STEM image from the same sample but different region, along with STEM-EDS element maps (in at.%). Dislocation structures can readily be observed in Cu grains in the ADF micrograph, and has been confirmed using weak-beam dark-field imaging. The yellow rectangle in the micrograph indicates the region from where EDS mapping was done. Two distinct regions may be seen from the element maps, assuming that the TEM sample was successfully made perpendicular to the weld interface. The layer closest to the Al filler material has been found to have an approximate 2:1 ratio of Al and Cu, respectively. The layer closest to the Cu base material was found to consist of an Al and Cu concentration gradient. Another observation from the element mapping is that there seems to be an accumulation of Si and Mg at the IMP layers.

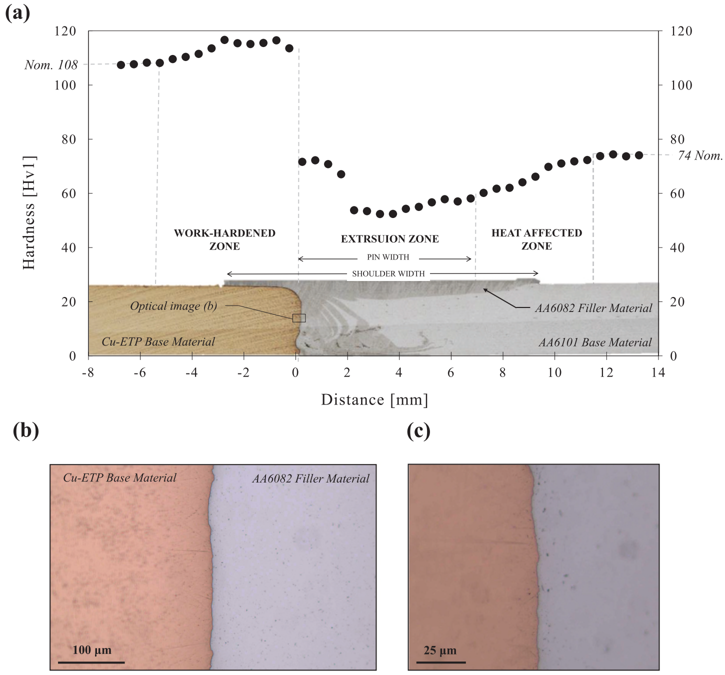

Fig. 3. Initial (without heat treatment) characterisation of 3 mm thick plates joined by HYB process including (a) Vicker hardness measurement across weld interface with reference to leached optical macrograph (b) & (c) higher magnification optical images of weld interface.

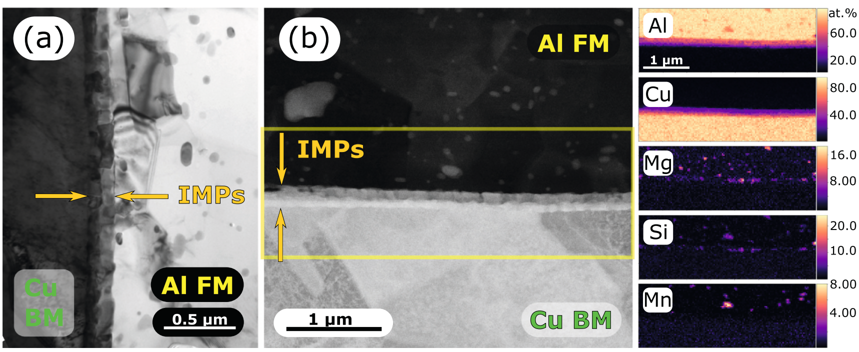

Fig. 4. (a) A bright field TEM image of the Al-Cu interface revealing small nanocrystalline grains constituting a continuous layer between the Cu BM and Al FM. (b) ADF-STEM image from a different region in the same sample. The yellow rectangle indicates the area from where STEM-EDS has been performed (colour bars are in at.%). The EDS element maps indicate the presence of two distinct layers of Al and Cu at the IMP layer: one layer composed of approximately 2:1 ratio of Al and Cu respectively closest to the Al FM, and one region closest to the Cu BM with an Al and Cu concentration gradient. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Electrical performance

Fig. 5 show electrical resistance measurements of different test specimens after thermal exposure. The measured resistances have been multiplied by the specimen's cross-sectional area. Hence, the graph's gradient shows the resistivity of each sample. Measurements across the copper are shown in orange and aluminum in blue. Extrapolating the gradient of each material to the interface identifies the interface resistance. In all cases, no significant interface resistance was identified. In fact, the total resistance of all specimens decreased after thermal exposure. The dotted line in each graph (except the 250 °C series) shows the resistance measurement before heat exposure. The gradient of aluminum has decreased relative to the dotted line indicating an increase in the aluminum conductivity. Therefore, as the interface resistance did not increase and the aluminum's resistivity decreased, the joint's overall resistance has decreased.

The AA6101 H19 base material and AA6082 filler material are both heat-sensitive aluminum alloys, and both alloys had undergone cold working before joining. The AA6101 had been rolled for maximum strain hardening to H19 condition, and the AA6082 had been cold drawn into a wire. Therefore, a reduction in strength and increase in conductivity is expected as the heat treatment would reduce the dislocation density. To quantify the conductivity increase, the conductivity of both base and filler materials were measured before and after 528 h exposure at 350 °C. The conductivity was measured using monometallic test specimens of Cu-ETP and AA6101, while for the AA6082, a 1 m

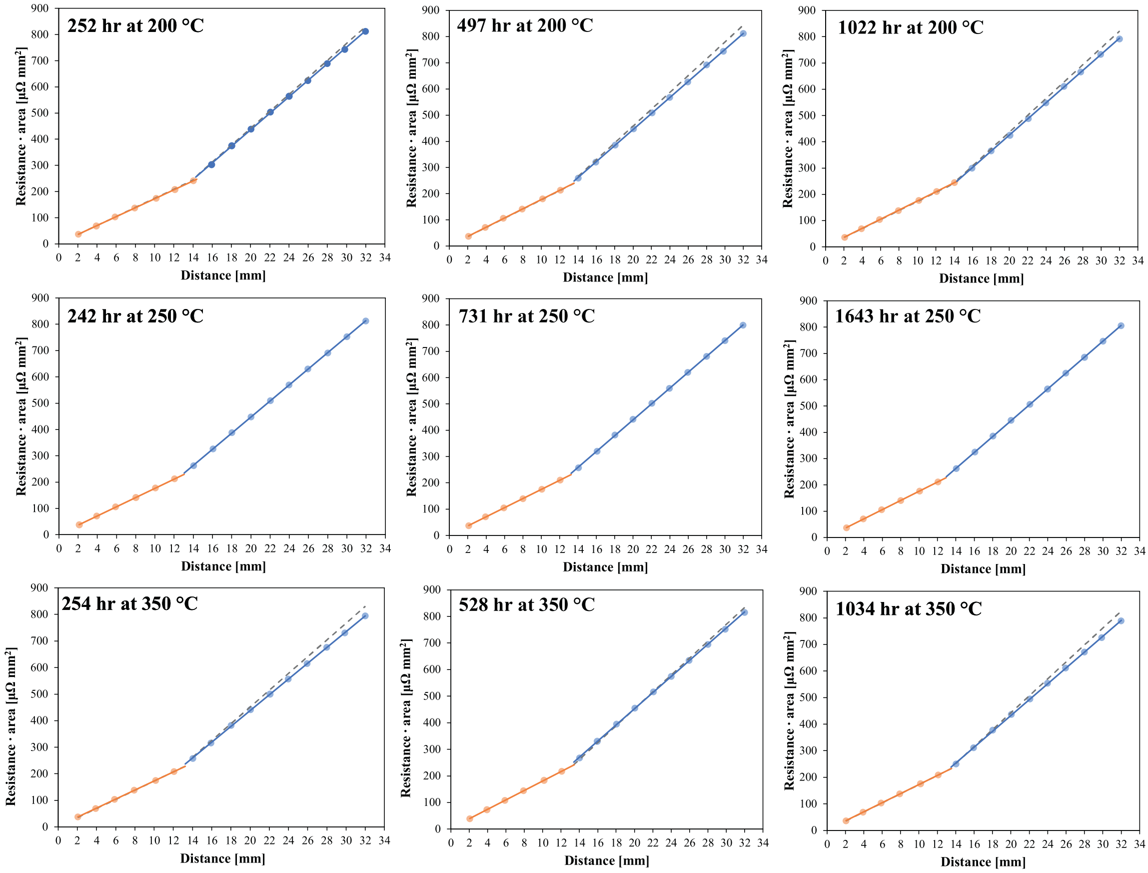

Fig. 5. Resistance measurements of samples heat-treated for increasing durations at 200 °C, 250 °C & 350 °C. Extrapolating resistance measurements to the interface of each sample (between 12 mm and 14 mm) shows the interface causes negligible resistance increase in all cases.

length of wire was measured. The measured conductivity before and after heat treatment is shown in Fig. 6. The AA6082 filler wire showed the greatest increase in conductivity; however, it is expected that the conductivity of the filler wire will increase during the extruding process due to the thermal and mechanical loads.

3.3. Microscopy inspection of heat treated samples

TEM samples taken from three heat treated joints at 200 °C and one at 250 °C were inspected. Fig. 7 shows bright-field TEM images of the maximum exposure 200 °C and 250 °C specimens. It can be seen that the heat treatment has caused Al and/or Cu interdiffusion to take place, giving positive conditions for intermetallic grain growth into a continuous layer.

All the samples studied using TEM have been observed with IMP grains that constitute a continuous layer with a wavy morphology. Some of the samples were also observed with voids both close to the IMP layers and in the Cu-BM a few micrometres away from the Al-Cu interface. The IMP layer of the non-heat treated sample and the specimen annealed at 200 °C for 252 h have a less rough IMP morphology compared with the samples heat-treated for 497 and 1022 h. A crack was discovered on the 1022 h sample on the interface IMP interface to the Cu-BM. TEM was also used to assess the chemical compositions and crystal structures of the grown phases in the heat-treated samples using STEM-EDS and electron diffraction techniques. The results were similar to the features obtained from the non-heat treated sample analysis with the presence of mainly Al_2Cu and Al_4Cu_9. Another observation of the heat-treated samples is that both the Al FM and Cu BM grains contain complex dislocation structures after annealing.

The samples heat-treated at 350 °C were inspected using SEM, as intermetallic phases were observable using light microscopy. Fig. 8 shows BSE images and EDS concentration line profiles across the interface of two materials heat-treated at 350 °C for 254 and 1034 h, respectively. The images and profiles show three distinct layers of intermetallic phases, and indicate the presence of the previously identified Al_2Cu (θ) and Al_4Cu_9 (γ_1), as well as the frequently reported AlCu (η) [12,13]. Several delimitation cracks were discovered in the 1034 h sample and occurred along the boundary of Al and the nearby IMP layer, as labelled in Fig. 8(b).

The mean values and corresponding standard deviation of the intermetallic thicknesses measured for each thermal exposure are shown in Table 2. The inspection method is specified in the table footnote.

4. Discussion

4.1. Electrical performance

A primary finding from characterisation of the Al-Cu HYB weld is the

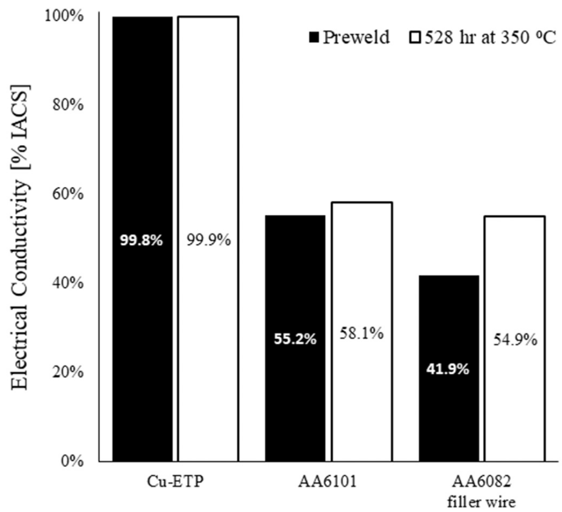

Fig. 6. Bulk conductivity measurements of weld materials before and after heat treatment at 350 °C for 528 h.

absence of increased electrical resistance. A critical concern for bimetallic busbars is increasing electrical resistance due to the growth of intermetallic compounds [7]. Previous studies have demonstrated that Al-Cu bimetallic welds have high resistance that can increase further from relatively short term exposure to temperatures above 150 °C [11,12]. On the other hand, the tested HYB welds in this study maintained low resistance even after a maximum thermal exposure of 1034 h at 350 °C. These results contrast the high thermal sensitivity of aluminum copper joining methods reported previously [11,12,27]. Newer studies have achieved the joining of aluminum and copper without increased electrical resistance [28–30]. However, subsequent thermal sensitivity has not been measured and remains identified as a potential risk. The low resistance and temperature stability of the HYB welds indicates good suitability for use in conductors, offering operation at higher temperatures and longer duration than alternative joining processes.

In the following section, the electrical performance of the HYB joint is compared to alternative processes. The comparison shows that the electrical resistance of HYB welds is the least heat-sensitive welds in published literature to the authors' knowledge.

4.1.1. *Electrical performance metrics of bimetallic weld interfaces*

Comparing Al-Cu joining processes is difficult due to variations in test methodology. The most common practice employs four-point resistance measurements [11–14,28–35], while in some cases (typically thin sheets) an eddy current resistivity measurement technique is used [18,36]. Focusing on the more accurate four-point methodology, the difficulty of comparing performance arises from variations in joint configurations and test specimen geometry.

To compare the HYB results to the alternative processes, we first review the frequently reported performance metrics before proposing a new metric, weld interface resistivity, for comparing and evaluating butt welded joint configurations.

Frequently reported electrical performance metrics of bimetallic welds are:

1. Comparison of measured joint conductivity to theoretical conductivity [11–14,28–32],
2. Joint performance factor [30,33–35]
3. Relative resistance increase [11,12].

All such metrics are useful when comparing results with the same geometry. However, they remain, in part, specific to the tested specimen geometry and are not suited for direct comparison across different studies.

The most popular performance metric is joint conductivity. An idealised schematic of the four-point measurement method to measure joint conductivity is shown in Fig. 9. Measuring the voltage drop across the joint, V_J, and current, I, allows the joint resistance, R_J, to be calculated from Ohm's law, Eq. (1). The joint conductivity or its inverse joint resistivity, ρ_J, can then be calculated from the cross-sectional area, A, and measurement length, L as shown in Eq. (2).

$$R_J = \frac{V_J}{I} \tag{1}$$

$$\rho_J = \frac{R_J A}{L} \tag{2}$$

The measured joint resistivity is then compared to the theoretical joint resistivity, ρ_T. The theoretical joint resistivity is determined by calculating the expected joint resistance, R_T, based on the volume-metric ratio of materials in the joint. Calculation of the theoretical resistance is

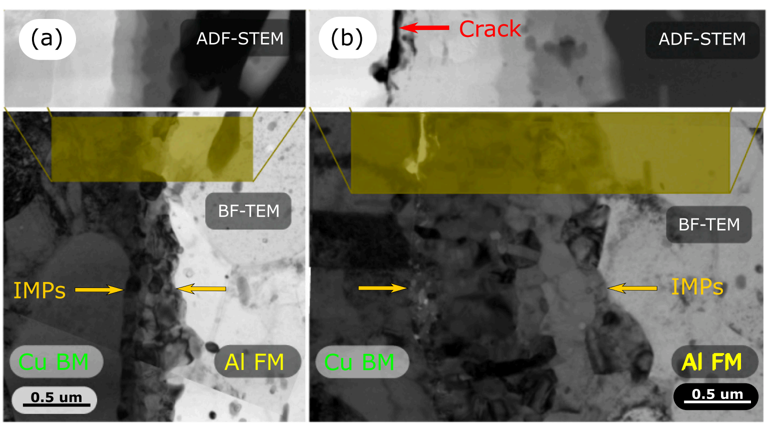

Fig. 7. (a) and (b) show BF-TEM micrographs of heat-treated samples at 200 °C and 250 °C after maximum thermal exposure, revealing growth of IMPs compared with the non-heat treated specimen.

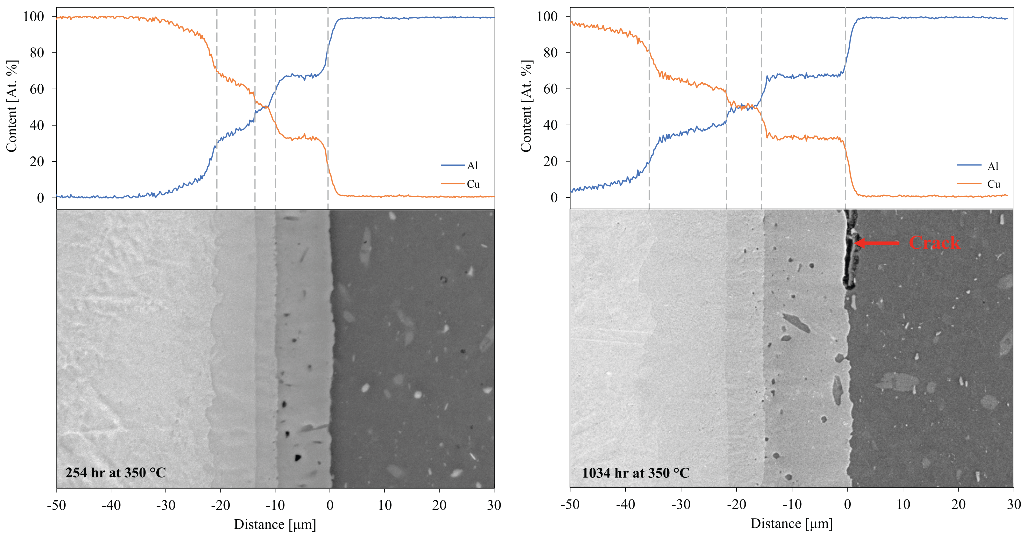

Fig. 8. (a) and (b) show BSE SEM-images and SEM-EDS concentration profiles of Al and Cu across the interface of heat-treated specimens at 350 °C for 254 and 1034 h, respectively.

Table 2
Measured total thickness of intermetallic phase layer after thermal exposure of 200 °C, 250 °C and 350 °C for increasing durations.

200 °C		250 °C		350 °C	
Time [hr]	Thickness [μm]	Time [hr]	Thickness [μm]	Time [hr]	Thickness [μm]
252[a]	0.17 ± 0.02	242[b]	0.84 ± 0.1	254[b]	21.4 ± 0.7
497[a]	0.29 ± 0.06	430[b]	0.88 ± 0.22	528[b]	31.4 ± 0.8
1022[a]	0.36 ± 0.04	731[b]	1.44 ± 0.22	1034[b]	34.9 ± 0.7
		1643[a]	1.63 ± 0.25		

[a] Total intermetallic thickness measured using TEM ADF-STEM images.
[b] Total intermetallic thickness measured using SEM BSE images.

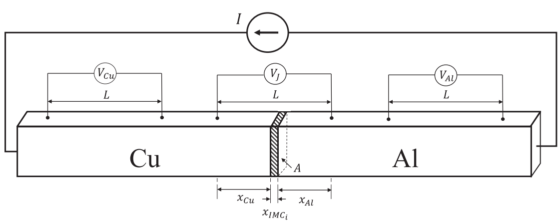

Fig. 9. Illustration of four point electrical measurement method for measuring joint conductivity and joint performance factor.

shown in Eq. (3) where measurement distance, L, illustrated in Fig. 9, is composed of copper length x_{Cu}, aluminum length x_{Al} and intermetallic thicknesses x_{IMC_i}. The theoretical joint resistivity is then calculated from the joint resistance as shown in Eq. (4).

$$R_T = \frac{1}{A}\left(\rho_{Cu}x_{Cu} + \rho_{Al}x_{Al} + \sum \rho_{IMC_i}x_{IMC_i}\right) \tag{3}$$

$$\rho_T = \frac{R_T A}{L} \tag{4}$$

In most cases, the volume-metric ratio of sample being measured is 50% Al: 50% Cu and the contribution of intermetallic compounds is neglected from the theoretical resistance. The quality of the joint is then assessed by how close the measured resistivity is to the theoretical resistivity. A quality metric, ε, may be defined to quantify the difference, Eq. (5), but in most cases results are compared graphically. Comparison of conductivity is both intuitive and practical yet conceals a few limitations for comparison between different studies.

$$\varepsilon = \rho_J - \rho_T \tag{5}$$

The first limitation is the importance of measurement length. For example, the perceived quality of the same joint can be increased by increasing the measuring length. Increasing the measurement length increases the joint conductivity as the relative contribution of the interface resistance is reduced. Therefore, a direct comparison of joint conductivity is only valid when comparing the same measurement length.

A second limitation when comparing to theoretical conductivity is the difficulty in controlling the volume-metric ratio of base materials in the test specimen. From the first limitation, it follows that measurement length should be minimised to maximise the contribution of interface resistance (i.e. minimise bulk resistance from the measurement). However, when measuring over shorter distances, controlling the volume-metric ratio becomes more challenging as the distance to the interface on each material side becomes smaller. For example, when the measuring distance is 10 mm, a deviation of 0.5 mm changes the ratio of base materials to 55%: 45%. Then, when comparing the measurements to a theoretical value of 50%: 50%, the perceived interface resistance will be higher for 55% Al or lower if 55% Cu. In some studies, the reported joint resistance is below the theoretical resistance, indicating that copper's volume-metric ratio in the measurement has not been suitably controlled [29,30]. Eslami et al. [30] highlighted the difficulty in achieving a consistent volume-metric ratio due to the non-uniform distribution of Al and Cu achieved in their friction-stir welded test specimens.

A third limitation when assessing conductivity is the need to compensate for, and potential inaccuracies in, bulk connectivity. The conductivity of aluminum and copper varies substantially due to alloying and manufacturing treatments. Reported material conductivity in the reviewed studies ranged from 48 to 63% IACS for Al and 82 to 105% IACS for Cu. Several studies did not specify if bulk conductivity was measured [11,12,28], and in a few studies it was not measured [30], or reported [13]. Accurate characterisation of bulk conductivity is important for assessing the joint conductivity and establishing the interface's contribution to resistance.

One method to suitably compensate for the bulk conductivity is to measure and report the joint performance factor, k. The joint performance factor is calculated by comparing the resistance of the joint to equivalent measurements of both bulk materials, Eq. 6. In this case, the voltage drop across the copper, V_{Cu}, and aluminum, V_{Al}, is measured over the same length, L, as the joint, see Fig. 9. Joint performance factor is suited for evaluating overlap joints as a meaningful length is established from the overlap distance. However, the joint performance factor of a butt joint relies on an arbitrary measurement length. Therefore, as different studies use different measurement lengths a direct comparison is not possible, and the metric is still susceptible to an erroneous volumetric ratio.

$$k = \frac{2V_J}{V_{Cu}V_{Al}} \tag{6}$$

The last typically reported performance metric is relative resistance increase and is useful in capturing the effect of heat treatment. This metric differs from the conductivity and joint performance factor assessment, as it does not assess the manufacturing quality but rather degradation from further environmental exposure. Eslami et al. [30] pointed out that most studies on friction stir Al-Cu welds focus on process parameters and not on subsequent functional testing of welds. As such, most studies have not performed heat treatment ageing and this metric was only identified in a few studies [11,12]. The metric effectively captures weld degradation. However, it is poorly suited for comparison across different studies. The starting resistance is specific to specimen geometry and therefore requires normalisation of measurement length and area for comparison, and to identify the weld interface resistance.

4.1.2. Weld interface resistivity

After reviewing previous studies on the electrical performance of Al-Cu joints, we propose using a new metric, weld interface resistivity, η ($\mu\Omega$ mm^2), for the electrical assessment of welds. Measurement of weld interface resistivity is analogous to the measurement of electrical or thermal contacts. In such domains, the performance metrics, specific contact resistivity ($\mu\Omega$ mm^2) [37], and thermal contact resistance, (K W^{-1} mm^{-2}) [38], are used to quantify the interface resistance. In both contexts, the interface resistance occurs over a very short distance and is normalised only for the cross-sectional area. Therefore, the bulk electrical or thermal resistances are excluded from the measurement allowing direct comparison to other processes. To exclude the bulk contribution from the measurement, several measurements are made on either side of the interface and extrapolated to the interfaces (as shown in Fig. 5).

Weld interface resistivity is an ideal metric for evaluating bimetallic materials as it envelopes multiple performance aspects. Several studies that measured the electrical resistance across weld interfaces have shown that the resistance increase cannot be attributed solely to the higher resistivity of the intermetallic compounds present in the weld [11–13,29]. Pfeifer et al. [39] have measured the resistance of individual Al_xCu_y intermetallic compounds, and shown they can be up to 11 times the resistivity of copper. However, when calculating the expected resistance across a weld interface, using the individual resistivity measurements and measured thicknesses of intermetallic phases, the measured resistance is even greater than predicted [11–13,29].

Braunovic & Alexandrov [12] suggest possible explanations for the increased resistance as porosity, cracking, changes in grain sizes, and increased dislocation density across the interface. Wang et al. [29] proposed a mechanism for the non-linear increase in resistance by relating intermetallic thickness to the base materials' grain sizes, as well as possible contributions from cracks, oxides and residual stresses. Traditionally, the criteria for acceptable Al-Cu bimetallic joints have been based on intermetallic thickness alone. However, consideration of thickness alone neglects the potential differences in joining processes and their non-linear contributions to resistance. The proposed properties by Wang and Braunovic & Alexandrov are influenced by the chosen joining process and its parameters. Therefore, it is not only the intermetallic thickness which determines the performance of the weld but the process and resulting weld structure. Wang et al.'s [29] results exemplify the importance of the process and weld structure over intermetallic thickness measurements alone, as they reported a diffusion brazed joint with 50 μm total intermetallic thickness that had a lower resistance than a flash welded joint with 2 μm total intermetallic thickness.

In contrast to intermetallic thickness, the weld interface resistivity metric captures process dependent factors, combining the intermetallic compounds resistivities, working length and structural defects into a single metric. Combining both resistivity and total intermetallic thickness into one measurable metric allows different processes to be directly compared. Furthermore, the metric is practical allowing comparison to bulk properties and functional performance for given geometric applications.

The weld interface resistivity has been calculated for several existing processes and compared to HYB performance in Fig. 10. The weld interface resistivity has been calculated for existing process from previous studies using the bulk conductivity and specified measurement distances. The calculation equations are shown in Eq. (7), and the input and result for each study is shown in Table 3. In each study, the best case, lowest resistance, has been used for comparison. For HYB, a value of <10 $\mu\Omega$ mm^2 has been considered, using the previously mentioned and more accurate methodology of forecasting multiple measurements, see Fig. 5.

$$\eta = AR_J - (\rho_{Cu}x_{Cu} + \rho_{Al}x_{Al}) \tag{7}$$

The comparison of weld interface resistivity in Fig. 10 is split into two groups, pre and post heat-treatment. The HYB joint is the only study in which the interface resistance is negligible in both groups. The HYB joint weld interface resistivity is comparable to the best friction-stir welded results of Eslami et al. [30] however Eslami et al. did not perform measurements after heat treatment. Garcia-Navarro et al. [40] recently highlighted that there is limited information on the electrical performance of friction stir weld. Therefore, it is worth highlighting that Fig. 10 shows several studies have reported lower electrical resistance of friction welds since the highly cited Braunovic & Alexandrov [12] characterisation.

The majority of studies on Al-Cu welds has focused on welding process parameters and have not measured artificially aged samples. Therefore, fewer results of samples post heat-treatment are reported. However, those that measured heat treated samples all showed increased resistance. Calculation of the weld interface resistivity for Wang et al.'s [29] diffusion brazed specimens is negative as Wang et al. reported a joint resistivity below the theoretical for the base materials. Wang et al. highlighted the “abnormal” results, and while the result indicates potential inaccuracy in measurement distance or bulk conductivity; we included the measurement as it provides another example of increased resistance from thermal exposure.

It is not appropriate to compare the weld interface resistivity increases from each study, as the samples were heat-treated at different temperatures and duration in each study, as specified in Table 3. Nevertheless, Table 3 shows the HYB samples thermal exposure was greater than the other studies and still did not increase in electrical resistivity. The HYB process has therefore formed a weld structure without added resistance and remained stable over the tested temperature range; indicating a conductor using a HYB joint could operate for longer, and at higher temperatures, compared to alternative joining processes.

4.1.3. Sample geometry resistance

The HYB joining process also provides the ability to further reduce

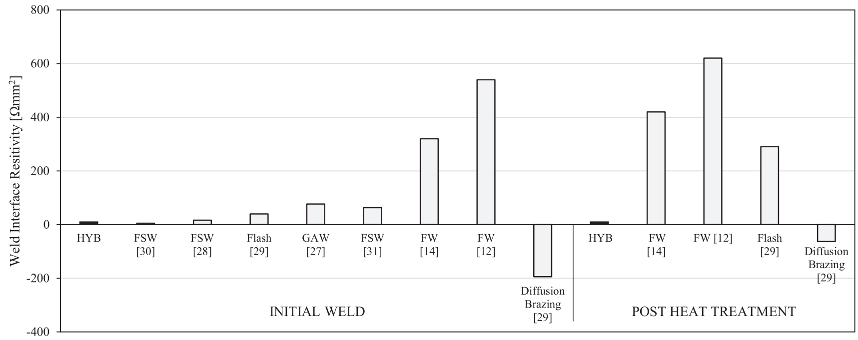

Fig. 10. Comparison of weld interface resistivity for different Al-Cu joining processes calculated from previous studies and compared to HYB results.

the weld interface resistance versus the reported measurements. The test specimens for resistance measurements were cut and ground into 2 mm × 2 mm × 50 mm samples to form a planar interface, see Fig. 11. However, the use of a rotating pin with 3 mm shoulder increases the weld interface area over the top of the copper as shown in Fig. 12. The weld interface area of 6 mm 2 per mm for a plate thickness of 3 mm provides a conductor area to weld interface area ratio of 2, whereas, the resistance measurement sample had a ratio of 1. Increasing the ratio of conductor area to weld interface area further reduces the interface resistance. Furthermore, the HYB process can be modified to extrude a weld reinforcement on top of the interface during joining, also shown in Fig. 12. A weld reinforcement would increase the cross-sectional area of the conductor therefore reducing the resistance locally. The local decrease in resistance would ensure the weld's operating temperature was lower than the nominal conductor temperature.

4.2. *Intermetallic growth rate*

Isothermal growth of intermetallic compounds in bimetallic materials typically follows a parabolic time law [41]. As such, the intermetallic thickness can be expressed by the equation $y = kt^n$, where, y, is the thickness, k, diffusion rate constant, t, reaction time, and, n, is the time exponent.

To assess the intermetallic growth rate of the HYB joints, the reported results in Table 2 are plotted on the log-log graph shown in Fig. 13. A log transformation of the parabolic equation provides a linear representation of the growth rate, n, as $\ln y = n \ln t + \ln k$. Kidson [41] showed by using Fick's first law of diffusion that a reaction rate controlled by volume-metric diffusion has a time exponent of 0.5. Fig. 13 shows the linear regression for each of the tested temperatures indicating volume-metric diffusion was occurring. The time exponents ranged from 0.35 to 0.55, and Gueydan et al. [42] reported a tolerance of 0.5 ∓ 0.1 as typical for bulk diffusion.

Assuming volume-metric diffusion; the intermetallic growth equation can be considered as $y^2 = k^2 t$ across the tested temperature range, and the diffusion rate constant can be predicted by the Arrhenius equation as follows:

$$lnk^2 = lnk_0^2 - \frac{Q}{RT} \tag{8}$$

Eq. (8) is only dependent on temperature, T, with the pre-exponential factor, k_0, growth activation energy, Q, and gas constant, R, all in principle constant.

Plotting the diffusion constants for each temperature on an Arrhenius plot, Fig. 14, shows a linear diffusion rate increase over the tested temperature range. From the linear regression, an activation energy of 152 kJ/mol and a pre-exponential constant of 1.2E−3 m^2/s can be used to describe the diffusion rate constant of the HYB welds.

4.3. *Comparison of growth rate with alternative processes*

The activation energy and pre-exponential constant for aluminum and copper interfaces have been reported for several processes [11–21,42–46]. A summary of the diffusion properties from each study is shown in Table 4.

The table shows the tested temperature range and duration applicable to the calculation of activation energy. In some cases the pre-exponential was not reported. Such cases are identified in the table and have therefore been calculated based on the provided measurements. Correct calculation of the pre-exponential was checked by confirming the reported activation energy was correctly calculated.

A widely used criterion for the integrity of Al-Cu welds is maintaining a total thickness of intermetallic compounds below 2 μm [11,12,31,40,47,48]. Therefore, it is interesting to quantify the operational conditions (temperature and duration) that a weld can tolerate before reaching 2 μm. Fig. 15 shows the time taken for the growth of 2 μm at 200 °C.

The calculated duration of the HYB weld to reach 2 μm is an order of magnitude greater than results from alternative processes. We chose to show performance at 200 °C as it is an important operating condition that has previously limited the utility of welded Al-Cu conductors [12]. Typically, maximum operating temperatures for conductors are 130 °C, and at nominal temperatures of 70 °C intermetallic growth is acceptable with existing processes [48]. However, Kemsies et al. [49] have highlighted a trend for higher operating temperatures, and Braunovic [12] has pointed out that temperatures of 200 °C and higher often occur in network overload conditions. Similarly, Gueydan et al. stated that local temperature of Al-Cu conductors in automotive applications may reach 200 °C. Therefore, a weld that can tolerate operation at 200 °C provides increased reliability for a realistic design condition. Fig. 15 shows that both friction welding and cold rolling are susceptible to failure from a relatively short duration at 200 °C temperatures, whereas the HYB process has a greater safety margin for such high-temperature events.

It should also be noted in Fig. 15 that the calculated durations are for 2 μm growth and exclude the starting thickness. An indication of the applicable starting thickness is shown in Table 4. However, in some case the initial thickness is not measured and therefore the first thickness, from shortest thermal exposure, is reported. The HYB weld starting thickness of 0.2 μm is at the lower range of reported value and therefore will not significantly reduce the calculated time to 2 μm in Fig. 15.

A detailed explanation for the thin intermetallic region and high activation energy achieved by the HYB process is beyond the scope of this work. However, the novel process conditions and resulting weld structure, with nanocrystalline interface shown in Fig. 4, contain several unique features compared to alternative processes.

In particular, the use of filler material in a solid-state process is unique to the HYB process. Compared to friction stir welding, the

Table 3
Calculation and comparison of specific interface resistivity from previous studies.

Source	Process	Aged condition	Specimen dimensions [mm × mm²]	Base material	[% IACS]	Base material	[% IACS]	Theoretical resistance [μΩ]	Measured conductivity [% IACS]	Measured resistance [μΩ]	Interface resistance [μΩ]	Specific interface resistivity [μΩ mm²]
Fig. 5	HYB	Initial weld	32 × 4	AA6101	55.2%	ETP-Cu	99.8%			164.9		<25
	HYB	1000 h at 350 °C		AA6101	55.2%	ETP-Cu	99.8%			161		<25
Zhang et al. (2020)	GAW	Initial weld	100 × 30	AA1060	60.7%	T2 Cu	104.7%	112.2	74%	116.0	3.8	76.7
Wang et al. (2020)	Flash	Initial weld	100 × 250	AA1060	60.5%	C11000	104.5%	9.0	75%	9.2	0.2	40
		350 °C 500 h							68%	10.2	1.2	290
	Diffusion Brazing	Initial weld							84%	8.2	−0.8	−194
		350 °C 500 h							79%	8.7	−0.3	−63
Braunovic & Alexandrov (1994)	FW	Initial weld	100 × 75.5	Al	50.7%	Cu	86.2%	137.5	53%	165	27.5	540
		325 °C 120 h (Oven)		Al	50.7%	Cu	86.2%	137.5	52%	169	31.6	620
Li et al. (2018)	FW	Initial weld	10 × 28	AA1060	49.3%	T2 Cu	82.1%	10.0	29%	21.4	11.4	320
		400 °C 2 h		AA1060	49.3%	T2 Cu	82.1%	10.0	25%	25.0	15.0	420
Savolainen et al. (2006)	FSW	Initial weld	99 × 160	EN AW-6060 T6	47.8%	Cu-OF	84.1%	17.5	60%	17.9	0.395	63.2
Eslami et al. (2019)	FSW	Initial weld	40 × 80	EN AW-1050A	59.5%	EN CW008A	98.5%	11.6	75%	11.46	−0.2	<5
Olafsson et al. (2020) & Olafsson (2017)	FSW	Initial weld	24 × 30	AA1050	57.5%	Cu OF 04	95.3%	19.2	84%	19.8	0.55	17

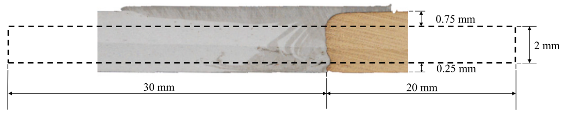

Fig. 11. Dimensions of resistance measurement test specimen with reference to weld cross-section showing the 3 mm plate thickness was reduced to 2 mm.

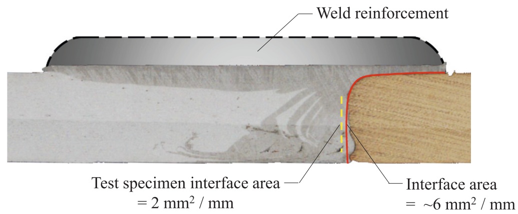

Fig. 12. Illustration of reinforced weld and weld interface area highlighted. Highlighted area shows as manufactured weld interface area (red) and weld interface area (yellow) of resistance measurement test specimen. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

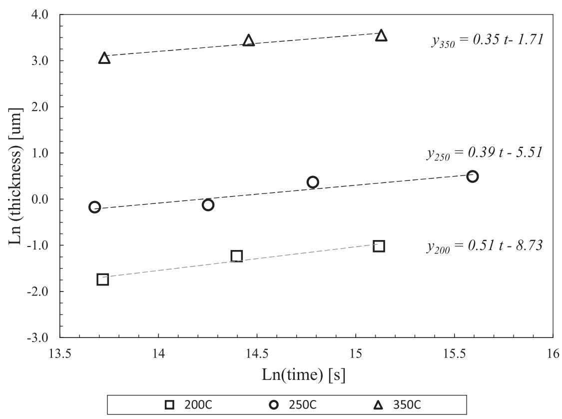

Fig. 13. Loglog plot of intermetallic thickness measurements at 200 °C, 250 °C & 350 °C.

interface temperatures are reduced by machining with lower rotations speeds and not cutting into the harder copper material. Therefore, using a filler material likely provides a less concentrated heat input at the interface than friction stir.

While the primary factors for the formation of intermetallics are temperature and exposure time; the weld microstructure properties may also impact diffusion rate. Hua et al. [16] have modelled the growth of intermetallic and shown that prediction of diffusion rates is improved by considering the unique concentration gradients across the weld. Their findings indicate that the weld structure (i.e. the number of intermetallic compounds and constituent elements present along with the relative thickness ratios of the layers) will impact the overall diffusion rate.

Fundamentally, a slow diffusion rate indicates a reduced density of vacancies across the HYB weld. Diffusion between two metals is dependent on atoms moving into vacancies in the opposite lattice structure [20]. The number of vacancies is influenced by microstructure properties, including dislocations, grain boundaries and defects, which are dependent on the joining process's thermomechanical conditions.

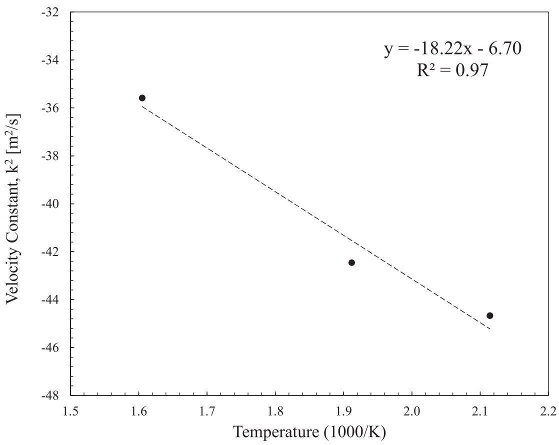

Fig. 14. Arrhenius plot of intermetallic growth rates at 200 °C, 250 °C & 350 °C.

Hence, the HYB results are a unique function of the process temperature profile, resulting intermetallic compounds present and susceptibility to generating vacancies.

5. Conclusion

This study evaluated the Hybrid Metal and Extrusion Bonding (HYB) process for joining copper and aluminum. The main findings were:

- The two materials were joined successfully. Optical examination of weld cross-sections showed a straight interface with minimal material transfer. Transmission electron microscopy identified a thin (0.2 μm) and consistent intermetallic layer had been achieved.
- Weld samples were artificially aged by heat treatment and examined under further electron microscopy to identify intermetallic compound growth. Diffraction pattern analysis indicated the presence of Al_2Cu (θ) and Al_4Cu_9 (γ_2) intermetallic phases. Composition analysis of samples exposed to the highest temperature also indicated presence of AlCu.
- The calculated activation energy for total intermetallic growth was higher than existing processes, including friction welding, cold rolling, and ultrasonic wire bonding, meaning that the intermetallic growth rate is lower for HYB welds.
- The weld interface was not a source of additional resistance, and heat-treated samples did not increase electrical resistance. A new metric, weld interface resistivity, was proposed for the comparison of weld resistance between different processes. The heat-treated HYB samples were found to have the lowest interface resistance of any Al-Cu joining process to the authors' knowledge.

HYB is a versatile joining method capable of joining bulk materials along joint lines. The HYB process allows the joining of larger conductors than possible with ultrasonic welding, and provides greater dimensional flexibility than cold rolling or rotary friction welding. The process is comparable to friction-stir welding; however, HYB forms an interface with significantly less material transfer and less impact on electrical resistance than previously reported for friction stir. Therefore, the novel HYB process shows excellent potential for joining aluminum and copper. This study is the first assessment of the HYB process for bimetallic electrical conductors prompting exciting opportunities for further development.

Table 4
Summary of Al-Cu bimetallic diffusion properties reported using different joining processes in previous studies.

Reference	Year	Author	Process	Initial IMC thickness [μm]	Thermal exposure before initial measurement	Temperature range [C]	Max duration [hr]	Heating method	K_o^2 [m^2/s]	Q_d [kJ/mol]
		Elkjaer et al.	HYB	0.2		200–350	1152	Oven	1.2E−03	151.6
[12] Oven	1994	Braunovic & Alexandrov	FW	<0.3	1 h at 200C	250–380	120	Oven	2.2E−10	72.0
						425–520			8.0E−05	136.9
[12] Electric						200–350	24	Electric current	5.9E−11	55.3
						400–500			3.3E−06	110.9
[13]	2005	Lee et al.	FW	<2		300–500	36	Oven	2.1E−06	110.6
[43]	2015	Xue et al.	FSW	~1		250,400	144	Oven	3.9E−05	125.5
[14] [44]	2018 2018	Li et al. & Pan et al.	FW	0.8		400–500	8	Oven	1.5E−05[a]	121.4
[11]	2001	Abbasi et al.	Cold rolled	<0.3	5 h at 250C	250	1000	Oven	na	na
[15]	2007	Chen & Hwang	Cold rolled	~0		300–540	2	Oven	3.1E−06[a]	107.9
[17]	2014	Hilz et al.	Cold rolled	<1		200–400	1000	Oven	2.7E−07	99.0
[16]	2020	Hua et al.	Cold rolled	1.88		320–400	0.4	Oven	–	–
[18]	2020	Li et al.	Cold rolled	<1.3	0.5 h at 300C	300–450	4	Oven	1.1E−05	108.0
[42]	2014	Gueydan et al.	Clad wire	~0		200–300	48	Oven	–	106.0
[19]	2003	Kim et al.	Wire bonding	~0		150–300	250	Oven	4.7E−07	108.9
[20]	2010	Xu et al.	Wire bonding	0.03		200–300	2904	Oven	1.1E−07	97.0
[21]	2019	Liu et al.	Wire bonding	0.2		150–250	3000	Oven	4.6E−11[a]	76.1
[45]	2011	Guo et al.	Diffusion	<5	10 min at 300C	400–500	0.5	Electric current	4.5E−08[a]	80.8
[46]	2014	Solchenbach et al.	Laser	<2.5	1 h at 200C	200–500	120	Oven	4.8E−08	90.3
						50–350	24	Electric current	–	–

[a] Pre-exponential not reported in study. Value has been calculated based on the provided data.

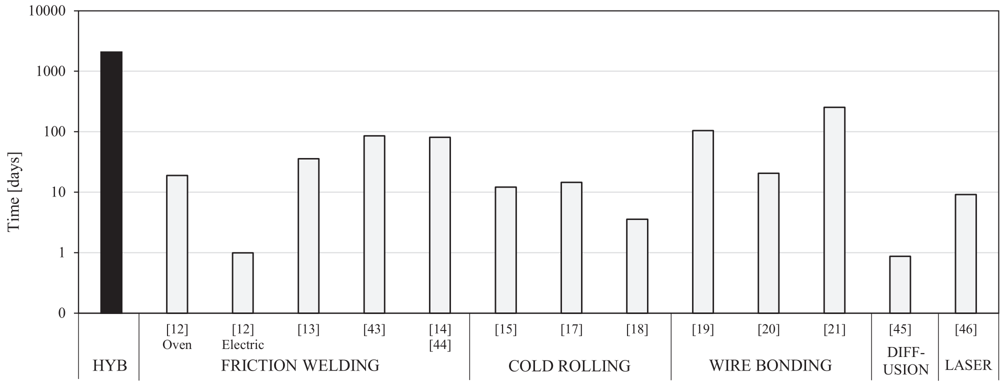

Fig. 15. Comparison of growth rates for different Al-Cu joining processes showing time taken for 2 μm of growth at 200 °C. Durations have been calculated based on reported activation energy and pre-exponential and compared to HYB results.

5.1. *Future work*

The negligible impact on electrical resistance and slow intermetallic growth are promising results of the potential functional performance. However, these initial results should be strengthened to fully characterise the functional performance of the HYB process for electrical conductors.

Assessment of structural integrity would be beneficial to confirm appropriate failure criteria. The electrical measurements in this study have shown that electrical resistance is not significantly impacted, even with an intermetallic thickness of 35 μm. However, the welds with a 35 μm thick IMP layer may have reduced structural integrity. Interestingly, despite the 2 μm criteria being widely cited, the criterion is mostly cited from two studies by Wallach & Davies [10] and Abbasi et al. [11]. The two studies are based on cold-rolled aluminum and copper and it would be useful to establish criteria specific for the butt welded HYB joints. Since fewer defects are suspected in the HYB weld it would be interesting to establish if this also improves the structural integrity. The structural characterisation should focus specifically on safety margin for electrical applications, such as bending and thermal fatigue. The characterisation should be performed versus intermetallic thickness to establish the design envelope for Al-Cu HYB welds.

In addition, continued testing of electrical resistance versus intermetallic thickness would be useful to establish the thickness at which electrical resistance is impacted. The maximum intermetallic thickness in this study was 35 μm and increasing to greater thickness may provide insight into the mechanisms causing electric resistance across weld interfaces. Moreover, additional artificial ageing should be conducted with electrical heating instead of using atmospheric heating from an oven. Braunovic & Alexandrov [12] and Solchenbach et al. [46] have shown that the diffusion rate is accelerated by electric current heating versus external heating. Therefore, establishing the diffusion rate from internal electric heating will be important for establishing the functional performance of the HYB process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Gold R. Status report on electrification policy: where to next?. In: Current sustainable/renewable energy reports; 2021. p. 1–9.
[2] Zuo YY, Gong P, Ji SD, Li QH, Ma ZW, Lv Z. Ultrasound-assisted friction stir transient liquid phase spot welded dissimilar copper-aluminum joint. J Manuf Process 2021;62:58–66.
[3] Galvão I, Loureiro A, Rodrigues DM. Critical review on friction stir welding of aluminium to copper. Sci Technol Weld Join 2016;21(7):523–46.
[4] Messner F. Material substitution and path dependence: empirical evidence on the substitution of copper for aluminum. Ecol Econ 2002;42(1–2):259–71.
[5] Green HE. Aluminium in the electrical industry. Electron Power 1973;19(19): 473–5.
[6] Lee SS, Kim TH, Hu SJ, Cai WW, Abell JA. Joining technologies for automotive lithium-ion battery manufacturing: a review. In: International manufacturing science and engineering conference. Vol. 49460; 2010. p. 541–9.
[7] Slade PG. Electrical contacts: principles and applications. 2nd Edition. CRC press; 2017.
[8] Jackson RL. Electrical performance of aluminium/copper bolted joints. In: IEE proceedings C (generation, transmission and distribution). Vol. 129. IET; 1982. p. 177–84.
[9] Kah P, Vimalraj C, Martikainen J, Suoranta R. Factors influencing Al-cu weld properties by intermetallic compound formation. Int J Mech Mater Eng 2015;10 (1):1–13.
[10] Wallach ER, Davies GJ. Mechanical properties of aluminium-copper solid-phase welds. Metals Technol 1977;4(1):183–90.
[11] Abbasi M, Taheri AK, Salehi MT. Growth rate of intermetallic compounds in Al/Cu bimetal produced by cold roll welding process. J Alloys Compd 2001;319(1–2): 233–41.
[12] Braunovic M, Alexandrov N. Intermetallic compounds at aluminum-to-copper electrical interfaces: effect of temperature and electric current. IEEE Trans Compon Packag Manuf Technol Part A 1994;17(1):78–85.
[13] Lee W-B, Bang K-S, Jung S-B. Effects of intermetallic compound on the electrical and mechanical properties of friction welded Cu/Al bimetallic joints during annealing. J Alloys Compd 2005;390(1–2):212–9.
[14] P. Li L. Pan X. Hao S. Li H. Dong , Effect of post-weld heat treatment on inhomogeneity of aluminum/copper rotary friction welded joint, Mater Res Express 5 (9).
[15] Chen C-Y, Hwang W-S. Effect of annealing on the interfacial structure of aluminum-copper joints. Mater Trans 2007;48(7):1938–47. The Japan Institute of Metals.
[16] Hua F-A, Song H-W, Sun T, Li J-P. Inter-diffusion based analytical model for growth kinetics of IMC layers at roll bonded Cu/Al interface during annealing process. Met Mater Int 2020;26(3):333–45.
[17] Hilz E, Dudziak S, Schmid-Fetzer R. Formation and properties of intermetallic compounds in an Al-Cu roll-bonded connection. In: ICEC 2014; The 27th international conference on electrical contacts, VDE; 2014. p. 1–6.
[18] Li H, Yang Y, Liang X, Zhang W, Cao L, Wu C, Zeng Z, Wang L. Effect of annealing temperature and time on the microstructure, mechanical properties and conductivity of cold-rolled explosive Cu/Al composite sheets. Mater Res Express 2020;7(10).
[19] Kim H-J, Lee JY, Paik K-W, Koh K-W, Won J, Choe S, Lee J, Moon J-T, Park Y-J. Effects of Cu/Al intermetallic compound (IMC) on copper wire and aluminum pad bondability. IEEE Trans Compon Packag Technol 2003;26(2):367–74.
[20] Xu H, Liu C, Silberschmidt VV, Chen Z. Growth of intermetallic compounds in thermosonic copper wire bonding on aluminum metallization. J Electron Mater 2010;39(1):124–31.
[21] Liu C-P, Chang S-J, Liu Y-F, Chen W-S. Cu-Al interfacial formation and kinetic growth behavior during HTS reliability test. J Mater Process Technol 2019;267: 90–102.
[22] Grong Ø, Sandnes L, Berto F. A status report on the hybrid metal extrusion & bonding (HYB) process and its applications. Mater Des Process Commun 2019;1(2).

[23] Grong Ø, Sandnes L, Ferro P, Berto F. Chapter 9 - hybrid metal extrusion & bonding. In: Pereira MDB, da Silva FJG, editors. Handbook of welding: processes, control and simulation. Nova Science Publishers; 2021.
[24] Sandnes L. On the mechanical integrity of welded joints made by hybrid metal extrusion and bonding. Ph.D. thesis. Trondheim: Norwegian University of Science and Technology; 2021.
[25] Turgun H. Electron microscopy characterization of aluminium-copper-titanium-steel joint made using the hybrid metal extrusion & bonding method. NTNU; 2020. Master's thesis.
[26] Peña FDL, Prestat E, Fauske VT, Burdet P, Lähnemann J, Furnival T, Jokubauskas P, Nord M, Ostasevicius T, MacArthur KE, Johnstone DN, Sarahan M, Aarholt T, Taillon J, pquinn dls, Migunov V, Eljarrat A, Caron J, Poon T, Mazzucco S, Francis C, Martineau B, Somnath S, Slater T, Tappy N, Walls M, Cautaerts N, Winkler F, Actions user. DENSmerijn, hyperspy/hyperspy: release v1.6.5. URL, https://zenodo.org/record/5608741; Oct. 2021. https://doi.org/10.5281/zenodo.5608741.
[27] Zhang J, Wang B-H, Chen G-H, Wang R-M, Miao C-H, Zheng Z-X, Tang W-M. Formation and growth of Cu–Al IMCs and their effect on electrical property of electroplated Cu/Al laminar composites. Trans Nonferrous Metals Soc China 2016;26(12):3283–91.
[28] Ólafsson D, Vilaça P, Vesanko J. Multiphysical characterization of FSW of aluminum electrical busbars with copper ends. Weld World 2020;64(1):59–71.
[29] Wang X-G, DongYuan X, Li J-N, Li X-G. Influence of interfacial inter-metallic compounds on the electrical characterization of Cu/Al joints produced by flash welding and diffusion brazing. Mater Res 2020;23.
[30] Eslami N, Harms A, Henke B, Fricke A, Böhm S. Electrical and mechanical properties of friction stir welded Al-Cu butt joints. Weld World 2019;63(3):903–11.
[31] Savolainen K, Mononen J, Saukkonen T, Hänninen H. A preliminary study on friction stir welding of dissimilar metal joints of copper and aluminium. In: 6th international friction stir welding symposium; 2006. p. 10.
[32] Zhang H, Shi Y, Gu Y, Li C. Effect of different filler wires on mechanical property and conductivity of aluminum-copper joints. Materials 2020;13(16).
[33] Solchenbach T, Plapper P, Cai W. Electrical performance of laser braze-welded aluminum–copper interconnects. J Manuf Process 2014;16(2):183–9.
[34] Dimatteo V, Ascari A, Fortunato A. Continuous laser welding with spatial beam oscillation of dissimilar thin sheet materials (Al-Cu and Cu-Al): Process optimization and characterization. J Manuf Process 2019;44:158–65.
[35] Shaikh UF, Das A, Barai A, Masters I. Electro-thermo-mechanical behaviours of laser joints for electric vehicle battery interconnects. In: 2019 electric vehicles international conference (EV), IEEE; 2019. p. 1–6.
[36] Sharma N, Khan ZA, Siddiquee AN, Shihab SK, Wahid MA. Effect of process parameters on microstructure and electrical conductivity during FSW of Al-6101 and pure copper. Mater Res Express 2018;5(4).
[37] Berger HH. Contact resistance and contact resistivity. J Electrochem Soc 1972;119(4):507.
[38] Madhusudana CV. Thermal contact conductance. Mechanical Engineering Series. Cham: Springer International Publishing; 2014.
[39] Pfeifer S, Großmann S, Freudenberger R, Willing H, Kappl H. Characterization of intermetallic compounds in Al-Cu-Bimetallic interfaces. In: 2012 IEEE 58th Holm conference on electrical contacts (Holm), IEEE; 2012. p. 1–6.
[40] García-Navarro D, Ortiz-Cuellar JC, Galindo-Valdés JS, Gómez-Casas J, Muñiz-Valdez CR, Rodríguez-Rosales NA. Effects of the FSW parameters on microstructure and electrical properties in Al 6061-T6-Cu C11000 plate joints. Crystals 2021;11(1):21.
[41] Kidson GV. Some aspects of the growth of diffusion layers in binary systems. J Nucl Mater 1961;3(1):21–9.
[42] Gueydan A, Domengès B, Hug E. Study of the intermetallic growth in copper-clad aluminum wires after thermal aging. Intermetallics 2014;50:34–42.
[43] Xue P, Xiao BL, Ma ZY. Effect of interfacial microstructure evolution on mechanical properties and fracture behavior of friction stir-welded Al-Cu joints. Metall Mater Trans A 2015;46(7):3091–103.
[44] Pan L, Li P, Hao X, Zhou J, Dong H. Inhomogeneity of microstructure and mechanical properties in radial direction of aluminum/copper friction welded joints. J Mater Process Technol 2018;255:308–18.
[45] Guo Y, Liu G, Jin H, Shi Z, Qiao G. Intermetallic phase formation in diffusion-bonded Cu/Al laminates. J Mater Sci 2011;46(8):2467–73.
[46] Solchenbach T, Plapper P, Greger M, Biagi J-L, Bour J, Bomfim JAS. Thermal and electrical aging of laser braze-welded aluminum–copper interconnects. Transl Mater Res 2014;1(1).
[47] Wang X-G, Li X-G, Yan F-J, Wang C-G. Effect of heat treatment on the interfacial microstructure and properties of Cu-Al joints. Weld World 2017;61(1):187–96.
[48] Dalgaard E, Wanjara P, Trigo G, Jahazi M, Comeau G, Jonas JJ. Linear friction welding of Al–Cu part 2–interfacial characteristics. Can Metall Q 2011;50(4):360–70.
[49] Kemsies RH, Milkereit B, Kessler O, Fuhrmann T, Schlegel S, Plonus F, Miller-Jupp SP, Hirsch J. Effect of dispersoids on long-term stable electrical aluminium connections. In: Materials science forum. Vol. 877. Trans Tech Publ; 2017. p. 409–15.

Paper IV

A Literature Review of the Integration of Test Activities into the Product Development Process

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Conferences on Systems Engineering Research, Recent trends and advances in Model Bases Systems Engineering, Springer
Published 2022

A Literature Review of the Integration of Test Activities into the Product Development Process

Aksel Elkjaer, Geir Ringen, and Cecilia Haskins

Abstract The purpose of this paper is to investigate product development test processes. A literature review examines research on test activities in product design, product development and systems engineering research fields. The publications reviewed have been categorized based on the stage in development and placed into a proposed test process framework. The proposed framework sets an agenda of functions and characteristics important for the integration of test processes into model-based systems engineering. The findings presented are of interest to researchers by structuring test activities from product development, systems engineering and prototyping research into a context for the design process. The findings also allow practitioners to identify research at the level of planning and development stage relevant to their test processes.

Keywords Product development · Test activity integration · Literature review

1 Introduction

Testing is an essential component of the development process; however, it's integration into the design process has received limited attention (Engel 2010; Tahera et al. 2018). A test of a design provides the possibility either to confirm a rationale or to learn from the discovery of unknown (and unexpected) outcomes, offering vital information to the design process. From this viewpoint, the purpose of a test in product development can be considered as a method to reduce uncertainty (Bjorkman et al. 2013). The reduction of uncertainty supports decision-making at any stage in development, but the value of information and new knowledge is inversely proportional with time (Kennedy 2008). Reduced uncertainty offers two outcomes. If the performance is as expected, the result is evidence which confirms

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A. M. Madni et al. (eds.), *Recent Trends and Advances in Model Based Systems Engineering*, https://doi.org/10.1007/978-3-030-82083-1_21

quality in a context. If the performance is not as expected (or expectation unknown), the result provides a pathway to new understanding.

Experience tells us that test activities incur a significant financial burden, typically accounting for a substantial proportion of total development costs (Tahera et al. 2017). In contrast, even greater costs from a late-stage failure are often attributed to the deficiency of untested decisions (Kukulies and Schmitt 2018). The planning of test activities during development requires carefully balancing the potential benefits of new knowledge relevant to risk mitigation against the applicable programmatic constraints.

Model-based systems engineering (MBSE) promotes the utilization of models throughout the development process, from needs analysis and requirement definition to the end of a product life cycle, to enhance development (INCOSE 2007). Such models offer the potential for the explicit connection of test processes to design, supporting traceability to both knowledge gains and risk mitigations. Model-based testing has arisen from the need to test formalized models generated from analysis and simulations. The research on how MBSE and model-based testing should be integrated, especially in a context outside of software development, is lacking. Raz et al. (2018) have used Design of Experiments methodology to link system architecting and the system design space through formal models showing the potential for the further integration of test processes. In this study perspectives from research on test activities of products and systems are presented to support the integration of testing perspectives into MBSE.

The motivation of this paper is to orient the reader to research into test activities and to provide a synthesis of research into test processes related to early development stages. A literature review has been conducted to classify research on test activities based on their aims, perspectives to planning and stage in development. The objective of the review is to develop a framework of test activity that supports integration into the development process. Two research questions were proposed as a foundation for establishing the framework.

1. In which stages of product development have the integration of test activities into the development process been researched?
2. What perspectives are taken in the planning of test activities?

The paper is structured as follows: Section 2 Methodology presents the literature search strategy; the findings are given in Sect. 3 Results, analysed in Sect. 4 Discussion and summarized in Sect. 5 Conclusion.

2 Methodology

2.1 Search Strategy

The review was performed with guidance from procedural literature by Machi and McEvoy (2016). The SCOPUS electronic database was searched for any combination of product development keyword AND testing keyword shown in Table 1. The search was conducted within the title, abstract and keywords. The search was limited to the journal sources listed in Table 2 with no restriction on year of publication. The sources were selected due to their focus on technical engineering design and their high reputation within the field, but are not considered exhaustive. Sources focused on engineering management were excluded to concentrate on the technical implementation of testing rather than related business and management topics.

2.2 Inclusion and Exclusion Criteria

The discovered articles were processed in three subsequent steps to remove articles not relevant to the intention of the study. First articles were removed based on title, then abstract and finally after reading the paper. The sample population for each stage is shown in Fig. 1 with a final population of 34 articles.

Table 1 Keyword search terms

Topic	Keywords
Product development	"product development" OR "product design" OR "system development" OR "design and development" OR "system design" OR "design method*" OR "design theory" OR "system engineering" OR "v model" OR "development process" OR "design process" OR "design for" OR "robust design" OR "knowledge based engineering" OR "knowledge management" OR "organi*ational learn" OR "model-based" OR "set*based"
Testing	"test and evaluation" OR "test plan" OR "test definition" OR "test specification" OR "test verification" OR "test validation" OR "test management" OR "verification activities" OR "physical test" OR "virtual test" OR "test activities" OR "testing" OR "set*based test" OR "prototyp*"

Table 2 Journal sources

Journals	Research in Engineering Design, Journal of Engineering Design, Systems Engineering, Concurrent Engineering, CIRP Journal of Manufacturing Science and Technology, Journal of Mechanical Design

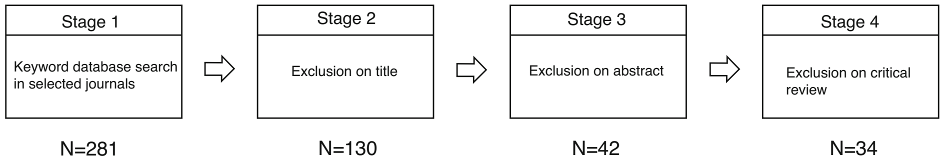

Fig. 1 Search processing stages

The article was included if the research addressed:

- The engineering design process, new product development practice, system engineering/design, development activities or design approach.
- Test activities or processes were integral to the paper's research question/thesis.
- Test activities were discussed in relation to the design process (e.g. use of test results contributing to design process/decisions).
- Tests were analysed as a method of verification/validation or source of discovery/learning/reusable knowledge.

The article was excluded if:

- "Test" used in reference to testing paper's hypothesis and not product development test activity. This includes the "testing" of a new design method – if test activities are not relevant to that design method.
- Studies addressing solely software products or construction projects.
- Studies focusing solely on the design improvement of a specific product for the benefit of that specific product – as opposed to development process/design methodology in general.
- "Design methodology" referred to as the methodological design of the study itself (i.e. not product development methodology).
- Virtual prototype, virtual testing, simulation or analysis research not discussed in a context of impact on the design/development process (i.e. research into improving specific modelling technique for a design problem was not included).

3 Results

Results from the literature review are summarised in the following two subchapters. First, the number of articles addressing each stage in development is presented, followed by their categorization into a model of perspectives on product development testing. Appendix A provides a complete list of the reviewed literature showing the classification of each article according to the presented frameworks.

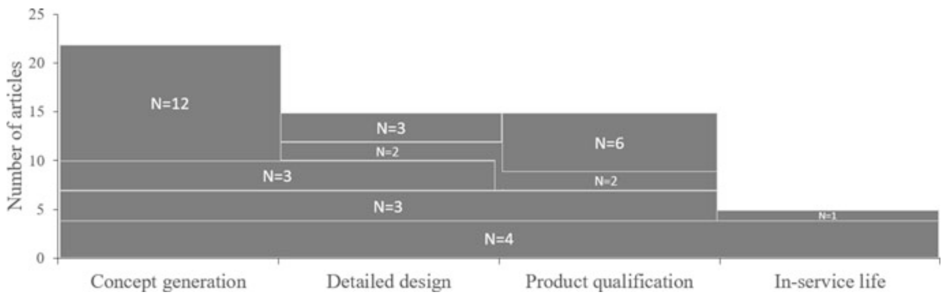

Fig. 2 Stage of product development in which testing was being investigated

3.1 *Stage of Product Development*

The research on test activities identified in this paper has been categorized with respect to the stage of the development process being investigated. Four stages, unique in respect to test activities, have been defined by the authors covering the fundamental stages from textbook literature (Ulrich and Eppinger 2012). The stages are concept generation, detailed design, product qualification and in-service life. The number of articles addressing each stage in development is shown in Fig. 2.

A test process is not necessarily unique to only one stage in development. It is possible for research to be conducted solely on testing during concept generation (one stage) or with a broader perspective of the development process covering multiple stages. Figure 2 therefore includes boxes spread across the applicable stages with the number of articles for each box specified.

3.2 *Test Process Perspective*

The perspective of testing that was studied was categorized into three areas of activity suggested by the literature. In test design, the research addressed the best way to perform a specific test. A second area was defined as test objectives and focused on determining what to test. Finally, test strategy is where a test campaign of defined test objectives was studied for optimization. The number of articles discovered for each perspective is shown in Fig. 3.

4 Discussion

Splitting the development process into stages allows the objective of testing in each phase to be discretized. In essence, testing with respect to stage in development can be considered as progressive investigations to discover: *Will the idea work?*

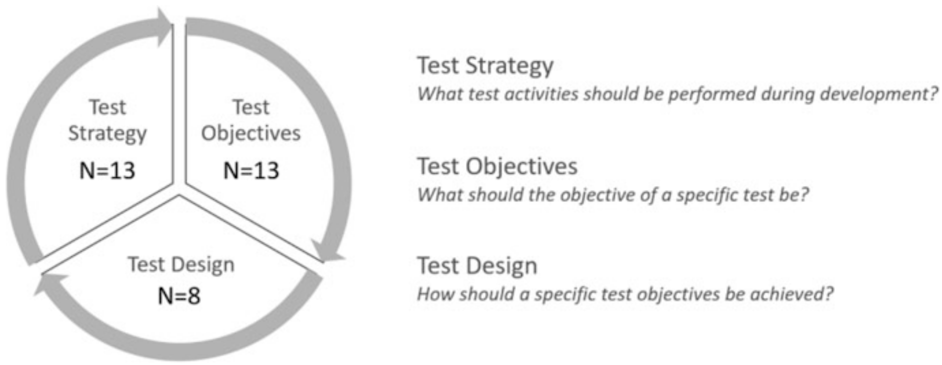

Fig. 3 Test process perspectives

Will the solution work? Does the product/system work? And finally *how well did the product/system work?* The greatest number of research articles addressed the earliest phase, concept development, which reflects the importance of starting with the right idea by frontloading activities and generating knowledge when it is most valuable. Whilst the understanding and maturity of the product is often limited in the concept phase, expanding the potential to answer the subsequent questions as early as possible achieves compounding benefits. Furthermore, it is specifically these compounding benefits that are the focus of integrating test activities into the development process.

Three test process perspectives are proposed as relevant for the integration of test activities in the development process. The following discussion highlights the key insights from the identified research from each perspective. The purpose is to distil the important considerations for the integration of testing into the development process.

4.1 Test Strategy

The category "test strategy" considers a holistic perspective of test activities during development. It concerns overall aspects of development, such as the duration, cost, quality or risk management. This requires analysing the test activities collectively and establishing the appropriate approach.

The systems engineering processes of verification and validation align with this perspective. Testing is technically a method of verification and validation. However due to testing's critical role in the process, it is considered a test strategy in the context of the proposed framework. Several articles were discovered modelling the set of activities in a verification and validation plan to compare and query development approaches.

Engel and Barad (2003) and Engel and Shachar (2006) developed a quantitative methodology of modelling the cost and duration of activities in a verification plan. Subsequently, Hoppe et al. (2007) performed a multi-case study analysis of the quantitative methodology, along with qualitative guidelines, and showed how frontloading of test verification activities was critical for the development life cycle. This advocates for the close integration of test strategy in the design phase. Similar models, which estimate the characteristics of a set of test activities for the mathematical assessment of optimal solutions, have been developed by Salado (2015) and Shabi et al. (2017). These approaches achieve optimized test strategies for given designs which, although useful for comparison of different designs, do not influence directly the design process. They view an optimized test strategy as output for a given design problem. This is similar to Tahan and Ben-Asher (2005) who investigated specifically the ideal number of incremental stages for verification for a design.

Two studies which did explicitly integrate test strategy into the design process were (Tahera et al. 2018) and (Shin et al. 2017). Tahera et al. (2018) addressed the importance of incremental stages of testing with direct dependences to design iterations, and Shin et al. (2017) modelled the sequence of design tasks and test activities to establish the process with the shortest duration. These studies emphasized the efficiency and effectiveness to overall development which testing can provide when considered early and throughout development.

A different area of research concerning test strategy was research on prototyping. The following three studies examined the role of prototypes on a strategic level: Barkan and Iansiti (1993), Camburn et al. (2015) and Lauff et al. (2018). They all addressed aspects of using prototypes throughout development, such as timing, scope and prototype characteristics, to understand how they influenced the process.

4.2 *Test Objectives*

Articles in this category investigated the objective of specific test activities. Three general approaches were discovered in the identified research. Test objectives could be defined from either (i) evaluation of design uncertainty, (ii) supporting virtual/simulation activities or (iii) leveraging benefits of physical tests.

Goh et al. (2007) proposed a method of modelling uncertainty to inform design decisions. The method addressed the trend of increased analysis during development by structuring the uncertainty of design decisions based on untested assumptions. In a similar manner, Bjorkman et al. (2013) and Kukulies and Schmitt (2018) have both established test objectives by evaluating the performance uncertainty of functional product characteristics. Whilst those studies prioritized attention to design parameters with greatest uncertainty, Sanders et al. (2013) examined unforeseen and low-probability aspects with high consequences. These potential high-consequence characteristics required discovering them in very early testing before necessary changes were unfeasible.

Another key area of focus within the test objectives category was physical versus virtual testing. Research in this category was addressing directly the role of simulation to reduce the need for physical testing or prescribing physical testing for model correlation (to achieve even greater use of virtual models). Sutcliffe and Gault (2004) exposed potential benefits that can be achieved by integrating virtual tests, from CAD models to augmented reality, highlighting possible objectives during development from such test methods. Mejía-Gutiérrez and Carvajal-Arango (2017) reported on the latest integration of development software in a case study directly linking virtual prototypes into systems engineering modelling software.

The final area of study defining objectives for test activities focused on leveraging the benefits of physical testing. Viswanathan has published a number of studies (Viswanathan et al. 2014; Viswanathan and Linsey 2012, 2013) investigating the effect of design fixation and sunk costs on physical models. Design fixation considers an unnoticed integration of test activities, which prevents improved solutions being discovered. Campbell et al. (2007) on the other hand showed that physical models provide the best understanding to the customer and therefore allow the best feedback to be gathered.

The research into test objectives considered a greater level of integration into the design process than the other framework perspectives due to the strong link between key design parameters and definition of tests.

4.3 Test Design

Research in the final category, "test design," investigated methodology for a defined objective. This category would be broad and extensive if it was to consider methodology for specific applications, e.g. what test methodology is best for measuring the health of batteries or the performance of passive dampers. However, the nature of such application-specific methodology has been excluded, according to the criteria defined in Sect. 2.2, as it is independent to the development process (or at most only applicable to development of a specific product type).

The eight articles identified in this category discuss the methodology in relation to the development process which means the methodology is generalizable to different development contexts. Two general areas of test design were discovered. The first was a Design of Experiments or Robust Engineering approach where the test process is structured statistically around the identification of parameters that will have greatest impact on performance. The second topic was related to understanding customer needs or, in a wider context, stakeholder analysis.

The impact of Design of Experiments theory on the design process was presented in case studies by Herrmann (2007, 2009). The case studies show how implementation of Taguchi methodology identifies the parameters with greatest effect on performance. This allows for informed concept tradeoffs to be performed based on maximizing intended performance and minimizing undesired effects.

The second area of test design methodology researched addressed the less quantitative field of stakeholder analysis. Research by Deininger et al. (2019), Starkey et al. (2019) and Wall et al. (1992) all investigated methodology relating to the influence of product representations on conclusions gathered. In contrast, Tovares et al. (2014), Artacho et al. (2010) and Engelbrektsson and Söderman (2004) emphasized the importance of capturing stakeholders' perceptions and preferences.

5 Conclusion

A broad search was conducted on a limited set of prominent sources within product development research. The resulting literature was not exhaustive for the discovered topics yet achieved a wide overview covering all stages in the product development process. The purpose of the review was to uncover the literature addressing the definition and utilization of testing throughout the development life cycle.

The literature review identified methods from the start of the development process to qualification testing and in-service life. This answers the first research question by showing that integration of test activities is important and has been considered in all stages of development. Research focusing on the integration of testing was most prominent in concept development where the greatest impact is achievable.

Answering the second research question, *What perspectives are taken in the planning of tests?*, prompted the first author to devise a framework of test planning perspectives that established three areas of importance. The research was categorized based on the contribution in defining: what key objectives can be realized by testing, how such tests should be designed and how to establish the overall strategy of test activities in development. The proposed framework with classification into three areas provides insight into different levels of detail needed during planning of tests in the development process. The dependencies and overlap between these groups highlighted both their sequential and iterative nature as represented in the framework in Fig. 3.

This study provides an overview of relevant research structured in a framework to assist the future analysis and development of test processes for integration into MBSE approaches.

Acknowledgements This study has been conducted as part of the KPN project VALUE, supported by the Norwegian Research Council and the industry partners Hydro and Alcoa.

Appendix A. Literature Review Study Sources, Evidence Categories and Aims

Study	Evidence category[a]	Stage of development[a]	Aim
Salado and Kannan (2019)	TS	2	Formalize the application of Bayesian networks to verification problems to facilitate instruction and communication among verification engineers and with researchers from other domains
Tahera et al. (2018)	TS	1–4	Establish importance of testing in product development to inform the development of pragmatic support methods
Shabi et al. (2017)	TS	2,3	Propose a method for determining the optimal verification activities with respect to product quality/risk
Shin et al. (2017)	TS	3	Demonstrate that model-based integration of T&E process and system safety process reduces development time
Salado (2015)	TS	3	Demonstrate the benefit of trade space exploration in the optimization of test strategy
Hoppe et al. (2007)	TS	1–4	Develop a generic verification, validation and testing methodology guideline and an economic VVT process model in order to realize improved product quality
Engel and Shachar (2006)	TS	2,3	Measure systems quality cost/times in a typical development project as well as suggest ways to optimize it in order to meet business objectives
Tahan and Ben-Asher (2005)	TS	3	Demonstrate that incremental integration offers both time and cost benefits vs single stage integration
Engel and Barad (2003)	TS	3	Propose a novel approach for modelling VVT strategies as decision problems
Lauff et al. (2018)	TS	1–3	Define the roles of prototypes in industry
Camburn et al. (2015)	TS	1,2	Provide a method to repeatedly enhance the outcome of prototyping efforts
Barkan and Iansiti (1993)	TS	1–4	Examine roles which prototyping plays in product development

(continued)

Study	Evidence category[a]	Stage of development[a]	Aim
Isaksson et al. (2000)	TS	1–3	Evaluate alternative design strategies and methods with respect to their impact on the development process time
Kukulies and Schmitt (2018)	TO	3	Investigate the use of uncertainty modelling to support design verification
Bjorkman et al. (2013)	TO	3	Present a methodology that uses an MBSE framework and Monte Carlo simulation to define uncertainty reduction goals for test planners to use in developing test strategies and detailed test designs for evaluating technical performance parameters
Sanders et al. (2013)	TO	1	Propose model for discovery of low probability events in the formative stages of the requirements definition and risk management planning activities in order establish the safety requirements and responsive conceptual designs for mitigation
Goh et al. (2007)	TO	4	Create framework for organizing uncertainty in product development simulation results therefore improving understanding between simulations and tested results for the purpose of assisting design decisions
Takala (2005)	TO	1	Propose a concept that bridges the gap between physical and virtual domains prototyping
Sutcliffe and Gault (2004)	TO	1	Propose guidelines for configuring virtual engineering technology and design of requirements analysis sessions
Mejía-Gutiérrez and Carvajal-Arango (2017)	TO	1,2	Investigate the usefulness of integrated virtual design verification simulation
Kiefer et al. (2004)	TO	1,2	Present the design development of a new product that explored many of the different prototyping technologies
Wang and Chen (2011)	TO	1	Introduce users' participation in the conceptual design stage of product development to avoid interpreting biased from marketers' information
Viswanathan et al. (2014)	TO	1	Study how physical models can assist novices in mitigating design fixation on undesirable features

(continued)

Study	Evidence category[a]	Stage of development[a]	Aim
Viswanathan and Linsey (2013)	TO	1	Investigate physical modelling role in idea generation and design fixation
Viswanathan and Linsey (2012)	TO	1	Investigate if physical models supplement designer's mental models and if physical models induce design fixation
Campbell et al. (2007)	TO	1–3	Demonstrate that physical models are the single presentation format that is readily understood by most customers
Wall et al. (1992)	TD	1–4	Develop a systematic method of evaluating prototyping processes in order to determine the best process for a given situation
Engelbrektsson and Söderman (2004)	TD	1	Investigate the use and perceptions of methods and product representations in Swedish companies and its possible impact on problems associated with late-discovered customer requirements
Starkey et al. (2019)	TD	1	Investigate the impact of prototype fidelity, concept creativity and risk aversion on perceived riskiness and concept selection
Deininger et al. (2019)	TD	1	Provide insights into how prototype type, group membership (stakeholder characteristics) and question type can influence stakeholders' perceptions of a design concept and the resulting feedback they provide
Tovares et al. (2014)	TD	1	Develop a method to elicit, capture and model consumer preference through experiential preference judgements
Artacho et al. (2010)	TD	1	Analyse how slight changes might affect users' perception as well as influence their intention to purchase a product
Herrmann (2009)	TD	2	Demonstrate that the successful use of Taguchi test methodology provides efficient and reliable design knowledge
Herrmann (2007)	TD	2	Demonstrate the successful use of Taguchi test methodology to support system design

[a]*TS* test strategy, *TO* test objectives, *TD* test design, *1* concept generation, *2* detailed design, *3* product qualification, *4* in-service life

References

Artacho, M.A., A. Ballester, and E. Alcántara. 2010. Analysis of the Impact of Slight Changes in Product Formal Attributes on User's Emotions and Configuration of an Emotional Space for Successful Design. *Journal of Engineering Design* 21: 693–705.

Barkan, P., and M. Iansiti. 1993. Prototyping: A Tool for Rapid Learning in Product Development. *Concurrent Engineering* 1: 125–134.

Bjorkman, E.A., S. Sarkani, and T.A. Mazzuchi. 2013. Using Model-Based Systems Engineering as a Framework for Improving test and Evaluation Activities. *Systems Engineering* 16: 346–362.

Camburn, B., B. Dunlap, T. Gurjar, C. Hamon, M. Green, D. Jensen, R. Crawford, K. Otto, and K. Wood. 2015. A Systematic Method for Design Prototyping. *Journal of Mechanical Design* 137: 081102.

Campbell, R.I., D.J. De Beer, L.J. Barnard, G.J. Booysen, M. Truscott, R. Cain, M.J. Burton, D.E. Gyi, and R. Hague. 2007. Design Evolution Through Customer Interaction with Functional Prototypes. *Journal of Engineering Design* 18: 617–635.

Deininger, M., S.R. Daly, J.C. Lee, C.M. Seifert, and K.H. Sienko. 2019. Prototyping for Context: Exploring Stakeholder Feedback Based on Prototype Type, Stakeholder Group and Question Type. *Research in Engineering Design* 1–19.

Engel, A. 2010. *Verification, Validation, and Testing of Engineered Systems*. Hoboken, United States: Wiley.

Engel, A., and M. Barad. 2003. A Methodology for Modeling VVT Risks and Costs. *Systems Engineering* 6: 135–151.

Engel, A., and S. Shachar. 2006. Measuring and Optimizing Systems' Quality Costs and Project Duration. *Systems Engineering* 9: 259–280.

Engelbrektsson, P., and M. Söderman. 2004. The Use and Perception of Methods and Product Representations in Product Development: A Survey of Swedish Industry. *Journal of Engineering Design* 15: 141–154.

Goh, Y.M., C.A. McMahon, and J.D. Booker. 2007. Development and Characterisation of Error Functions in Design. *Research in Engineering Design* 18: 129–148.

Herrmann, D.K. 2007. Taguchi Optimization in the Design of a Printer Registration System. *Journal of Engineering Design* 18: 1–11.

———. 2009. Application of Multiparameter Optimization for Robust Product Design. *Journal of Mechanical Design* 131.

Hoppe, M., A. Engel, and S. Shachar. 2007. SysTest: Improving the Verification, Validation, and Testing Process—Assessing Six Industrial Pilot Projects. *Systems Engineering* 10: 323–347.

INCOSE. 2007. Systems Engineering Vision 2020. INCOSE-TP-2004-004-02.

Isaksson, O., S. Keski-Seppälä, and S.D. Eppinger. 2000. Evaluation of Design Process Alternatives Using Signal Flow Graphs. *Journal of Engineering Design* 11: 211–224.

Kennedy, M. 2008. *Ready, Set, Dominate: Implement Toyota's Set-Based Learning for Developing Products and Nobody Can Catch You*. Oaklea Press.

Kiefer, S., L. Silverberg, and M. Gonzalez. 2004. A Case Study of Prototyping Methods and Design for Manufacture: Electrostatic Window Blinds. *Journal of Engineering Design* 15: 91–106.

Kukulies, J., and R. Schmitt. 2018. Stabilizing Production Ramp-Up by Modeling Uncertainty for Product Design Verification Using Dempster–Shafer Theory. *CIRP Journal of Manufacturing Science and Technology* 23: 187–196. https://doi.org/10.1016/j.cirpj.2017.09.008.

Lauff, C.A., D. Kotys-Schwartz, and M.E. Rentschler. 2018. What is a Prototype? What Are the Roles of Prototypes in Companies? *Journal of Mechanical Design* 140: 061102.

Machi, L.A., and B.T. McEvoy. 2016. *The Literature Review: Six Steps to Success*. Corwin Press.

Mejía-Gutiérrez, R., and R. Carvajal-Arango. 2017. Design Verification Through Virtual Prototyping Techniques Based on Systems Engineering. *Research in Engineering Design* 28: 477–494.

Raz, A.K., C.R. Kenley, and D.A. DeLaurentis. 2018. System Architecting and Design Space Characterization. *Systems Engineering* 21: 227–242. https://doi.org/10.1002/sys.21439.

Salado, A. 2015. Defining Better Test Strategies with Tradespace Exploration Techniques and Pareto Fronts: Application in an Industrial Project. *Systems Engineering* 18: 639–658.

Salado, A., and H. Kannan. 2019. Elemental Patterns of Verification Strategies. *Systems Engineering* 22: 370–388.

Sanders, G.A., S. Sarkani, and T. Mazzuchi. 2013. High Consequence Systems Phenomenological Characterization: A Tutorial. *Systems Engineering* 16: 464–472.

Shabi, J., Y. Reich, and R. Diamant. 2017. Planning the Verification, Validation, and Testing Process: A Case Study Demonstrating a Decision Support Model. *Journal of Engineering Design* 28: 171–204.

Shin, Y.-D., S.-H. Sim, and J.-C. Lee. 2017. Model-Based Integration of Test and Evaluation Process and System Safety Process for Development of Safety-Critical Weapon Systems. *Systems Engineering* 20: 257–279.

Starkey, E.M., J. Menold, and S.R. Miller. 2019. When Are Designers Willing to Take Risks? How Concept Creativity and Prototype Fidelity Influence Perceived Risk. *Journal of Mechanical Design* 141: 031104.

Sutcliffe, A., and B. Gault. 2004. The ISRE Method for Analyzing System Requirements with Virtual Prototypes. *Systems Engineering* 7: 123–143.

Tahan, M., and J.Z. Ben-Asher. 2005. Modeling and Analysis of Integration Processes for Engineering Systems. *Systems Engineering* 8: 62–77.

Tahera, K., C. Earl, and C. Eckert. 2017. A Method for Improving Overlapping of Testing and Design. *IEEE Transactions on Engineering Management* 64: 179–192.

Tahera, K., D.C. Wynn, C. Earl, and C.M. Eckert. 2018. Testing in the Incremental Design and Development of Complex Products. *Research in Engineering Design*. https://doi.org/10.1007/s00163-018-0295-6.

Takala, R. 2005. Product Demonstrator: A System for Up-Front Testing of User-Related Product Features. *Journal of Engineering Design* 16: 329–336.

Tovares, N., P. Boatwright, and J. Cagan. 2014. Experiential Conjoint Analysis: An Experience-Based Method for Eliciting, Capturing, and Modeling Consumer Preference. *Journal of Mechanical Design* 136: 101404.

Ulrich, K.T., and S.D. Eppinger. 2012. *Product Design and Development*. 5th ed. New York: McGraw-Hill.

Viswanathan, V.K., and J.S. Linsey. 2012. Physical Models and Design Thinking: A Study of Functionality, Novelty and Variety of Ideas. *Journal of Mechanical Design* 134: 091004.

———. 2013. Role of Sunk Cost in Engineering Idea Generation: An Experimental Investigation. *Journal of Mechanical Design* 135: 121002.

Viswanathan, V., O. Atilola, N. Esposito, and J. Linsey. 2014. A Study on the Role of Physical Models in the Mitigation of Design Fixation. *Journal of Engineering Design* 25: 25–43.

Wall, M.B., K.T. Ulrich, and W.C. Flowers. 1992. Evaluating Prototyping Technologies for Product Design. *Research in Engineering Design* 3: 163–177.

Wang, C.-H., and R.C.-C. Chen. 2011. A MPCDM-Enabled Product Concept Design Via User Involvement Approach. *Concurrent Engineering* 19: 19–34.

Letter

Correction to Braunovic & Alexandrov's 1994 Article on Intermetallic Compounds at Aluminum-to-Copper Electrical Interfaces

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MRS Communications, Commentary letter
Published 2024

Correction to Braunovic & Alexandrov's 1994 Article on Intermetallic Compounds at Aluminum-to-Copper Electrical Interfaces

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ABSTRACT
Interest in aluminium and copper joining processes has increased in recent years due to the growing appeal of using aluminium in electrical applications. Braunovic & Alexandrov's 1994 article, *Intermetallic Compounds at Aluminum-to-Copper Electrical Interfaces: Effect of Temperature and Electric Current*, has become a seminal contribution on Al-Cu joining for electrical applications. Their detailed measurements of resistance and intermetallic diffusion rates have become a baseline for assessing the operational performance of Al-Cu joints. The paper has had an increasing citation rate since publication and is in multiple electrical contacts textbooks. However, a minor error has been discovered in the presented analysis. In this short communication, the error is identified and a corrected analysis is provided. The corrected analysis shows that Al-Cu intermetallic growth is ten times slower than previously presented. The corrected analysis has a consequential impact on the utility of Al-Cu joints in electrical applications. Therefore, highlighting the error provides valuable insight for utilising and developing Al-Cu welding in electrical applications.

KEYWORDS
Aluminium; Copper; Intermetallic; Diffusion rate;

1. Introduction

Braunovic & Alexandrov's [1] research has found increasing interest since its first publication, Figure 1. Their research is a central pillar in multiple textbooks [2,3] on the formation and growth of intermetallic compounds in Al-Cu welds. Interest in Al-Cu welds is growing as aluminium conductors become more attractive in electrical applications. The price of copper has been increasing in recent years, and for the last decade, aluminium has been 6x cheaper than copper for the same resistance [4]. However, aluminium's price advantage is counteracted by its greater difficulty in forming reliable electrical connections.

Introducing aluminium conductors into electrical circuits often requires interfacing with existing copper components. A reliable mechanical connection (such as a bolted, crimped, or press-fitted connection) with aluminium is more challenging than a copper-to-copper connection [2,3]. This is because aluminium's hard and non-conductive oxide layer must be broken to form conductive metal-to-metal contact. These locations of metal-to-metal contact are only a fraction of the apparent area and must tolerate thermal expansion caused by resistive heat losses in the conductor. As aluminium and

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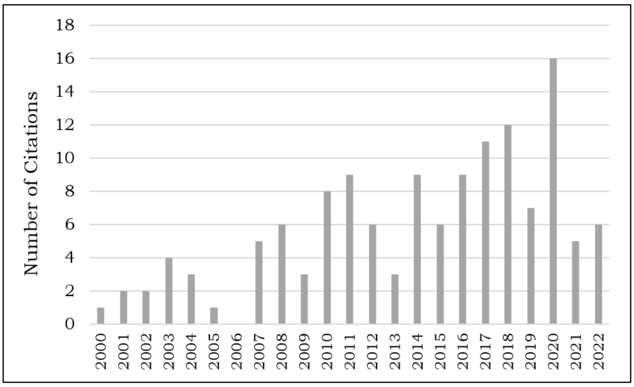


Figure 1. Number of citations each year for Braunovic & Alexandrov's [1] since 2000 from the Scopus database.

copper have different coefficients of thermal expansion, the mismatch produces relative displacement. This relative displacement can lead to fretting, where the motion causes non-conductive oxide particles to build up between the two surfaces, reducing the metal-to-metal contact. A high clamping force would be desirable to maximise and maintain the metal-to-metal contact; however, the applied stress must be balanced against aluminium's generally lower strength and susceptibility to creep.

Compared to a mechanical connection, a welded Al-Cu connection eliminates the vulnerability of electrical contact through limited contact spots. Welded connections mitigate fretting failure by providing contact over the entire interface and preventing oxide from forming between the surfaces. However, Al-Cu welds are challenging due to their chemical compatibility. Aluminium and copper as base metals have dissimilar melting temperatures and thermal conductivity, while together form various brittle and electrically resistive intermetallic compounds [5]. Creating a robust Al-Cu weld requires achieving a bond between the materials, but the heat input must be controlled to limit the amount of intermetallic compounds formed. Multiple studies have shown that the structural integrity can decrease significantly when the intermetallic thickness exceeds 2 µm [6,7]. Solid-state joining processes, such as cold rolling, wire bonding, or friction welding, can join Al-Cu with relatively little heat input therefore achieving acceptable levels of intermetallic compounds [8–10]. However, the amount of intermetallic compounds must remain within acceptable limits over the weld's operational life . In particular, electrical conductor welds are subject to elevated temperatures due to internal resistive heating. This internal heating can accelerate the formation of intermetallic compounds with the potential to cause failure over time. As such, it is paramount to be able to predict the intermetallic compounds' growth rate over the conductor's operational life.

2. Materials and Methods

Braunovic & Alexandrov's comprehensive study investigated the growth kinetics, chemical composition and electrical resistance of Al-Cu friction welding. Their measurements were performed at 200 °C - 500 °C to provide measurable results within a feasible time frame. In Braunovic & Alexandrov's §4 Discussion [1], they relate their results to the operating conditions of electrical conductors, which are typically below 200 °C for many years. Figure 11 in their research article shows two plots of the predicted intermetallic growth rate at 100 °C - 200 °C for 1 hour to 10 years. This figure is helpful to the designer for estimating the lifetime of intermetallic welds. From the presented figure, the temperature and time taken to reach a critical thickness (2 µm [1,6,11–13]) can be identified. This figure is shown in multiple textbooks [2,3] and reproduced in another research article [14]. The figure indicates that the intermetallic growth rates for Al-Cu welds from electrical self-heating are rapid and likely unsuitable for applications where even intermittent operation above 100 °C is possible. However, the predicted growth rates in Figure 11 do not correspond to the experimental data reported. For example, in Table 3 [1], the intermetallic thickness after 24 hr of annealing by electrical current at 200 °C was measured as 1.6 µm, whereas the predicted thickness in Figure 11 [1] is over 10 µm. Analysing the presented test measurements, it is apparent that an error has been included in the formation of Figure 11. A corrected analysis and updated version of Figure 11 is provided in the next section.

3. Results

The predicted intermetallic thicknesses in Figure 11 [1] are calculated using the data provided in Tables 2 and 3 of the research article [1]. Tables 2 and 3 show the thickness measurements over time for each temperature from furnace and electrical self-heating, respectively. Braunovic & Alexandrov's Figure 3 plots the measurements on a square root function to establish the growth rate at each temperature. These growth rates are then plotted on an Arrhenius plot (Figure 4 in the article [1]) to determine the activation energy and pre-exponential factor. Braunovic & Alexandrov found it appropriate to split the activation energy into two sections, 200 °C to 300 °C and 360 °C to 500 °C, and report the values both in Figure 4 and back in Tables 2 and 3. The activation energy from the 200 °C to 300 °C region is then used to predict the growth rates below 200 °C in their Figure 11.

Using the model presented in Braunovic & Alexandrov with activation energy, Q, and pre-exponential factor, D_o, the intermetallic growth rate, D, at any constant temperature, T, can be calculated using the universal gas constant, R, and eq. 1. The intermetallic thickness, x, for any time interval, t, can then be calculated using eq. 2.

$$D = D_o e^{-Q/RT} \tag{1}$$

$$x = \sqrt{Dt} \tag{2}$$

The eq. 1 & eq. 2 have been used to recalculate all data points in Braunovic & Alexandrov's Figure 11 in Table 1 below. The results are then plotted in Figure 2 below to provide a corrected replicate of Braunovic & Alexandrov's Figure 11. Comparing Figure 2 below with the original Figure 11, the updated predicted thicknesses are much lower. In Braunovic & Alexandrov's figure, the intermetallic thickness exceeds 2 µm in less than a day of electrical self-heating at 100 °C, while in Figure 2 below, a month is required. The tabulated data for Figure 11 is not provided in the paper, and the low resolution provided by the wide range makes comparing the exact figures

Table 1. Calculation of diffusion rates and intermetallic thicknesses at 100 °C, 150 °C & 200 °C for both electrical current annealing and furnace annealing. Calculation is based on activation energy Q and pre-exponential D_o from Braunovic & Alexandrov [1]. Thicknesses over 2 µm are shown in bold.

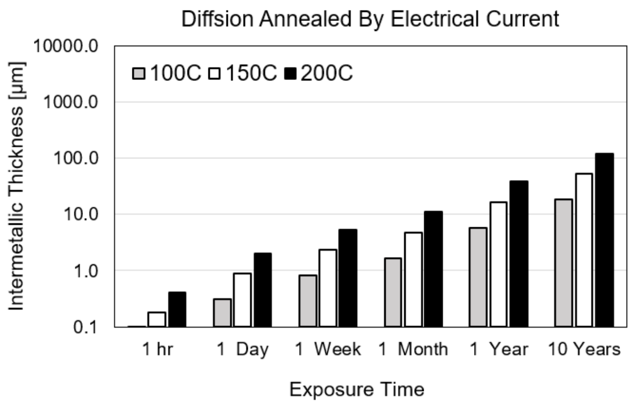
	Electrical Current			Furnace		
Q [kcal/mol]	13.2			17.2		
Do [cm^2/s]	5.9E-07			2.2E-06		
Temperature [^{o}C]	100	150	200	100	150	200
Intermetallic Thickness [μm]						
1 hr	0.1	0.2	0.4	0.0	0.0	0.1
1 day	0.3	0.9	**2.0**	0.0	0.2	0.5
1 week	0.8	**2.3**	**5.3**	0.1	0.4	1.2
1 month	1.7	**4.8**	**11.0**	0.2	0.9	**2.5**
1 year	**5.8**	**16.7**	**38.3**	0.8	**3.0**	**8.8**
10 years	**18.4**	**52.8**	**121**	**2.4**	**9.4**	**27.8**

difficult. However, it appears Braunovic and Alexandrov predict a factor 10 higher intermetallic thickness in all cases. Such a discrepancy could simply have arisen from an error on the y-axis scaling or a cm to m conversion error in the diffusion rate before the thickness is calculated.

The activation energy and pre-exponential calculation were also checked for additional rigour. The resulting activation energy and pre-exponential was 11.8 kcal/mol and 7.9E-8 cm^2/s for electrical self-heating, and 21.8 kcal/mol and 2.2E-4 cm^2/s for furnace annealing. The updated model values give equivalent intermetallic thickness predictions for electrical self-heating and a minor improvement in correlation for the furnace heating measured values. However, the magnitudes are comparable in all cases, resulting in an inconsequential difference in the predicted long-term performance. The suitability of Braunovic & Alexandrov's activation energy and pre-exponential is apparent in comparing the updated thickness after 24 hr of electrical self-heating (2 µm), to the measured thickness reported in Braunovic & Alexandrov's Table 3 (1.6 µm). Expanding the assessment of Braunovic & Alexandrov's activation energy and pre-exponential to all measured values at 200 °C to 325 °C results in a difference of only a few microns; therefore, it can be concluded that the updated predictions and measured results are now in good agreement.

4. Discussion

The corrected analysis has a notable impact on the performance of Al-Cu welds for electrical applications. Nominal operating temperatures for conductors are typically below 100 °C for safety and energy efficiency. However, conductors must be fault tolerant and not degrade from transient load increases or intermittent failure cases that could cause higher temperatures. Braunovic & Alexandrov's research [1] has reached wide circulation with a conclusion that the integrity of Al-Cu conductors can be comprised in just hours of operation above 100 °C. The corrected analysis results in a notable increase in the durability of Al-Cu welds in electrical applications. Good news for society's continuing electrification.



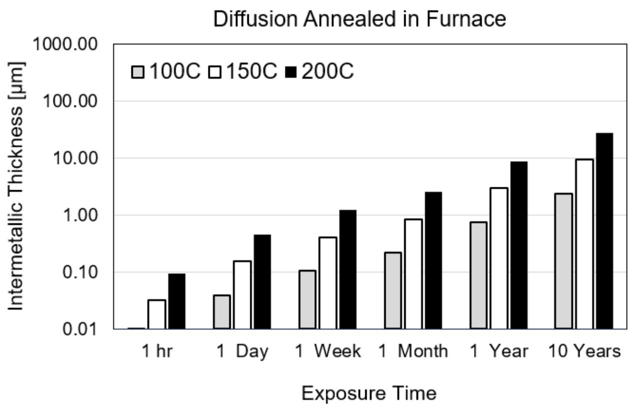


Figure 2. Corrected version of Figure 11 from Braunovic & Alexandrov [1]. The figures show predicted thicknesses in micrometers of the intermetallic phases formed in Al-Cu bimetallic joints following diffusion annealing in a furnace (bottom) and by an electrical current (bottom) for different durations at 100 °C, 150 °C & 200 °C.

5. Declaration of interest statement

The author reports there are no competing interests to declare.

References

[1] M. Braunovic and N. Alexandrov. Intermetallic compounds at aluminum-to-copper electrical interfaces: effect of temperature and electric current. *IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part A*, 17(1):78–85, 1994.

[2] P. G. Slade. *Electrical contacts: principles and applications*. CRC press, 2nd. edition, 2017. ISBN 1-138-07710-0.

[3] M. Braunovic, Valery V. Konchits, and N. K. Myshkin. *Electrical contacts: fundamentals, applications and technology*. CRC press, 2017. ISBN 1-57444-727-0.

[4] IMF Primary Commodity Prices, December 2021. URL `https://www.imf.org/en/Research/commodity-prices`.

[5] S. Pfeifer, S. Großmann, R. Freudenberger, H. Willing, and H. Kappl. Characterization of intermetallic compounds in Al-Cu-Bimetallic interfaces. In *IEEE 58th Holm Conference on Electrical Contacts (Holm)*, pages 1–6. IEEE, 2012.

[6] M. Abbasi, A. K. Taheri, and M. T. Salehi. Growth rate of intermetallic compounds in Al/Cu bimetal produced by cold roll welding process. *Journal of Alloys and Compounds*, 319(1-2):233–241, 2001.

[7] E. R. Wallach and G. J. Davies. Mechanical properties of aluminium-copper solid-phase welds. *Metals Technology*, 4(1):183–190, 1977.

[8] Huizhong Li, Yong Yang, Xiaopeng Liang, Wending Zhang, Liangming Cao, Chunping Wu, Zhiheng Zeng, and Li Wang. Effect of annealing temperature and time on the microstructure, mechanical properties and conductivity of cold-rolled explosive Cu/Al composite sheets. *Materials Research Express*, 7(10), 2020.

[9] C.P. Liu, S.J. Chang, Y.F. Liu, and W.S. Chen. Cu-Al interfacial formation and kinetic growth behavior during HTS reliability test. *Journal of Materials Processing Technology*, 267:90–102, 2019.

[10] L. Pan, P. Li, X. Hao, J. Zhou, and H. Dong. Inhomogeneity of microstructure and mechanical properties in radial direction of aluminum/copper friction welded joints. *Journal of Materials Processing Technology*, 255:308–318, 2018.

[11] K. Savolainen, J. Mononen, T. Saukkonen, and H. Hänninen. A preliminary study on friction stir welding of dissimilar metal joints of copper and aluminium. In *6th International Friction Stir Welding Symposium*, page 10, 2006.

[12] D. García-Navarro, J. C. Ortiz-Cuellar, J.S. Galindo-Valdés, J. Gómez-Casas, C.R. Muñiz-Valdez, and N.A. Rodríguez-Rosales. Effects of the FSW Parameters on Microstructure and Electrical Properties in Al 6061-T6-Cu C11000 Plate Joints. *Crystals*, 11(1):21, 2021.

[13] X. G. Wang, X.G. Li, F. J. Yan, and C. G. Wang. Effect of heat treatment on the interfacial microstructure and properties of Cu-Al joints. *Welding in the World*, 61(1): 187–196, 2017.

[14] E. Dalgaard, P. Wanjara, G. Trigo, M. Jahazi, G. Comeau, and J. J. Jonas. Linear friction welding of Al–Cu part 2–interfacial characteristics. *Canadian Metallurgical Quarterly*, 50 (4):360–370, 2011.