NTNU
Norwegian University of
Science and Technology

Corrosion and wear protection of wheel axles on trains

Anders Opsahl Bredesen

Mechanical Engineering

Submission date:	May 2016
Supervisor:	Roy Johnsen, IPM
Co-supervisor:	Espen Ringnes, NSB

Norwegian University of Science and Technology
Department of Engineering Design and Materials

NORGES TEKNISK-
NATURVITENSKAPELIGE UNIVERSITET
INSTITUTT FOR PRODUKTUTVIKLING
OG MATERIALER

MASTEROPPGAVE HØST 2015
FOR
STUD.TECHN. ANDERS BREDESEN

Korrosjon- og slitasjebeskyttelse av hjulaksler på tog
Corrosion and wear protection of wheel axels on trains

Beskrivelse

Hjulaksler på et tog er en kritisk komponent og er underlagt streng kontroll og vedlikehold. Med sin plassering er de naturlig utsatt for slag/støt fra snø/is, pukk og dyrepåkjørsler. For å beskytte akslingen brukes i dag forskjellig type overflatebeskyttende belegg. Problemet er at belastningene fra slag/støt er så store at beleggene slites bort. Resultatet er bart stål som starter å korrodere. I tillegg kan slagene/støtene gi lokale skader på akslingen som igjen kan bli initieringspunkt for utmatting. Akslingene må derfor inspiseres ofte og jevnlig utbedres. Dette er tidkrevende og kostbare prosesser.

NSB Materiell ønsker å gjennomføre et prosjekt hvor målsettingen er å fremskaffe mer kostnadseffektive løsninger for beskyttelse av hjulakslinger mot slag/støt under drift. I utgangspunktet er både beleggsystem og mekanisk beskyttelse aktuelle løsninger. Denne masteroppgaven vil fokusere på å fremskaffe forbedrede beleggsystem.

NSB Materiell har allerede satt i gang noen aktiviteter for å teste ulike typer belegg. Informasjon fra dette arbeidet vil bli gjort tilgjengelig for masterstudenten.

Følgende hovedaktiviteter er planlagt inkludert i oppgaven:

1. Sette seg inn i problemstillingen inkludert gjennomgang av tilgjengelig informasjon fra NSB.
2. Utarbeide en kravspesifikasjon i nært samarbeid med NSB Materiell.
3. Fremskaffe ulike alternative beleggløsninger, vurdere disse opp mot kravspesifikasjonen og velge 2-3 løsninger for nærmere undersøkelser. Dette skal skje ved gjennomgang av tilgjengelig informasjon og ved kontakt med leverandører.
4. Utarbeide planer for dokumentasjon/laboratorietesting av egenskapene til de utvalgte beleggene i Pkt. 3.
5. Gjennomføre laboratorietestingen og om mulig innhente dokumentasjon på egenskaper via dokumenterte tester utført av leverandører.
6. Skrive MSc rapporten inkludert anbefalinger.

Formelle krav:

Senest 3 uker etter oppgavestart skal et A3 ark som illustrerer arbeidet leveres inn. En mal for dette arket finnes på instituttets hjemmeside under menyen masteroppgave (http://www.ntnu.no/ipm/masteroppgave). Arket skal også oppdateres en uke før innlevering av masteroppgaven.

Risikovurdering av forsøksvirksomhet skal alltid gjennomføres. Eksperimentelt arbeid definert i problemstilling skal planlegges og risikovurderes innen 3 uker etter utlevering av oppgavetekst. Konkrete forsøksvirksomhet som ikke omfattes av generell risikovurdering skal spesielt vurderes før eksperimentelt arbeid utføres. Risikovurderinger skal signeres av veileder og kopier skal inngå som vedlegg til oppgaven.

Besvarelsen skal ha med signert oppgavetekst, og redigeres mest mulig som en forskningsrapport med et sammendrag på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse, etc. Ved utarbeidelse av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelse legges det stor vekt på at resultater er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte og diskuteres utførlig.

Besvarelsen skal leveres i elektronisk format via DAIM, NTNUs system for Digital arkivering og innlevering av masteroppgaver.

Kontaktperson: Espen Ringnes, NSB Materiell

Torgeir Welo
Instituttleder

Roy Johnsen
Faglærer

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for produktutvikling og materialer

Abstract

Wheel axles are critical components on the train, and subjected to strict inspections and maintenance. With its placement underneath the train units, they are naturally susceptible of shocks and impact loads from ice, snow, gravel and collisions with animals. Due date the axles are protected with an organic coating solution. The problem is that the loads from impacts and shocks are large, and the coating is worn away. This result in bare steel that starts to corrode. In addition, the impact loads can cause local damages in the axle surface that can be point where fatigue cracks can be initiated.

The objective of this master thesis has been to evaluate and test alternative protective coatings for train axles. In collaboration with NSB a set of requirements for the new solution have been set up. Based on the requirements, operating conditions and a literature study of different types of protective coatings, a selection of four coatings have been made. The properties which was detrimental for the selection was; the impact resistance, corrosion resistance, adhesion to the substrate and experience from similar applications.

A test program was set up to document and test the properties of the different coatings. A thermal sprayed NiCrBSi, Electrodeposited Ni-SiC, Rubber lining, and a 3-layer organic epoxy coating was tested. Through the test program there were possible to see a trend of the performance of each coating. The thermal sprayed and the electrodeposited coating showed positive adhesion properties, but negative properties in corrosion and impact resistance. The two organic coatings; rubber lining and epoxy coating showed good properties in all the tests. In the impact test at -65°C the rubber lining became brittle and lost the adhesion to the substrate resulting in large damage.

The 3-layer epoxy coating is the best solution for protection of the axles. There are no modifications of the substrate surface, and the adhesion is good. Coating 4 performs well in the salt spray test. The impact resistance of the coating is excellent. The coating had consistently the best performance throughout the test program, and are therefore the chosen coating system.

Sammendrag

Hjulaksler på tog er en kritisk komponent og er underlagt streng kontroll og vedlikehold. Med sin plassering er de naturlig utsatt for slag og støt fra is, snø, pukk og dyrepåkjørsler. For å beskytte akslingene brukes i dag et organisk overflatebeskyttende belegg. Problemet er at belastningene fra slag og støt er så store at belegget slites bort. Resultatet er bart stål som starter å korrodere. I tillegg kan slagene gi lokale skader på akslingens overflate som igjen kan bli initieringspunkt for utmatting.

Målsettingen med denne masteroppgaven er å evaluere og teste alternative beskyttende belegg for hjulakslinger. I samarbeid med NSB har det blitt utarbeidet en kravspesifikasjon til den nye løsningen. Ut ifra kravene, gjeldene driftsforhold og et litteraturstudie av ulike typer belegg, har fire belegg blitt valgt ut til testing. De viktigste kravene som dannet grunnlaget for utvelgelsen var; slagfasthet, korrosjonsbestandighet, adhesjon til underlaget og erfaringer fra tilsvarende anvendelser.

Testprogrammet ble satt opp for å teste og dokumentere egenskapene til de forskjellige beleggene. Et Termisk sprøytet NiCrBSi, elektrokjemisk Ni-SiC, gummibelegg og et 3-lags epoxy belegg ble testet. Gjennom testene var det mulig å se en trend der et belegg hadde egenskaper som egnet seg bedre enn de andre. Det termisk sprøytet og det elektrokjemiske belegget hadde gode adhesjonsegenskaper, men dårlige egenskaper i korrosjon- og slagfasthet. Gummi belegget og epoxy belegget viste gode egenskaper i alle testene. I slagtesten på -65°C ble gummibelegget sprøtt og mistet heft til underlaget, noe som resulterte i store skader.

Gjennom testene utført kan det konkluderes med at 3-lags epoxy belegget er den beste løsningen for beskyttelse av hjulakslinger. Belegget viser gode resultater i korrosjonstesten, slagfastheten er god, og adhesjonen til underlaget er god. Belegget viser gjennomgående best resultater i testprogrammet, og er derfor det valgte belegget.

Preface

This Master's thesis was written at the Department of Engineering Design and Materials. It is a part of the study program Engineering Design and Manufacturing at the Norwegian University of Sience and Technology (NTNU). It was carried out during the second half of the fall semester 2015 and the first half of the spring semester 2016. The aim for the thesis was to find a better coating solution for protection of train axles used on the Norwegian railroads by the Norwegian State Railways (NSB).

Different coating solutions have been selected to undergo a test campaign. The results of this test campaign are used to select the best suited solution as protective coating for the train axles operating in Nordic conditions.

I would like to thank Mr. Espen Ringnes and Alf-Bjarne Langballe at the Material Division at NSB for introducing me to the topic, answering questions and giving me flexibility throughout the project. I would like to thank my supervisor Roy Johnsen for being enthusiastic about the topic, and giving me guidance through all the phases of the thesis. I also like to give a huge thanks to everyone at the workshop at IPM and especially to Mr. Nils-Inge Nilsen at the SINTEFF Materials and Corrosion Lab for being very helpful with all kind of issues I stumbled upon during the testing process.

Trondheim, 2016-05-09

Anders Opsahl Bredesen

Contents

List of Figures

List of Tables

Abbreviations

NSB	Norwegian State Railways
PDS	Product Demand Specification
DFT	Dry Film Thickness
PPG	Pittsburgh Plate Glass Company
PVD	Physical Vapor Deposition
CVD	Chemical Vapor Deposition
HAZ	Heat-Affected Zone
HS	High Speed
VHS	Very High Speed
EPDM	Ethylene Propylene Diene Monomer
HVOF	High-velocity-oxy-fuel
RT	Room Temperature

Chapter 1

Introduction

1.1 Background

The Norwegian State Railways (NSB) operates most passenger trains and the cargo trains in Norway. NSB have a broad fleet of train units, both electric and diesel. On each unit, there are fitted axles which are the main component of the rolling gear on the train. The axles are critical components and are subjected to strict inspections and maintenance. With its placement underneath the train units, they are naturally susceptible of shocks and impact loads from ice, snow, gravel and collisions with animals. The trains operate in corrosive environment with high humidity. If the axle is damaged by impacts, the impact zones can cause a initiation point for corrosion on the bare steel and cause stress concentrations which can lead to fatigue failure of the axle. To protect the axle surface from such hazards, a protective coating is applied on the axle surface. In Figure 1.1 and Figure 1.2 axles with damages from impacts and corrosion is shown. The drawbacks with today's solution:

- The coating system has low impact resistance and are easily damaged by impacts.

- The impact result in bare steel which start to corrode, which can cause fatigue failure of the axle.
- Poor durability leads to high frequency of inspections and maintenance, which leads to higher costs.

FIGURE 1.1: Impact damages on an axle

FIGURE 1.2: Corrosion on an axle

On this background, the material division of NSB has started a research and development project. The objective of the project is to provide more cost effective solutions for protection of the axles. Both mechanical protection and coating based protection are relevant solutions. The aim of this master thesis is to evaluate and test alternative coating solutions.

1.2 Approach

This thesis will begin with a review of the problem and gather available information and data from NSB. A Product Demand Specification (PDS) is to be developed in collaboration with NSB, based on the information. On the basis of the review and the PDS various coating materials and solutions should be researched. The thesis shall not deal with development of new coatings. The characteristics of the alternatives shall be assessed against the PDS and the coating solutions which fulfills the requirements will be selected to undergo a test program. The test program will be developed on the basis of the PDS and related standards. The experimental data will be used to determine the most robust solution by comparing and evaluating the test result. The final step of the thesis will describe how the chosen coating system can be implemented by NSB in their existing production and maintenance routines of axles. The grade of complexity is also an important factor for the new solution. The complexity can be described as; how complex the coating process is. Is there any risk associated with the application, if there is any parts of the application process that can go wrong and affect the finished product.

1.3 Thesis Outline

The structure of the report is based on the natural process to research, test and document the performances of different technical solutions in a project.
Chapter 2 consists of the development of the PDS, what requirements NSB have and what else should be included to find different good solutions.
In **Chapter 3** the possible solutions that exists in protective coatings are presented. Evaluation of the solutions and a selection of the best suited coatings.
In **Chapter 4** the selected solutions and their supplier are presented.
In **Chapter 5** the development of the test program are described. The theoretical background of the tests, the experimental method and the evaluation methods of the results are presented.
Chapter 6 describe the experimental performance and results.
In **Chapter 7** the results and performances of the test program are discussed.
Chapter 8 presents the conclusion of the thesis as well as recommendations for further work.

Chapter 2

Requirements

When the demands of the new solution is to be determined, it is important to fully understand what type of loads and environment the axle undergoes throughout the lifetime. All phases during the lifetime of the axles were thoroughly reviewed in collaboration with representatives from the material division of NSB[4]. The International Standard EN 13261 - "Railway applications, Wheelsets and bogies, axles, product requirements" [3] is the parent standard. This standard addresses the issues around definition of all axle characteristics and definition of qualification procedures for axles and protective coating used on the axles.

Factors that determines the requirements for the new solution can be divided into groups:

- Material boundary conditions.
- Operating conditions.
- Standard EN 13261.
- Intervention, service and maintenance during the lifetime of the axle.

2.1 Axle material and assembly

The material used in the axles are normalized carbon steel type EA1N [3]. The chemical composition is presented in Table 2.1. The mechanical characteristics of the EA1N steel are presented in Table 2.2. To maintain the fatigue characteristics of the axle there is requirements to the surface finish. The axle sections where components such as break discs, wheels and transmission are fitted have different requirements to surface finish. The sections which will be coated are required to have Surface roughness no larger than $R_a = 1.6\mu m$ as Figure 2.1 show. This value can not be any higher before the coating is applied.

TABLE 2.1: Chemical composition, EA1N [3]

	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Cu**	**Mo**	**Ni**	**V**
EA1N	0,40	0,50	1,20	0,020	0,020	0,30	0,30	0,08	0,30	0,06

TABLE 2.2: Mechanical characteristics, EA1N [3]

R$_e$(N/mm^2)	**Rm(N/mm^2)**	**A$_5$(%)**
≥ 320	550-650	≥ 22

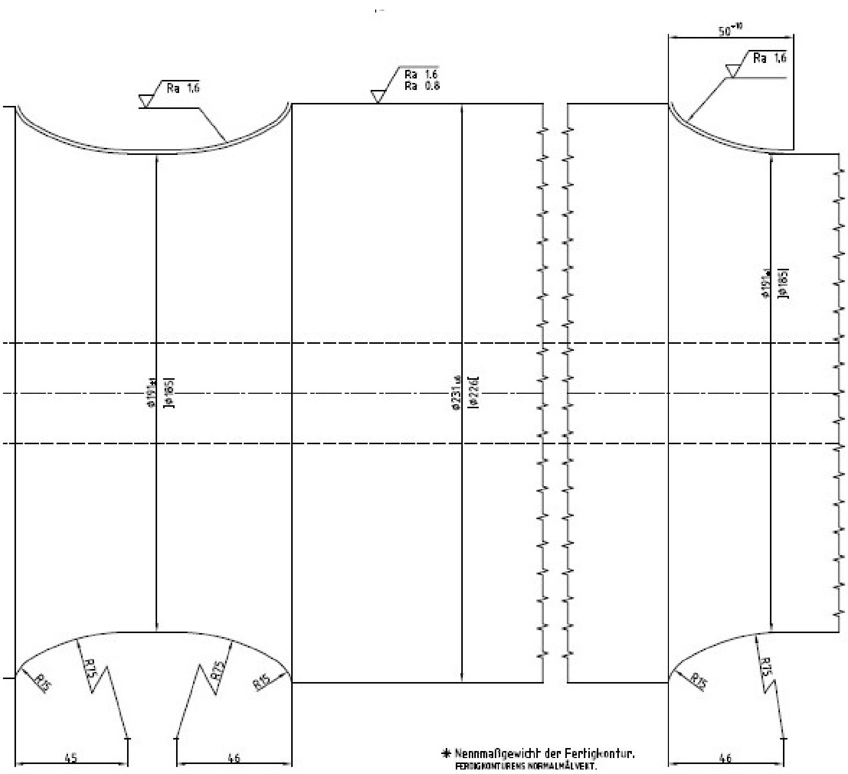


FIGURE 2.1: Technical drawing of an axle with requirements to surface finish

The protective coating needs to be applied to the axle before the other components are mounted in the assembly. In the assembly; the wheels, break discs and transmission components are mounted to the axle by shrink connection. It is done by heating the components up to 300 °C and placing them on the axle. The shrink connection occurs when the temperature of the components decrease. The procedure induces a high, local temperature around the fitted components. The temperature can be 300 °C and the protective coating has to maintain integrity through the heating and cooling process.

2.2 Operating conditions

The trains are operating in temperatures from -40°C to +40°C. During the winter ice and snow can get packed under the train body. This case is illustrated in Figure 2.2, where snow and ice is packed around a roller wheel axle. During normal operation, vibration can cause this ice-pack to break loose. The ice detached from the train body can fall down on the track and form projectiles of ice and gravel; sharp, heavy and at high speed. Another concern on the railways in Norway is the vast areas of wilderness with large amounts of animals. By collision between train and animal at high speed the impact forces can cause damage to the axle surface. The trend indicates that higher speeds is desired on the Norwegian railways. Higher speed means higher impact energies of the projectiles. The new protective coating has to withstand the impact caused by snow, ice, gravel and animals. The conditions near the coastline are corrosive and high humidity environment. The corrosivity category can be C4 High according to ISO12944 [5]. If the coating is damaged by impact, bare steel of the axle can be exposed. The corrosion of these exposed impact zones can cause pits and cavities that becomes points of stress concentration where fatigue cracks can develop. The protective coating has to maintain the integrity through the lifetime of the axle.

The trains are operating at speeds up to 200 km/h. The rotational speed of the axle is high and the axle must be balanced to reduce risk of high cyclic stresses and

FIGURE 2.2: Ice formation under the train vehicle [1]

vibrations. If the coating thickness is large, the cyclic stresses and vibrations can be too high if not the coating is balanced. The lifetime of the axle is 7.000.000 km in total mileage. This gives a lifetime of 40 years, depending on the operation and type of service. Every 1.200.000 km a full bogie revision is conducted by Mantena AS [1], where all the rolling equipment is dismantled and inspected. An ultrasonic inspection is conducted during the revision where a ultrasound probe is inserted into the hollow axles.

The coating solution used on the axles due date is specified in Table 2.3. As shown in Figure 1.1 and Figure 1.2, todays solution is not able to cope with these operating conditions.

TABLE 2.3: The current coating solution [4]

Layer	Description	Tolerance
Base	PPG Delfleet Cromate free HS epoxy DF 3991, Applied in two coats with 20-30 min drying in between. Drying of min. 1hour at 60°C.	70-100μm DFT
Top-coat	PPG Delfleet 350-F341 (akryl/polyuretan), Drying 20min before owen. Drying of 40min at 60°C.	40-60μm DFT

[1]Mantena AS is a specialist in the maintenance of rail vehicles and does all the maintenance for NSB

2.3 Characteristics

To withstand the above mentioned conditions before and during operation, the new coating solution needs to be defined by some characteristics. The characteristics are measurable and will serve as a verification that the new solution fulfill the requirements. The International Standard EN 13261 [3] defines which characteristics that is required for a protective coating. There are different characteristics that are valid for different types of environment classes. All axles in service shall be protected against corrosion for the areas where there are no fitted components. For some axles, it is necessary to have protection against mechanical aggression.

Four classes of protection are defined, according to the use of the axle and the maintenance policy that is applied to the axle:

- Class 1: section of axles that are subjected to atmospheric corrosion and to mechanical impacts;
- Class 2: section of axles that are subjected to action of specific corrosive products;
- Class 3: section of axles that are subjected to atmospheric corrosion;
- Class 4: axles that are subject to atmospheric corrosion when the stresses calculated according to EN 13103 and EN 13104 in the sections that are subject to atmospheric corrosion are less than 60% of the permissible stresses.

TABLE 2.4: EN 13261, Table 11 - Protective coatings [3]

	Class 1	**Class 2**	**Class 3**	**Class 4**
Coating thickness	x	x	x	-
Coating adhesion	x	x	x	-
Resistance to impacts	x	-	-	-
Resistance to gritting	x	x	x	-
Resistance to salt spray	x	x	x	-
Resistance to specific corrosive products	-	x	-	-
Coating resistance to cyclic mechanical stresses	x	x	x	-

All the axles on the trains in Norway need a protective coating of class 1. Where both atmospheric corrosion and mechanical impacts are present. The requirements defined in Table 2.4 for a class 1 coating are stated as tests it should pass before the coating is qualified. The Product Demand Specification (PDS) was set up in collaboration with representatives from the materials division of NSB [4] and contains requirements from EN 13261 and other supplementary characteristics, see Table 2.5. The PDS also state which Standard to test the given characteristic by.

TABLE 2.5: Product demand specification

Characteristic	**Standard**	**Requirements**
Thickness	EN ISO 2808 [6]	The axle with coating shall have clearance to other components. Maximum 15mm
Adhesion	ISO 2409 [7], ISO 4624 [8]	The coating shall have satisfying adhesion on the axle surface with surface roughness Ra 1.6 μm
Impact resistance	NS EN 13261; Annex C [3]	No visible cracks or damages after a impact of 11,3 J
Resistance to gritting	NS EN 13261, Annex D [3]	After the test, the coating surface shall comply with; coating loss of level 3.
Corrosion resistance	NS EN 13261 [3], EN ISO 9227 [9]	No corrosion more than 2mm of the edges of the incision after salt spray test
Resistance to cyclic mechanical loading	NS EN 13261; Annex F [3]	A class 1 coating shall satisfy the given standard for level 5 loads
Resistance to temperature	-	Shall not change characteristics after subjected to a temperature of 300 °C for a short period. Shall not change characteristics under normal operation temperature of +/- 40 °C. during the whole lifetime.
Lifetime	-	40 years, 7.000.000 km total, 300.000 km/year
Maintenance	-	If damaged, the coating should be possible to repair easily on sight or at a reasonable price.
Inspection	NS EN 13261 [3], ISO 5948 [10]	The axle integrity shall be inspected with ultrasonic apparatus.
Surface	-	No chemical or metallurgical changes of the substrate
Price	-	

2.3.1 Thickness

When the components are mounted on the axle, as mentioned in subsection 2.1, the break discs and wheels are directed on to the axle. If the thickness of the coating is too large, the components could not be fitted on the axle. From the technical drawing in Appendix D the maximum thickness a coating can have is; 15mm. The thickness is also an important characteristic because it will affect the corrosion resistance of some types of coating. The thickness of the coating shall be controlled in order to ensure that it follows the specified from supplier.

2.3.2 Adhesion

The strength of adhesion between a coating and its substrate is critical to the survival of both coating and substrate. Many coatings, especially wear resistant coatings are subject to extremely high levels of mechanical stress and if there is inadequate adhesion between coating and substrate, the coating will simply detach and expose the substrate. If the coating displays strong adhesion to the substrate, then its failure mechanism is usually by wear or corrosion of the coating, which are much slower processes than uncontrolled detachment of the coating. The strength of the adhesion has to be evaluated against the performance of the other characteristics. Good adhesion prevent corrosion creep under the coating.

2.3.3 Impact resistance

The impact resistance of the new solution is of big interest for NSB. The existing solution have today a poor impact resistance and this is the main concern. How good impact resistance are depends on various properties of the coating solution. Properties like toughness, ductility, thickness, adhesion- and cohesion strength. To be able to protect against impact loads these properties play an important matter. If the coating have a lack of one of these properties it will fail on impact. There are two principals that is used to protect against impacts:

- The protective coating can function as a damper. The damper principle utilizes the ductility and the elasticity of the material to absorb the impact energy. This have a good protective effect if the thickness of the coating is large and the projectile has a rounded shape.

- Repellent material. This principle utilizes the protective material hardness and toughness to repel the projectiles. The projectile will break and loose its energy if the toughness and hardness of the material is higher than the projectiles.

2.4 Requirements

In Table 2.6 the most important requirements are listed. The requirements are graded from 1 to 3. Where 1 is the most important and 3 is less important.

Table 2.6: Important requirements

Rating	**Requirement**	**Description**
1	Adhesion	Good adhesion to the axle, without microstructural or chemical changes of the axle surface
2	Impact	Resist impacts of 11,3J
3	Corrosion	The coating can loose its adhesion due to corrosion creep

Chapter 3

Coating Selection

There are three different surface-engineering methods for preventing wear and corrosion: Changing the surface chemistry, Change the surface metallurgy and Add a surface layer or coating. Due to the requirement in Table 2.6 , no changes in chemistry or metallurgy can be made on the axles.

A wide range of processes are used to deposit metal, ceramic, and organic (paints or rubber linings) coatings [11]. In this chapter a selection of materials that may meet the requirements mentioned in Table 2.5, are described. At the end of the chapter the selected materials will be assessed against the PDS.

3.1 Organic Coatings

Epoxy coatings er widely used in protection of structures against exposure in marine atmosphere, water immersion, chemicals. The epoxy provides good barrier properties, adhesion, chemical resistance, and impact resistance. However the epoxy must be protected against light due to degradation by UV light [2]. Components such as pigments and reinforcement are added in the paint system to ensure good corrosion- and impact resistance, as shown in Figure 3.1. An organic coating can be customized to get the desired characteristics and properties. The application of the coating can be carried out in various ways, such as high pressure spraying, conventional spraying, brush/roll, stripe coating and powder coating.

- By acting as a barrier against transport of reactants such as oxygen, water and ions.
- By serving as a reservoir for anti- corrosive pigments such as metallic zinc particles.
- By serving as a reservoir for pigments that react chemically with moisture and the metal in the structure. the reaction passivate the surface, thus reducing the corrosion rate.

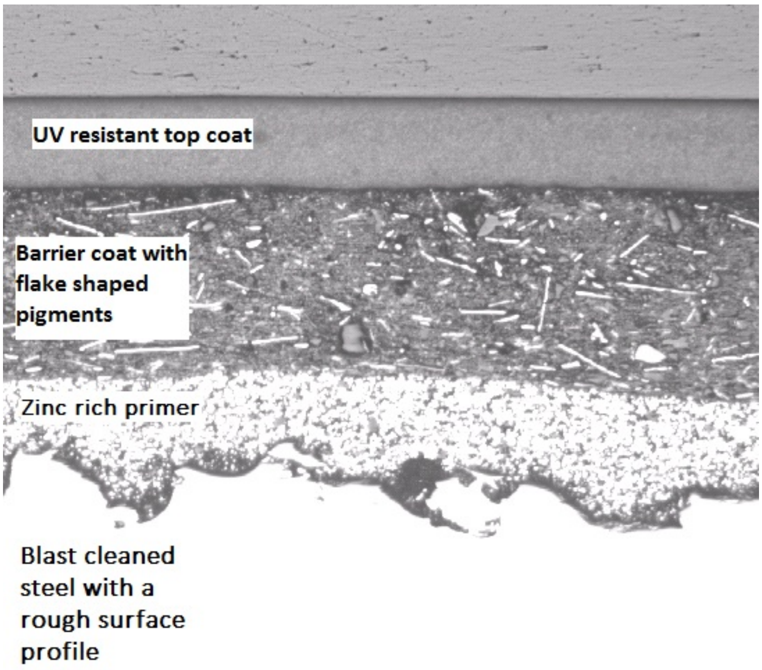


FIGURE 3.1: Example of a 3-layer organic coating system [2]

3.2 Rubber lining

Rubber lining is the skilled application of unvulcanized rubber sheets to prepared metal surfaces. The lined equipment is then vulcanized in a steam autoclave, fully bonding the rubber to the metal surface creating a durable and resilient protective rubber coating [12]. The principal benefits of rubber lining are its excellent resistance to corrosive and abrasive chemicals and materials, e.g., acids, alkalies, salt water, slurries, sand, shot blast media, crushed ores etc. In addition to this, rubber linings provide other benefits including noise and vibration reduction, electrical and thermal insulation and product protection[12]. The rubbers can be formulated with different hardness and chemical resistances [11].

Rubber dampens by transforming kinetic energy into static energy. This basic rubber property is utilized in protection against explosion and impact and effectively reduces or eliminates noise, vibration and water hammer in pipelines and reaction tanks with agitators [12].

3.3 Metallic coating

Electrochemical Deposition

Electrochemical methods are well-established processes for applying metal coating for improved surface properties of materials. Electrochemical or electroplating is defined as the deposition of a coating by electrolysis, that is, depositing a substance on an electrode immersed in an electrolyte by passing electric current through the electrolyte. Modifications of the electroplating process include occlusions or composite deposition plating.

The electroplating deposition process is substrate-shape dependent. The anode/-cathode configuration, the current density, and the composition and conductivity of the electrolyte are important process parameters. Other considerations in the process are the problem with evolution of hydrogen at the electrodes when the cathode efficiency is less than 100%. Maximum adhesion depends on both the elimination of surface contaminants in order to induce a metallurgical bond and the generation of a completely active surface to initiate plating on all areas. The cleaning process before electroplating is of the chemical methods. In general, electroplating has minimal or no effect on substrate properties (apart from hydrogen embrittlement). Coated samples can also be post-heat treated to promote interdiffusion to increase the bond strength.

Composite deposition plating is a further extension of electroplating in that particles or fibers are suspended in the electrolyte, then enclosed in the deposit. Oxides, carbides, silicides, refractory powder, metallic powder, and organic powder can be introduced into the electrolyte. The most widely used electrodeposited composites are cermet coatings, with Al_2O_3, ZrO_2, TiO_2, and SiC added to increase strength, hardness, thermal- and wear resistance.

Weld-Overlay Coatings

Welding is a solidification method for applying coatings with corrosion, wear and erosion resistance. Weld-overlay coatings offer unique advantages over other coating systems in that it provides a metallurgical bond. It is not susceptible to spallation and can easily be applied free of porosity or other defects. The coating thickness can be greater than most other techniques, typically in the range of 3 to 10mm. During weld-overlay surfacing, the coating material is raised to its melting point and then solidified on the surface of the substrate, which means that metals and alloys used for this purpose must have melting points similar to or less than the substrate material.

During welding, the base material is subjected to peak temperatures that will cause a heat affected zone (HAZ). The properties of the weld and the adjacent HAZ strongly depend on the thermal history as dictated by the heat input. Preheating the part may be a necessary step in reducing the residual stress and distortion associated with welding. Interpass temperature is another important factor that needs to be controlled in order to prevent increased dilution and HAZ grain growth at high temperatures.

3.4 Ceramic coating

Thermal Spray coatings

Thermal spray is a generic term for a group of coating processes use to apply metallic or nonmetallic coatings. These processes are grouped into two categories: Combustion and Electric/Plasma. The energy sources are used to heat the coating material to plastic or semimolten state, from powder, wire or rod form. The heated particles are accelerated toward a prepared surface by either process gas or atomization jets. Upon impact on the substrate, a bond forms with the surface, with numerous particles which cause thickness buildup and forming a lamellar structure. [13]

- Substrate adhesion, or bond strength is dependent on the materials and their properties and generally is characterized as a mechanical bond between the coating and the substrate, unlike the metallurgical bond in weld-overlay coatings.
- Thermal spray processes are usually used on cold substrates, preventing distortion, dilution, or metallurgical degradation of the substrate.

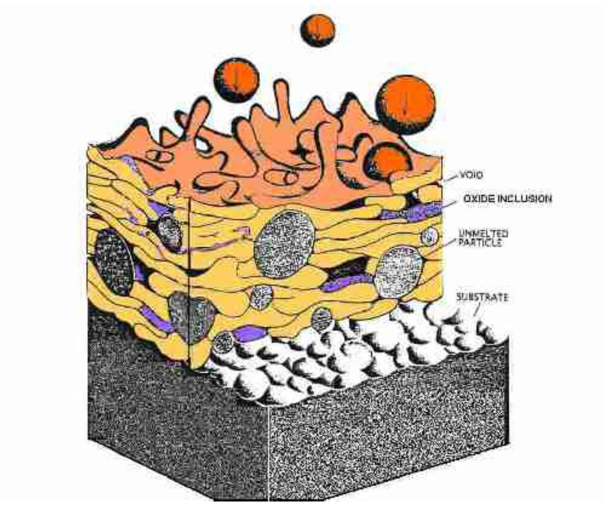


FIGURE 3.2: General Thermal Spray Coating build-up on the substrate

The variations in oxide content and porosity, as well as the chemical composition of the coating, greatly affect the properties of the deposit and, in case of corrosion, the underlying substrate. The splat morphology and, more importantly, the splat/splat and splat/substrate interface are critical to properties such as bond strength, wear, erosion, and corrosion. The mechanical properties of thermal spray coatings are not well documented except for their hardness and bond strength.

Factors effecting bonding and subsequent build up of the coating:

- Cleanliness
- Surface area, topography or profile
- Temperature (thermal energy)
- Time (reaction rates and cooling rates etc.)
- Velocity (kinetic energy)
- Physical and chemical properties/reactions

Cleaning and grit blasting are important for substrate preparation. This provides a more chemically and physically active surface needed for sufficient bonding. The surface area is increased which will increase the coating bond strength. The rough surface profile will promote mechanical interlocking, which is highly important for Thermal Spray coatings.

Vapor Deposition coatings

Vapor deposition processes can principally be divided into to types: Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD). PVD processes requires creation of material vapors and their subsequent condensation onto a substrate to form a film. CVD processes are generally defined as the deposition of a solid material from the vapor phase onto a heated substrate as a result of numerous chemical reactions. Vapor deposition coatings can be used in wear applications. It is mainly carbide, oxide and nitride coatings that are used as hardfacing coatings in wear applications. Vapor deposition coatings can be tailored to specific applications where abrasion, fretting, impact and corrosion are present. Vapor deposition processes are very expensive and have a limitation in the sizes of the substrate.

3.5 Process Evaluation

When abrasion takes place under high loads, and where impact occurs and erosion is not prevalent, then hardness is not a reliable parameter on which to select the appropriate surface treatment. The surface must not only be hard, it must also be tough and resilient and able to withstand high specific loading without deforming into the substrate.

The coating processes are evaluated by comparing the characteristics and parameters of the processes up against the requirements in the PDS. In Table 3.1 pros and cons are listed for each process. As the table indicates, each process have their advantages and weaknesses. It is therefor important for the evaluation, to look at the weaknesses which can not be changed or modified.

The **Weld-Overlay** coating process can not be used as surface treatment on the axles. The PDS states that no changes can be made on the axles microstructure. The peak temperature of the welding process cause HAZ and residual stresses which affects the strength and fatigue properties of the axles.

The **CVD** and **PVD** coating processes have also limitations that make them unusable in this application. The size limitation of the components to be coated is the determining factor. The axles have a large dimension which can not be coated with either CVD or PVD. The process is time consuming and repair on the axles is one of the limitations.

TABLE 3.1: Pros and cons of the different coating solution

Material	**Pros**	**Cons**
Epoxy Organic coating	- Corrosion resistance - Wear/impact resistance -Can be taylor made to fit the requirements - High temperatures	- UV-resistance - Adhesion mechanism - Low temperatures
Rubber lining	- Barrier effect - Corrosion resistance - Impact resistance - High temperatures - Chemical resistance	- Adhesion mechanism - Low temperatures
Electrochemical	- Adhesion mechanism - Corrosion resistance - Temperature resistance - No changes of substrate properties	- Thickness - Impact resistance - Maintenance/repair - Bath and electrode size
Metallic Weld-overlay	- Adhesion - Thickness - Wear and corrosion resistance	- Changes in substrate properties
Thermal spray	- Corrosion resistance - Wear resistance	- Adhesion to fine surface - Toughness - Impact resistance
PVD/CVD coating	- Adhesion - Wear resistance - Corrosion resistance	- Size limitations - Thickness - Impact resistance

The processes that can be used are Organic Coating, Electrochemical Deposition Coating and Thermal Spray coating. In the following chapter, a selection of products from each process are selected.

Chapter 4

Product Selection

The selection of surface treatment products within the different categories are presented in this chapter. The variety of different solutions is great and only the chosen coatings are presented. Selection is based on technical specifications of the various coatings, the experiences with products operating in similar conditions, and requests from the material division of NSB [4]. By conversation and discussions with several suppliers of coating, they have recommended and suggested different solutions. The technical specifications and their experience with the products have been the deciding factor in this selection. The coating products are presented and the manufacturing company is briefly presented.

4.1 Epoxy - Lucchini RS

The Lursak product is an organic coating solution, epoxy composition reinforced by synthetic fibres applicable in room temperature with standard airless spray system. It is composed by three layers with a Methal Adhesion Primer, Primer and the Protective Top-coat.

The three layers have a total thickness of 4-5mm as Figure 4.1 shows:

A : Methal Adhesion Primer, around 10 µm thickness,a chromate-free wash-primer which is composed by 3 components and has been designed as alternative to traditional chromate wash-primers. Applied for improving the adhesion to steel and the protection from corrosion.

B : Primer with high thickness, flexible and reinforced with fibres. 15-F4-HTP EPOXY AEROSPACE HT PRIMER is a two-pack modified-epoxy primer for interior and exterior deck systems as per EN-13261(2003) Class 1 intended uses. The exceptional mechanical and physical properties provides considerable versatility for a broad range of aerospace, industrial and marine coating applications.

C : Protective Top-coat with high thickness, reinforced with fibres for protection against scratches and creeps. 25-F4-HTF/FP EPOXY AEROSPACE HT FINISH Fireproof is a two-pack modified-epoxy top-coat for interior and exterior* deck systems as per EN-13261(2003) Class 1 intended uses. The exceptional mechanical and physical properties provides considerable versatility for a broad range of aerospace, industrial, marine and railways coating applications.

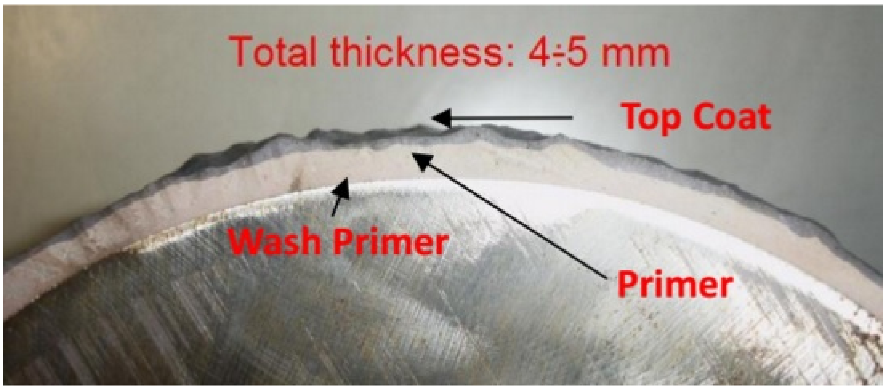


FIGURE 4.1: Cross section view of Lurask

Lucchini RS have subjected the Lursak solution to a test program according to EN 13261, where their results will be evaluated against the results obtained in this thesis. The solution is widely used on axles operating in high speed (HS) and very high speed (VHS) in central Europe and Asia with approximate 9000 wheelsets in operation. On freight vehicles there are more than 10000 wheelsets coated with Lursak in operation per June 2015 [1].

Lucchini RS

Lucchini RS is a steel manufacturing group which offers a diversified range of high-tech products and services, globally. The group's core business is the production of high-end railway components – wheels, axles and wheelsets for high-speed applications, locomotives, passenger trains, trams and underground trains. The Lucchini head office is located in Lovere, Italy. The contact person at Lucchini RS is Mr. Dimitri Sala [14].

Lursak is the Lucchini RS solution to the increasing demand to guarantee the total protection of railway axles against corrosion and damages derived from ballast impacts in full agreement with EN 13261 requirements.

Evaluation

The Lursak solution was developed in 2008 after requirements of the European Standard EN 13261. It meets all the requriements for a Class 1 protective coating and have been subjected to an extensive test program. The results and test data in Appendix F. The Lursak system is widely used on the train fleet in Europe and the high speed trains in Asia [1]. No field tests in the Nordic countries have been done. Lucchini have developed a Repairing kit for Lursak, this could be used when impacts on the axle have caused the protective coating to flake off. The total repairing time with this kit is 70-150 minutes, and can be done on sight [1]. The Widespread use of this solution on the European train fleet and well-documented test program enables the Lursak solution to be used as a reference when the test program in this thesis is conducted.

4.2 Rubber lining - Trelleborg

The process of applying a rubber-lining is different from a organic coating applied by brush or spray. The first step of the process is cleaning and pretreatment. The axle will be primed using a primer to ensure sufficient adhesion to the steel and improve the corrosion protection. The rubber-lining is rolled on after the primer have cured. The rubber is then vulcanized in a baking process using a furnace. The vulcanization process will cause a microstructural change in the polymer as it is crossbinding. The rubber-lining will function as a barrier against corrosive media. The elastic behaviour of the polymer of 650% elongation at break, provide the impact resistance. The material data sheet of Compound 73181 in Appendix A. This is a EPDM rubber (ethylene propylene diene monomer) [15]. The glass transition temperature is -54 °C. The main properties of EPDM are its outstanding heat and weather resistance. Trelleborg are using this material in weather protection and in bellows for pipeline connections. The most common use is in vehicles for seals and hoses.

Trelleborg Offshore AS

Trelleborg AS is a global engineering group focused on polymer technology. The division Trelleborg Offshore located in Krogstadelva, Norway, deliver polymer products tailor made after the costumers demands. Their primary clients are in the oil and gas inustry. The contact person at Trelleborg AS is Mr. Svein Gabrielsen [16].

Evaluation

Rubber protection will act as a barrier to water and corrosive products due to its high crosslinking density. The rubber will act as a damper of impacts from ballast, ice and animals. The rubber is very flexible and can resist large impacts.

The temperature limits of the coating is well inside the requirements of the EN 13261. The adhesion properties of the rubber to the fine surface of the axle has to be evaluated further during testing. Also the thermal ageing resistance has to be tested.

4.3 Thermal Spray - Aquamarine

The Thermal spray solution suggested by Aquamarine is a High-velocity-oxy-fuel (HVOF) coating. The type of coating is a pure NiCrBSi coating. It is a hardfacing wear and corrosion resistant material, which are widely used in cutting, grinding and drilling application. HVOF coatings are used in applications in the oil and gas industry for seal surfaces, gates and seats in valves with high temperature.

Aquamarine Subsea Solutions AS

Aquamarine is a developer and producer in Thermal spray coatings and welding technology for offshore oil and gas industries. Aquamarine's advanced thermal spray coatings extend component life and increase value; decreasing equipment downtime, and improving performance in a wide variety of applications. The contact person at Aquamarine AS office at Vestby, Norway, is Mr. Roy Liltvedt [17].

Evaluation

A Thermal spray coating have very good wear- and corrosion resistance. Which is well suited for the axle protection application. The HVOF coating process demands a certain surface roughness of the axle. The coating have good resistance against abrasive wear. The resistance against impacts has to be evaluated through the test program. The pretreatment to ensure that the coating will adhere to the surface is to grit blast with Al_2O_3 to increase the surface roughness of the substrate. The effect on the axle surface has to be evaluated further after it has been sprayed.

4.4 Electrodeposited Ni-SiC - Benoni S.N.C

In collaboration with Maria Lekka at the university of Udine, Benoni S.n.C have developed a method to deposit an electrolytic Ni-SiC coating [18]. The coating have been developed for copper moulds usually used for steel continuous casting which suffer from severe wear at relatively high temperatures and low friction loads. Co-deposition of hard particles in metal matrix coatings have shown to be a cheaper solution than other coating processes. The addition of the SiC micro- or submicro-particles in the nickel matrix lead to a significant increase to both hardness and wear resistance of the composite coating [18]. The hardness of pure electrodepisited Ni is 267 $HV_{0,3}$ while electrodeposited Ni+SiC have a hardness of 756 $HV_{0,3}$ which is an increase of about 180% [18].

Benoni S.n.C

Benoni S.N.C is manufacture of nickel and chromium coatings with office based in Verona, Italy. It has specialized in some sectors such as hard chrome plating of tubular ingot moulds for steel continuous casting. The contact person at Benoni S.n.C is Mr. Stefano Benoni [19].

Evaluation

The coating have well documented properties in wear and hardness tests. The coating have been tested on railway axles in the past with positive results. But these results are not documented. The corrosion resistance of the coating, and the resistance to mechanical impacts have to be assessed. The The method of electrodeposition of the coating demands large scale production to have a reasonable cost comparing with the other solutions. Repairs of damaged axles can be difficult and demanding.

4.5 Selection

The selection of coating types consists of four different types of coating process and four different coating materials. The materials have different strengths and weaknesses. Through the test program in the following chapter, all the coatings will be evaluated against the same criteria and differences in behavior will be evaluated.

In the following chapters are the selected products mentioned as in Table 4.1.

TABLE 4.1: Selected coating products

Number	**Coating product**	**Supplier**
1	Electrodeposited Ni-SiC	Benoni S.N.C
2	Thermal Spayed NiCrBSiC	Aquamarine AS
3	Vulcanized rubber	Trelleborg AS
4	Lursak epoxy	Lucchini RS

Chapter 5

Test Program

To make sure that the coating will fulfill the requirements in the product demand specification in Table 2.5, a test program is set up. The test program in Table 5.1 consists of a set of standards and a description of the tests. After the test program have been defined, size, shape and number of samples for testing is decided.

TABLE 5.1: Test Program for the different solutions

Properties tested	**Standard**	**Method**
Thickness	ISO 2808 [6]	Optical microscope with camera to record and measure the thickness.
Microstructure		Examine the microstructure of the coating
Roughness	JIS2001 [20]	Measure roughness before and after pretreatment to ensure no change in surface characteristics.
Adhesion	ISO 4624 [8]	Pull-off test.
Impact resistance	NS EN 13261; Annex C [3]	Impact test with dropping object
Resistance to salt spray	ISO 9227 [9], ASTM B117 [21]	Salt spray test

5.1 Coating thickness

The thickness of a coating is an important parameter. For epoxy coatings the corrosion resistance is highly dependent on the thickness due to the distance the ions have to travel before reaching the substrate material. If the impact resistance do not fulfill the requirements, the thickness could be the determining factor. The thickness will be measured to ensure the that it meet the suppliers value by using a optical microscope with camera, according to Standard ISO 2808 [6].

Method

The samples observed have been polished to allow adequate light reflection from the surface. For the test samples used for microscopical analysis, a gradual grinding process that included SiC papers were used. The roughness of the papers went through 220, 500, 1000, 2000 and 4000, with a final diamond polishing at 3μm. Coating 1 and 2 were molded in epoxy to ease the grinding process. Coating 3 and 4 changed characteristics while they were molded, so they were prepared without molding.

5.2 Microstructure of coating

The microstructure will strongly influence the coating properties. A high amount of pores and defects in the coating will be deterimental to the corrosion resistance as water and corrosive agents can penetrate to the substrate. For the thermal sprayed, and electrodeposited coatings, the amount and distribution of hard particles in the softer matrix can be deterimental to the impact and wear resistance. The characterization of the microstructure is conducted with an optical microscope.

Method

The same samples which was prepared for thickness measurements are also used in the characterization of the microstructure.

5.3 Roughness

The roughness of a surface is a measurement of the surface texture. There are several different ways of characterizing the roughness of a surface. Roughness is an important factor to determine how the surface will interact with its environment, and has a major influence on the fatigue characteristics. The requirement in Table 2.5 state the roughness can not exceed R_a=1.6 μm. This value is calculated by measuring the average distance between the actual surface and the center line of the profile, see Equation 5.1.

$$R_a = \frac{1}{L}\int_0^1 |z(x)|dx \tag{5.1}$$

Where L is the length measured and the $z(x)$ value is the peak value on point x, compared to the center line.

For the coatings with mechanical pre-treatment of the substrate (Coating 2 and Coating 3), the roughness will be measured before and after pre-treatment. For the coating 1 and Coating 4, the roughness is measured before they are coated. The apparatus used is a Mitutoyo SJ-301 profilometer in Figure 5.1 according to standard JIS2001 [20].

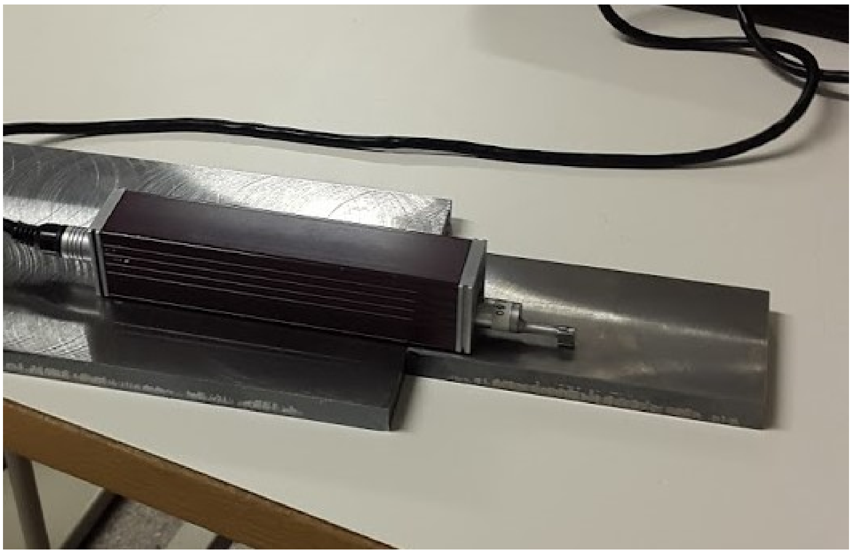


FIGURE 5.1: Roughness measurement

5.4 Adhesion tests

The bonding force between the substrate material and the coating characterizes adhesion of the coating. Testing of this strength is important to control the quality of the pre-treatment and coating procedure. The test can provide several different results, depending on the location of fracture. The adhesion strength of the coating is given if the rupture is in the coating-substrate interface. The cohesion strength is given if the rupture is within the coating.

As described in Table 5.1, the adhesion strength can be measured by two different methods. The method used in this test program is the Pull-Off test described in the following.

Pull-off test

The pull-off test according to ISO 4624 [8] is used to determine a coating's adhesion to a substrate and to compare the adhesion behaviour of different coatings. It is most useful in providing relative ratings for a series of coated panels exhibiting significant differences in adhesion.

Plates are coated by the coating supplier. Pull-off dollies are bonded directly to the surface of the coated panel, using an adhesive, 3M Scotch-Weld™, Epoxy Structural Adhesive, DP 490. After curing of the adhesive, the dollies are isolated from the surrounding coating by cutting around the dolly through to the substrate. The bonded dolly assemblies are placed in a suitable tensile tester shown i Figure 5.2. A tensile test is then performed on the assembly and the force required to pull off the dummies are measured. The surface of both dolly and coated plate are examined for adhesive and cohesive failure. An optical microscope will be used to determine the location of failure if it is difficult to determine by visual inspection.

The pressure required to pull off the dollies are calculated:

$$\sigma = \frac{F}{A} \tag{5.2}$$

Where F is the force required to pull off the dolly. A is the surface area of the dolly.

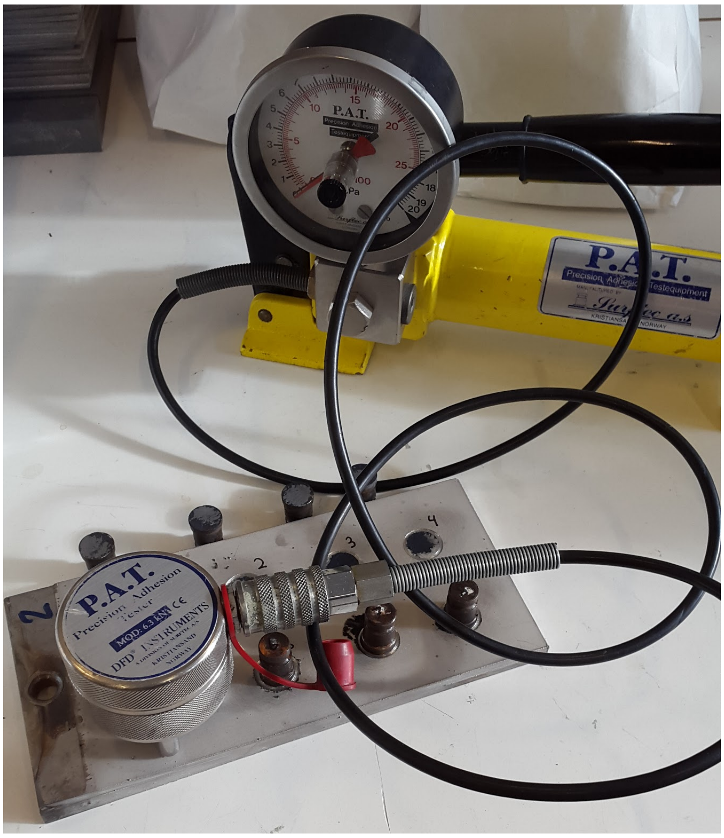


FIGURE 5.2: Pull-off test apparatus

5.5 Resistance to impacts

An impact is essentially energy transfer from one object with relative velocity to another. The impact occurs at the point of physical contact between the objects. From the perspective of impact protection the most important factors are peak force, energy transferred, shape of the projectiles and energy transfer time. Peak force during impact is besides impact energy the most important factor that determines the extent of damage in an impact. The impact force can be determined by the impactor shape, impact energy, energy transfer time, impacted material and boundary conditions. These are all variables that one should be able to control. By controlling *drop height, impactor shape and directional guidance* during drop, and by using the same support-structure in every test, it is believed that a relatively accurate impact scenario can be simulated.

Method

A impact resistance test is conducted by dropping an indenter with a weight onto the coating sample. The apparatus has a indenter that can be adjusted to different heights and weights, for adjusting the impact energy. The weight is dropped onto the coated sample and the sample is investigated for cracks and damages around the impact zone. In the PDS (Table 2.5) it is stated that the NS EN 13261, Annex C [3], is the standard test for assessing the impact resistance for a protective coating on railway axles. The apparatus needed for this test is comprehensive to get hold of, where compressed air is used to propel the projectile towards the sample. The test setup in the Standard ISO 6272 [22] is less comprehensive and the apparatus is already in the laboratory. The method will be calibrated to use the same impact energy and conditions as the NS EN 13261.

In Standard EN 13261 the test parameters are defined as in Table 5.2.

TABLE 5.2: Test parameters of EN 13261

Parameter	**Value**
Impact energy	11,3 J
Indenter mass	60 gram
Indenter shape	r = 16 mm

The impact energy will reach 11,3 J. This is the required value for what impact energy the coating system have to withstand according to EN 13261 [3]. When ISO 6272 [22] is used, the same impact energy will be obtained.

ISO 6272, Impact test

The test apparatus used consists of a guide tube of $2m$, a rack for positioning the test sample, and indenter mass of $2{,}9kg$ see Figure 5.3 with shape $r = 16mm$. The setup for the test rig is shown in Figure 5.4 and Figure 5.5.

FIGURE 5.3: Indenter used for the impact test

This test will be performed as a classification test. The standard suggests making the first drop at a low height, where no cracking is expected. Between each drop, the surface is examined for cracks. If no cracks are visible after inspection, the test will be carried out at increasing height in intervals of 50cm. And the impact energy for each height is given in Table 5.3.

TABLE 5.3: Impact energy for indenter of 2913gram

Height [m]	**Impact enegy [J]**
0,1	2,85
0,4	11,3
0,6	17,14
1,0	28,57
1,5	42,86
2,0	57,15

If no cracks are observed after the weight is dropped from the maximum height, will the coating pass the test at the given temperature. The test is going to be conducted at three different temperatures; at Room Temperature, at -25°C, and at -65°C, with the apparatus in Figure 5.4 and Figure 5.5.

FIGURE 5.4: Impact test apparatus

FIGURE 5.5: Impact test apparatus detail

Evaluation of results

The damage after impact can be difficult to evaluate through visual inspection. Cracks, deformation and penetration of the coating surface may not be visible for visual inspection. An alternative method for evaluating the damages is used. A corrosion test after impact can be used to see if the coating has been damaged so that corrosive media can penetrate the coating and reach the surface of the axle. After impact tests are conducted on the coated samples, they will be placed in the salt spray test. The apparatus for this test is described in the following subsection. This test will be evaluated by visual inspection.

5.6 Salt spray test

Is used to determine the protective coatings ability to resist corrosion accelerated by an artificial salt spray. In corrosion, material loss occurs through electrochemical reactions at the surface.

Method

The assessment of resistance to salt spray is carried out in accordance with ASTM B117 [21]. The cabinet used is of the type Ascott S1000ip shown in Figure 5.6. The corrosive media used is 5% NaCl in distilled water. The duration of the exposure is set to 720 hours at 35°C, and the spraying shall not be interrupted during the prescribed test period. The test cabinet shall only be opened for visual inspection. The test pieces shall be an axle section covered with the coating to be evaluated, in which an aperture has been made. [3]. The aperture in the coating have the dimensions 60x10 mm and the aperture extends to the substrate surface. As shown in Figure 5.7.

After the test, the specimens should be dried in air before rinsing. The evaluation of the test result will consist of a comparison of the different types of coating.

Figure 5.6: Salt spray cabinet

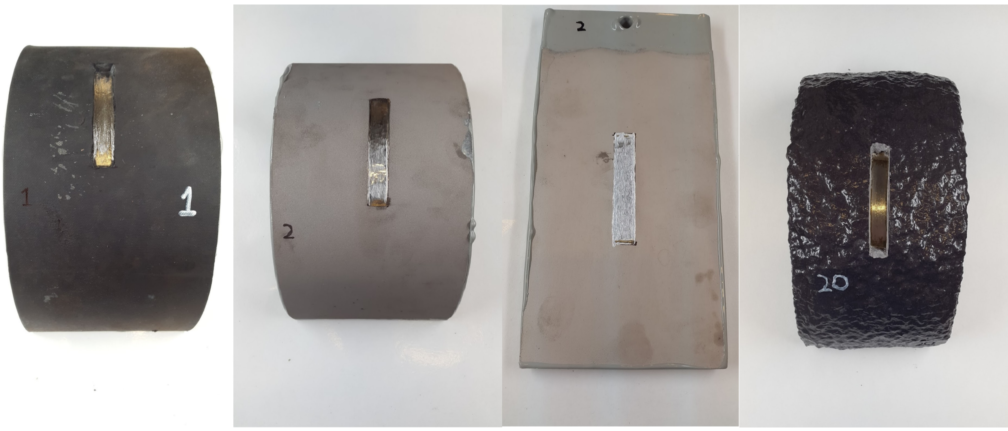


Figure 5.7: The aperture in all four coatings

The criteria for comparison are: appearance after test, number and distribution of corrosion defects (pits, cracks, blisters, rusting or creep in the aperture), and change revealed by micrographic examination. The criteria for the test; no corrosion shall be found under the coating, nor shall there be any corrosion present at a distance of more than 2 mm from the edges of the incisions under the coating. The determination of corrosion creep is carried out by cutting cross sections of the aperture and examine them in a optical microscope.

5.7 Samples for testing

The test program described in this chapter consists of eight different tests in Table 5.1. Some of the tests can be performed on the same sample. To ensure full control over the properties and characteristics of the samples, all the samples were ordered from Nomek AS. According to drawings and descriptions, the samples were machined and delivered. The material used is plain carbon-steel.

According to the Standard EN 13261 [3], the samples for impact, gritting, and salt spray test should have the geometry and dimensions of an axle section. A pipe of plain-carbon steel, with dimensions Ø180mm and $t = 10mm$ was machined and cut into sections. The electrochemical coating process could only coat flat samples of maximum dimension of 200x100 mm. A complete list of samples used in testing and characterizing of the coatings are presented in Table 5.4 below. A selection of some of the samples are shown in Figure 5.8.

TABLE 5.4: Samples for testing - Drawings in Appendix B

Sample	**Dimension [mm]**	**Quantity**	**Test**
Plate 1	200x100x10 Drawing 1	20	Adhesion (ISO4624) , Microstructure, Thickness (ISO2808)
Plate 2	200x200x10 Drawing 5	3	Temperature
Plate 3	100x50x10 Drawing 6	2	Roughness (JIS2001)
Pipe section long	Ø180, L=200, t=10 Drawing 2	10	Impact (ISO6272), Gritting
Pipe section short	Ø180, L=100, t=10 Drawing 4	12	Salt spray (ASTM B117), Impact (ISO6272)
Pipe	Ø180, L=200 t=10 Drawing 3	3	Impact (ISO6272), Gritting

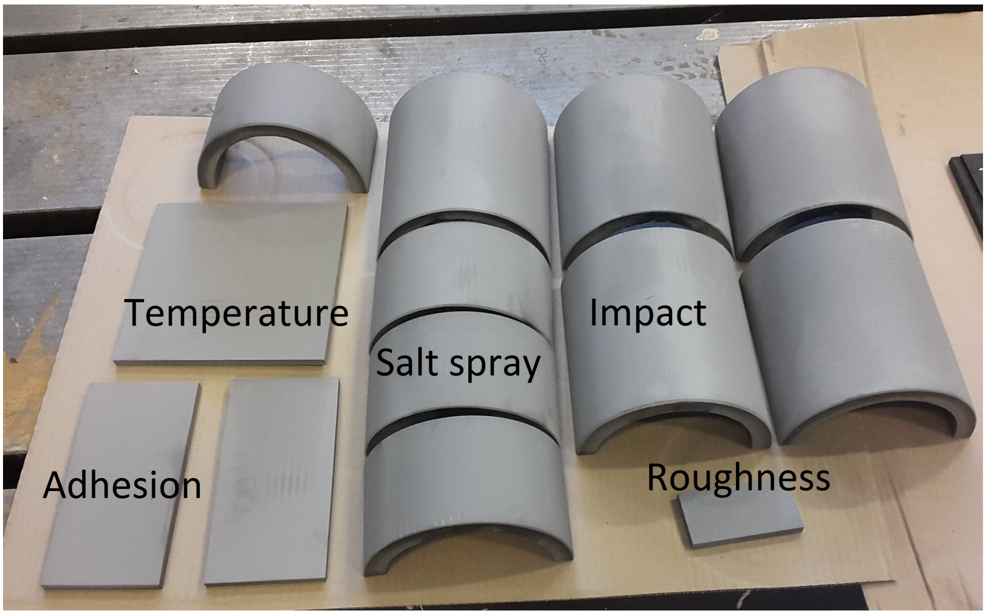


FIGURE 5.8: A selection of the samples for testing

Chapter 6

Results

The coating products listed in Table 6.1 are tested as described in Chapter 5. The results are presented in this chapter.

TABLE 6.1: Selected coating products for testing

Number	**Coating product**	**Supplier**
Coating 1	Electrodeposited Ni-SiC	Benoni S.N.C
Coating 2	Thermal Spayed NiCrBSiC	Aquamarine AS
Coating 3	Vulcanized rubber	Trelleborg AS
Coating 4	Lursak epoxy	Lucchini RS

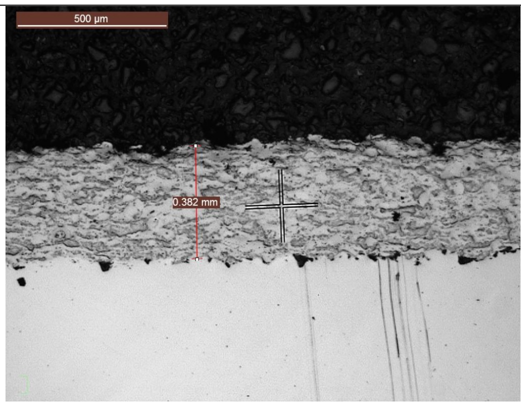
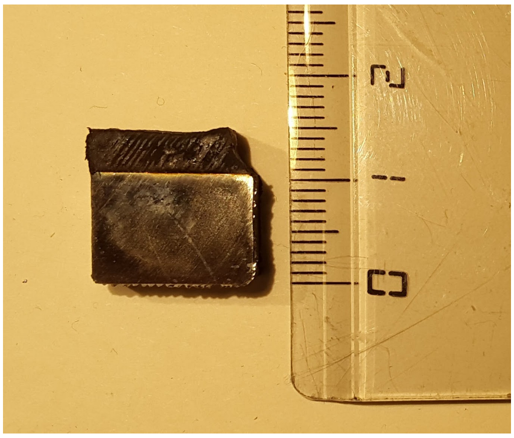
6.1 Thickness

TABLE 6.2: Coating thickness

Coating type	**Thickness** μm
Coating 1	100 ± 3
Coating 2	380 ± 10
Coating 3	3200 ± 10
Coating 4	$12{,}0 \pm 1{,}5$ [mm]

On Coating 1 and Coating 2 were the thickness measured with a optical microscope with a camera. Several measurements were taken of different cross sections, the value represented in Table 6.2 is the average thickness. Coating 3 and Coating 4 have a thickness too great to be measured using a microscope. These thicknesses was measured using a caliper. Pictures of all four coating thicknesses are presented in Table 6.3.

TABLE 6.3: Pictures of the coating thickness

 Coating 1	 Coating 2
 Coating 3	 Coating 4

6.2 Hardness

The measurements of the coating hardness were conducted using a vickers hardness tester. The results for each coating are presented in Table 6.4.

The measurements on Coating 1 were conducted on the top surface of the sample. The indents on the surface was easy to read and the results exhibit low deviations. No other measurements were taken of Coating 1.

Table 6.4: Measured hardness

Coating type	**Number of tests**	**Average Hardness [$HV_{0.3}$]**	**Standard deviation**	**Comments**
Coating 1	10	238,3	12,3	Measured on the top surface
Coating 2	15	678,8	83,3	Measured in the cross section see Figure 6.1
Coating 3	-	55 ± 5 [°shore A]	-	Measured by supplier

Hardness tests of Coating 2 were performed on the cross-section of the samples. Hardness measurement for the top surface was attempted as well, but as the surface is rather rough and the indent was difficult to read. Big deviations came from this test, and the values are not taken further into account for this test. Coating 1 is a composite coating that consists of different phases with different hardness, so the results exhibit a larger deviation deviations.

The hardness of Coating 3 is measured in the unit °*shore A*, which is the standard unit for measuring hardness of rubbers. The measurements are taken by the supplier, no additional tests were conducted. The hardness of the coating is 55 ± 5 °shore A, tested according to ISO 7619-1. Appendix A.

The hardness of Coating 4 was not possible to measure by using the vickers hardness tester. The epoxy coating have a elastic behaviour, and the vickers hardness test is dependent on plastic deformation of the surface. The coating have three layers where layer B (see Section 4.1) have a softer texture than Layer C.

6.3 Roughness

The roughness measurements were taken on the machined parts before they were sent to the suppliers for application of coating.

The test parameters used are presented in Table 6.6. The measurements were taken on the surface of the specimen to ensure that the roughness meets the required value from the PDS (Table 2.5). Four measurements in each direction on

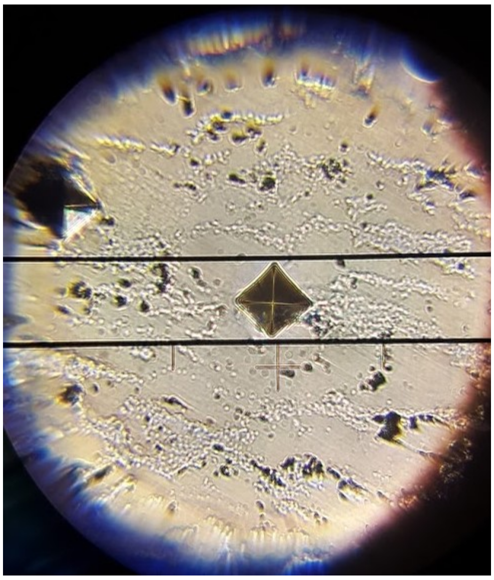


FIGURE 6.1: Hardness measurement of Coating 2 in the cross section

the parts were taken. The pre-treatment before application of coating for Coating 2 and Coating 3 are grit-blasting. The surface roughness after pre-treatment was measured in the same manner. Coating 1 and Coating 4 have no modifications of the surface during application of coating, and therefore no measurement after pre-treatment. Measurements before and after pre-treatment are presented in Table 6.5.

TABLE 6.5: Before pre-treatment Roughness

Before	**Coating 1**	**Coating 2**	**Coating 3**	**Coating 4**
R_a	0,59μm	0,66μm	0,68μm	0,55μm
R_z	3,94μm	3,82μm	4,10μm	3,77μm
After				
R_a	-	8,26μm	5,76μm	-
R_z	-	69,59μm	38,74μm	-

Table 6.6: Profilometer Test Parameters

Parameter	**Value**
Standard	JIS2001
Profile	R
Filter	Gauss
Evaluation length	4,0 mm
N	5
λ_C	0,8 mm
λ_S	2,5 μm
Speed	0,25 mm/s

6.4 Adhesion

The adhesion test was conducted according to the Standard and method described in Chapter 5. The dummies were glued onto the coating surface. The bonding agent was cured in an owen of 65 °C over night. The dummies were pulled off using a manually operated pump. A number of eight dummies were glued to each plate and two plates of each coating were tested. For the hardfacing coatings, dummies with diameter of $D = 14mm$ was used. on the softer coatings dummies with a diameter of $D = 20mm$ was used. The measured tensile load required to pull off the dummies and location of the fracture is presented in the following sections.

Table 6.7: Adhesion test results

Coating type	Number of tests	Average Tensile Strenght [MPa]	Standard deviation	Location of fracture
Coating 1	14	43,95	4,88	Bonding agent
Coating 2	14	46,64	4,09	Bonding agent
Coating 4	16	2,82	0,62	Within the primer
Coating 3 grit blasted	2	5,5	1,5	In the coating
Coating 3 not grit blasted	3	2,6	0,99	Between primer and metal

The adhesion test of **Coating 1** and **Coating 2** was performed using small dummies, giving greater pressure for the same applied force. Both coatings gave the same result, as shown in Figure 6.2 and Figure 6.3. The tests exhibit great adhesion strength with a average pressure of 43,95 MPa for Coating 1 and 46,64 MPa for Coating 2. Location of fracture is in the bonding agent between the dummy and the coating top surface. Figure 6.4 shows the fracture sruface. The adhesion strength of the coating is greater than the strength of the bonding agent.

FIGURE 6.2: Coating 1 after test

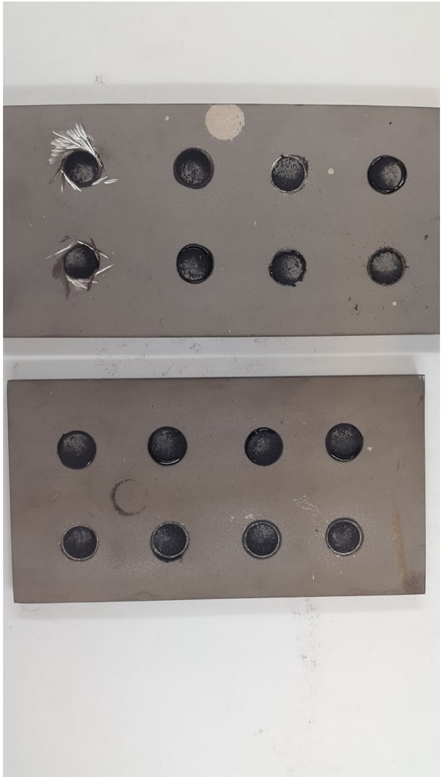


FIGURE 6.3: Coating 2 after test

FIGURE 6.4: Fracture surface of Coating 2

Coating 3 is highly elastic and does not suffer from brittle fracture in the adhesion test. As requested Trelleborg conducted adhesion tests on the coated parts according to Standard ISO 813 - Determination of adhesion [23]. The test is performed by peeling off a 25mm band of rubber and measuring the force required. The measured force to peel off the rubber on the grit blasted part is 350 N see Figure 6.5 . The force required to peel off the rubber on the part without grit blast is 280 N as we can see in Figure 6.6. The test datasheet is presented in Appendix C. The test results presented in Table 6.7 are from a pull-off test that was conducted to easier compare the results. The pull-off test was performed with large dummies on the available surface of the samples, hence the few number of tests.

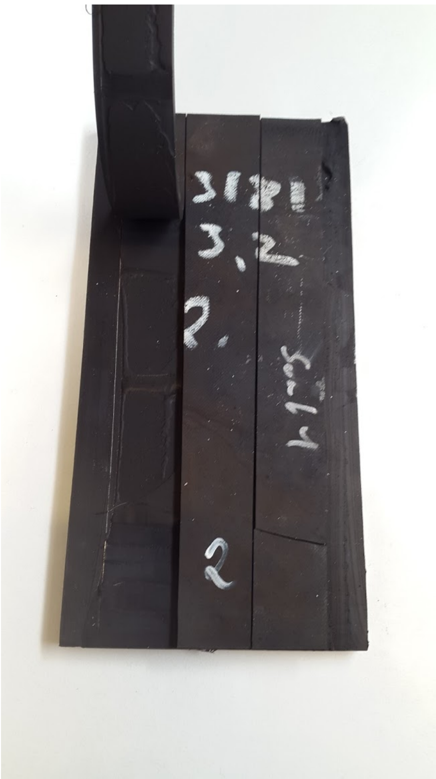


Figure 6.5: Coating 3 grit-blasted

Figure 6.6: Coating 3 not grit-blasted

The adhesion test on **Coating 4** was performed with large dummies. A number of 8 dummies were bonded to each sample and cured in an owen on 65 °C over night. The test exhibit an average fracture strength of 2,82 MPa with deviation of 0,62. The location of fracture in Coating 4 is in Layer B ref. Chapter 4.1, in the epoxy primer. Figure 6.7 shows that all the test dummies failed at the same depth in the coating. Figure 6.8 show a detailed picture of the location of failure. As shown, the epoxy primer layer have failed.

FIGURE 6.7: Coating 4 after adhesion test

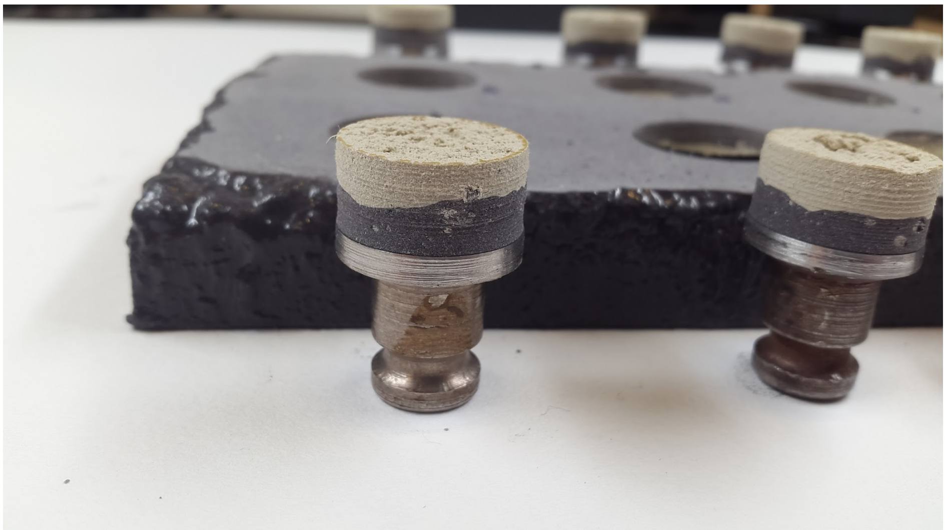


FIGURE 6.8: After adhesion test detail

6.5 Resistance to impacts

The impact resistance of the solution are assessed by impact test as shown in Figure 5.4. The impact energy is adjusted by the drop height of the projectile. The projectile is the indenter shown in Figure 5.3. The indenter has a mass of 2913 gram. In the PDS Table 2.5, the requirement for the impact resistance is "No visible cracks or damages after impact of 11,3 J". The height required to reach an impact energy of 11,3J is 0,4m. Impact energies for other heights are listed in Table 6.8 .

TABLE 6.8: Impact energy for indenter of 2913gram

Height [m]	**Impact enegy [J]**
0,1	2,85
0,4	11,3
0,6	17,14
1,0	28,57
1,5	42,86
2,0	57,15

The impact test was conducted on samples at three different temperatures at Room temperature (RT), -25°C and -65°C. The samples was cooled down using a freezer set at the given temperatures. The test at -65°was carried out after an evaluation of the results from the two other temperatures. To make the test as similar as a real life conditions for the train axles, are the test samples shaped like axles. The shape makes it easy to controll where the point of impact will be located. The location of impact are spread out over the sample surface as shown in Figure 6.9. Forces acting on the coating from the indenter are different when the impact location is changed. When the coating is impacted on the top surface there will be mostly compressive forces acting on the coating. When the impact is in the inclined plane on the side of the axle, there will be both compressive and shear forces acting on the coating.

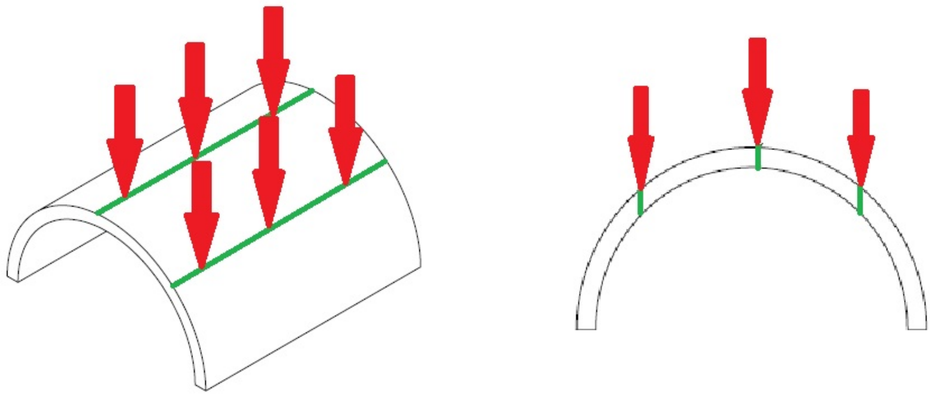


FIGURE 6.9: Scetch of impact location

6.5.1 New evaluation method

After impact testing at RT there were problem determining the severity of damages or cracks, by visual inspection. One sample of each coating was impacted with a energy of 57J at RT and then placed in the Salt spray test for a period of 480 hours. This method will reveal if there has been formed any cracks or openings down to the substrate in the area of impact. The coating has failed if corrosion products are visible in the impact area. The results of this test are described in Subsections 6.5.3.

6.5.2 Results

Coating 1

The first tests at room temperature started with a drop distance of 1,0m. This resulted in a small deformation, and the drop distance was increased to 2,0m. There were made six impacts with an impact angle of 90°and six with 45°. Figure 6.10 shows impact 1-3 with drop distance 1,0m and impact 4-6 with drop distance 2,0m. Coating 1 showed more damages on the inclined impacts than the flat. When the temperature was decreased to -25°C were the damages from flat impact just as bad as the inclined, Figure 6.13. At -65°C, the damages tend to be less severe. It is less deformation of the material at this temperature than for the higher temperatures, as seen in Figure 6.14.

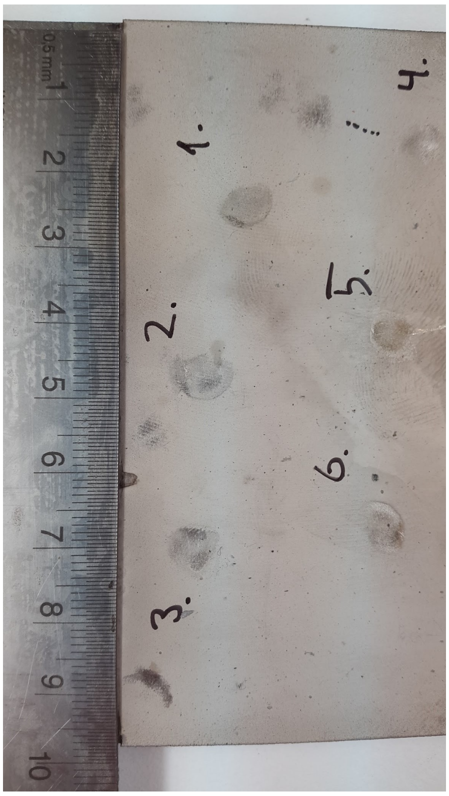


FIGURE 6.10: Coating 1 at RT, 6 flat impacts

FIGURE 6.11: Coating 1 at RT, 5 inclined impacts

FIGURE 6.12: Coating 1 at -25°C, 12 impacts

FIGURE 6.13: Coating 1 at -25°C, details

FIGURE 6.14: Coating 1 at -65°C, 12 impacts

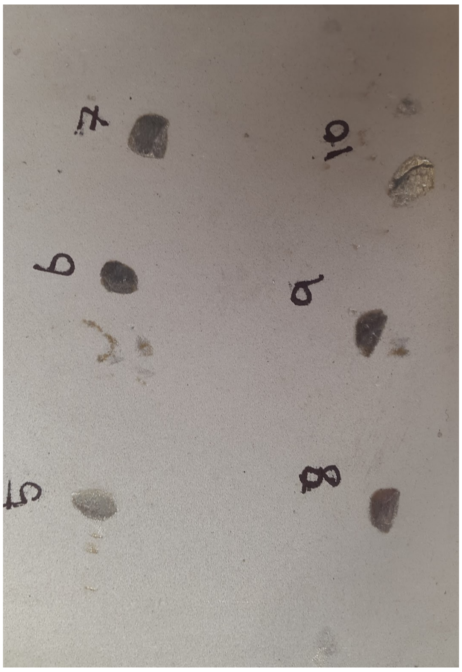


FIGURE 6.15: Coating 1 at -65°C, inclined

Coating 2

The same procedure was used when impact testing Coating 2. As seen in Figure 6.16 of the test at room temperature, was the damages difficult to evaluate. There are deformation in the impact zones in the flat impacts. For the inclined impacts there are scratch like damages as seen in Figure 6.17, 6.19 and 6.21. The deformation of the impact zone had the same dimensions for all three temperatures. The test exhibit the same result for the extreme temperature of -65°C, as for the the lower temperatures.

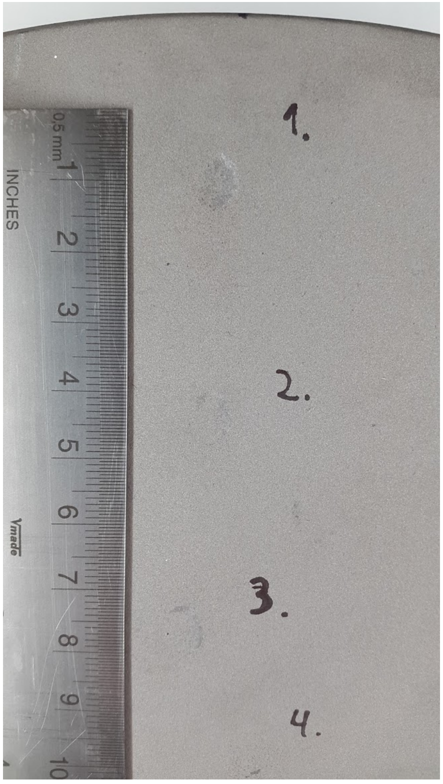


FIGURE 6.16: Coating 2 at RT, 3 impacts

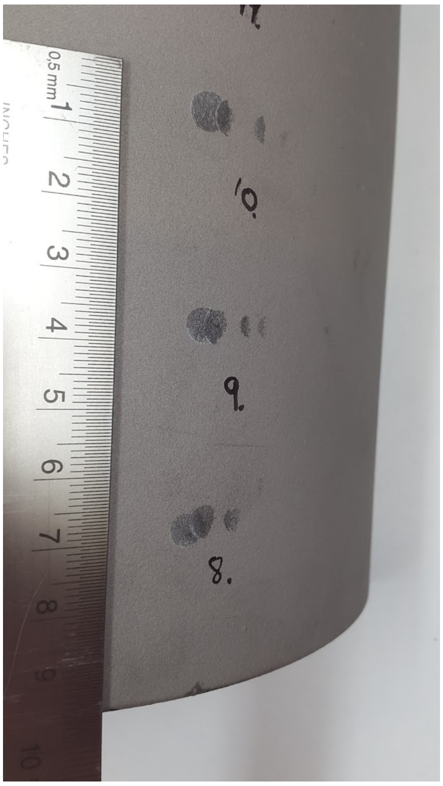


FIGURE 6.17: Coating 2 at RT, 3 impacts

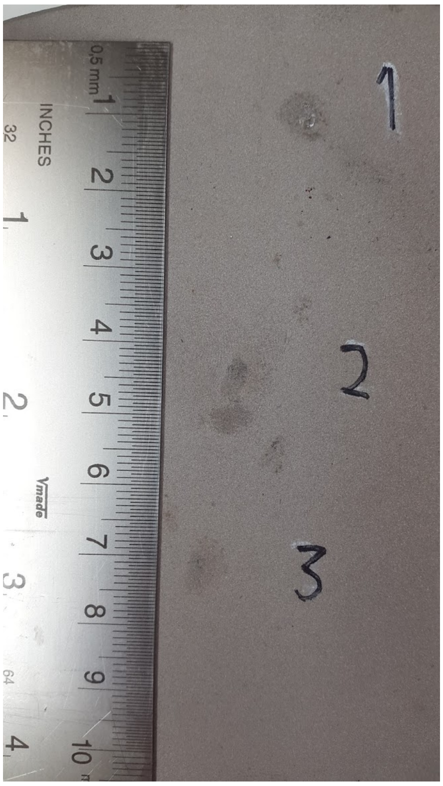


Figure 6.18: Coating 2 at -25°C, 3 impacts

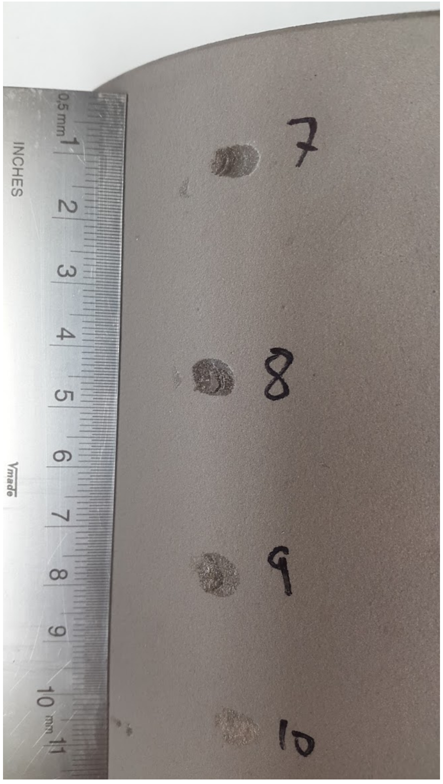


Figure 6.19: Coating 2 at -25°C, 3 impacts

Figure 6.20: Coating 2 at -65°C, 14 impacts

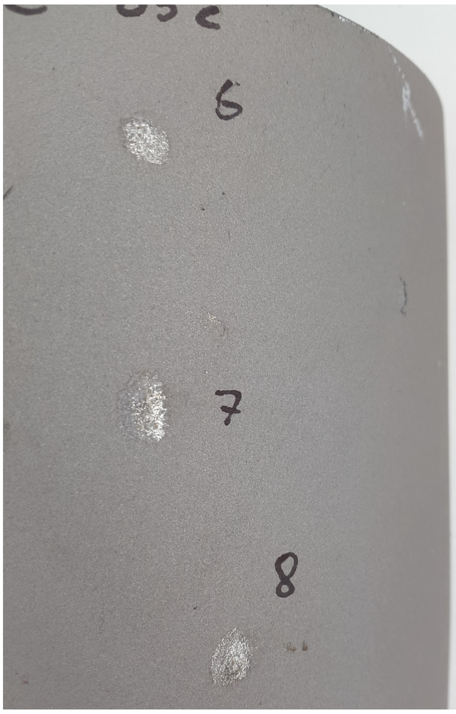


Figure 6.21: Coating 2 at -65°C, 3 impacts

Coating 3

As shown in Figure 6.24 to Figure 6.25 for the impacts at room temperature and -25°C, there are no deformation. The impact zones can be evaluated by visual inspection, as no cracks or deformation were visible. For the samples tested at -65°C a drastic change in the behaviour took place. The impacts of 57J resulted in major cracks and large flakes broke loose. Seven impacts were made on the sample (Figure 6.26), and severe damages occurred in five of the impacts. Impact number 2, 3 and 4 resulted in a large loose flake as shown in Figure 6.29. After cutting off all the loose rubber, the exposed area was 110x70mm. Impact number 1 resulted in an exposed area of 50x30mm.

FIGURE 6.22: Coating 3 at RT, 3 impacts

FIGURE 6.23: Coating 3 at RT, 3 impacts

FIGURE 6.24: Coating 3 at -25°C, 2 impacts

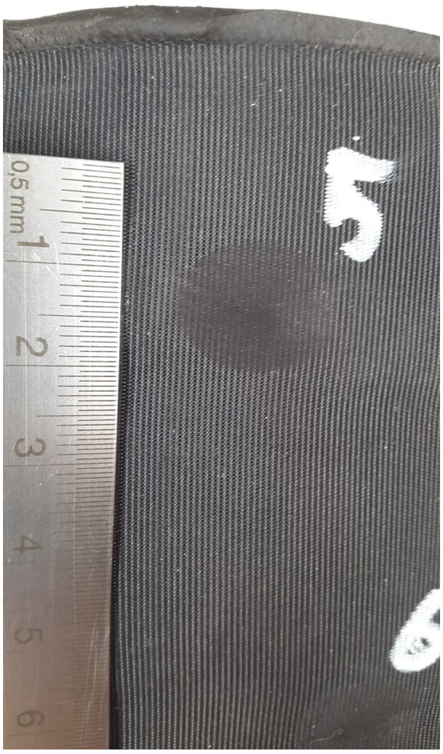


FIGURE 6.25: Coating 3 at -25 °C, 2 impacts

FIGURE 6.26: Coating 3 at -65°C, 7 impacts

FIGURE 6.27: Coating 3 at -65°, impact 2,3,6

Figure 6.28: Coating 3 at -65°C, impact 2,3

Figure 6.29: Coating 3 at -65°, damage

Coating 4

Coating 4 did not suffer from any damages before the temperature was decreased to -65°C. The flat impacts made at RT in Figure 6.30 exhibits no damage. When the samples was impacted on the inclined surface there were scratches on the surface, but no damage in the coating, see Figure 6.31. For the impacts made at -25°C the impact zones were slightly more visible, but no damages in the coating were observed. In Figure 6.34 are the cracks of the sample tested at -65°C, highlighted. The visible cracks are propagating from the impact zone. Of the 13 impacts made, there were visible crack in four of the impact zones. The cracks occurs after the impacts of 57J.

FIGURE 6.30: Coating 4 at RT, flat impact

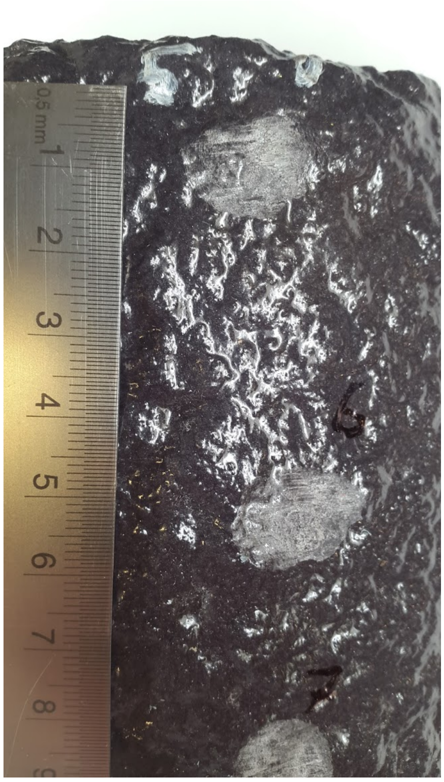


FIGURE 6.31: Coating 4 at RT, incline impact

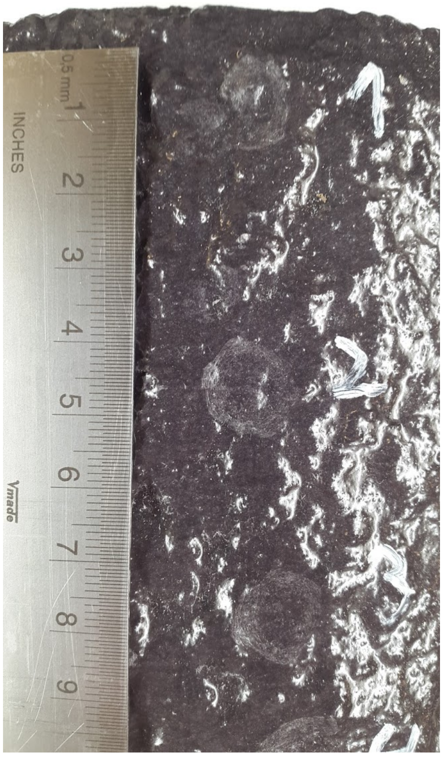


Figure 6.32: Coating 4 at -25°C, flat impact

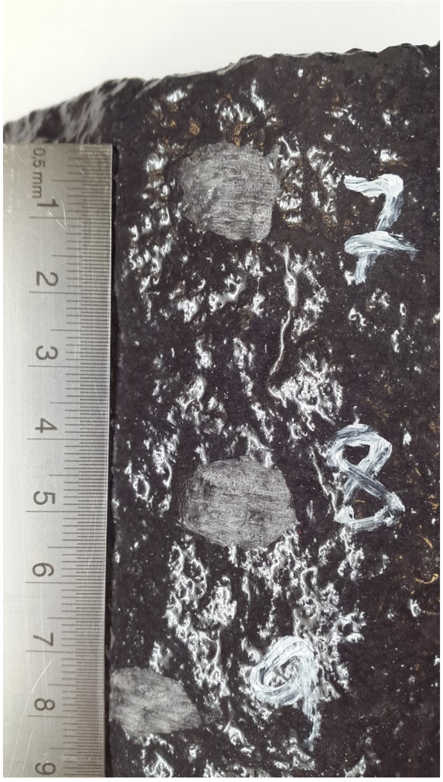


Figure 6.33: Coating 4 at -25°C, incline impact

Figure 6.34: Coating 4 at -65°C, cracks

Figure 6.35: Coating 4 at -65°C, Cracks

TABLE 6.9: Results of impact test for all four coatings

	Flat 90°			**Incline ∼45°**		
	1,0m 28,6J	**1,5m 42,8J**	**2,0m 57,1J**	**1,0m 28,6J**	**1,5m 42,8J**	**2,0m 57,1J**
Coating	**Room Temperature**					
1	∼OK	∼OK	Failed	-	-	Failed
2	∼OK	∼OK	Failed	-	-	Failed
3	OK	OK	OK	OK	OK	OK
4	OK	OK	OK	OK	OK	OK
	-25°C					
1	∼OK	Failed	Failed	-	-	Failed
2	-	-	Failed	-	-	Failed
3	OK	OK	OK	OK	OK	OK
4	OK	OK	OK	OK	OK	OK
	-65°C					
1	-	-	Failed	-	-	Failed
2	-	-	Failed	-	-	Failed
3	-	-	Failed	-	-	Failed
4	-	-	∼OK	-	-	∼OK

6.5.3 Corrosion after impact

As shown in the pictures above of the samples who are impacted at room temperature, the impact zone is visible. The severity of the impact is difficult to evaluate by visual inspection. As described in Subsection 6.5.1, a selection of samples were put in the salt spray chamber, after impact test had been completed. After 480 hours in the chamber, was the samples taken out and investigated. The pictures in this subsection are taken before and after the salt spray test. **Coating 1** shows corrosion in Impact number 3,4,5 and 6 in Figure 6.37. Four other pits are visible on the surface, not impacted. **Coating 2** shows that all six impact zones are filled with corrosion products in Figure 6.39. **Coating 3** and **Coating 4** have not failed after impact. There are no visible corrosion in the impact zones nor the on surface in Figure 6.41 and Figure 6.43.

FIGURE 6.36: Coating 1 before corrosion test

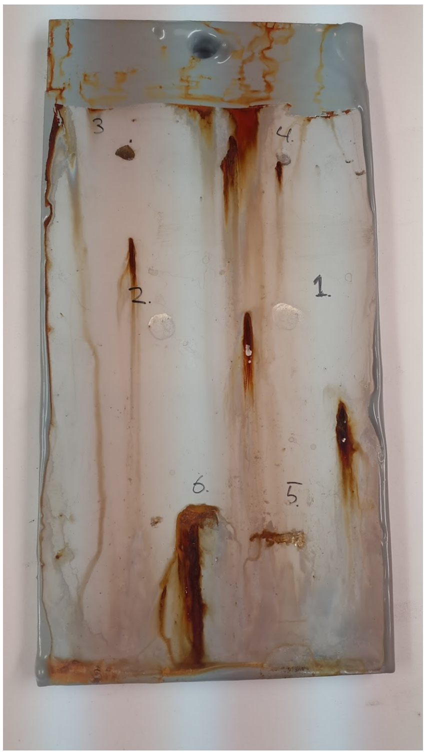


FIGURE 6.37: Coating 1 after corrosion test

FIGURE 6.38: Coating 2 before corrosion test

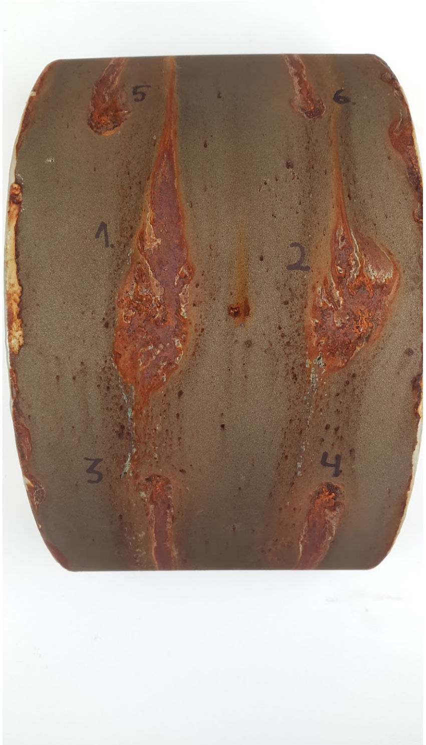


FIGURE 6.39: Coating 2 after corrosion test

FIGURE 6.40: Coating 3 before corrosion test

FIGURE 6.41: Coating 3 after corrosion test

FIGURE 6.42: Coating 4 before corrosion test

FIGURE 6.43: Coating 4 after corrosion test

TABLE 6.10: Results of salt spray after impact

Coating	**Result**	**Comments**
1	Failed	Impact zones and pits
2	Failed	Impact zones
3	Passed	No corrosion
4	Passed	No Corrosion

6.6 Salt spray test

After the salt spray test the samples were removed from the cabinet, washed in running water and dried. Figure 6.44, 6.45 and 6.46 of the samples right after the samples were cleaned. All the test had severe build-up of corrosion products in the aperture in the middle of the sample. Visual inspection of **Coating 1**; Figure 6.44, show that the corrosion of the aperture is extensive. Some corrosion pits are also visible on the surface of the coated part, these are described in the following subsection "Other defects". On **Coating 2**; Figure 6.45, the aperture has even more build-up of corrosion products. No other defects on the surface are visible. **Coating 3**; Figure 6.46, has less build-up of corrosion products in the aperture. There are no other defects on the surface of the coating. **Coating 4** has build-up of corrosion in the aperture, Figure 6.47. There are no other corrosion defects on the surface.

FIGURE 6.44: Coating 1 after 720 hours in the salt spray test

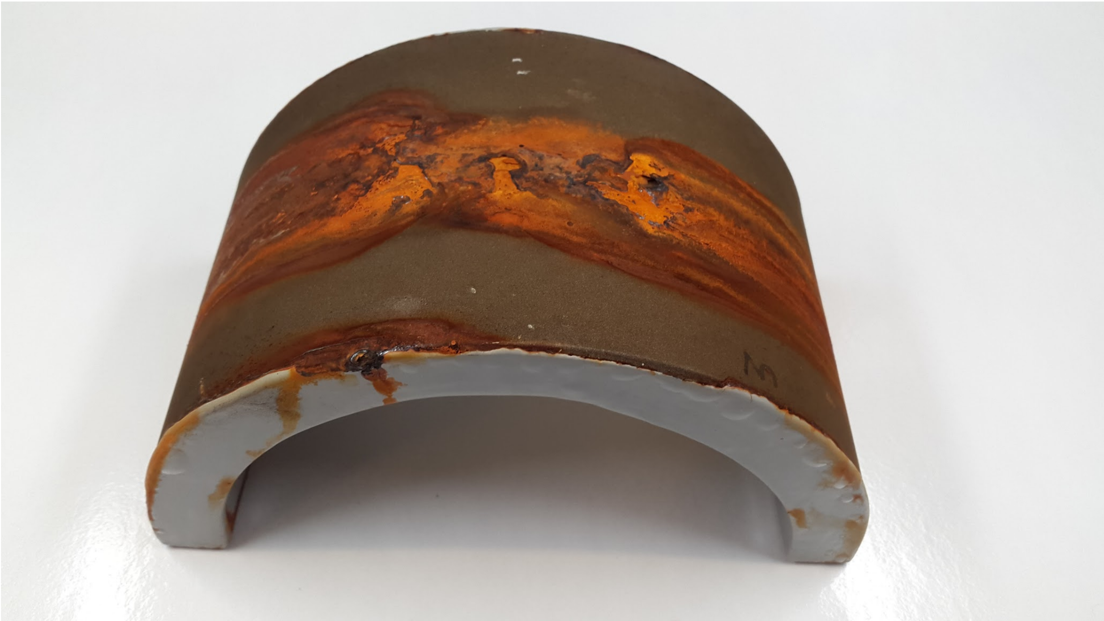


Figure 6.45: Coating 2 after 720 hours in the salt spray test

Figure 6.46: Coating 3 after 720 hours in the salt spray test

FIGURE 6.47: Coating 4 after 720 hours in the salt spray test

After visual inspection, the samples were cut to observe the cross section of the coatings. The cross cut enables inspection of the corrosion on the surface of the aperture. The samples were cut using a wheel cutter. The samples of the cross sections were not prepared any further so the result was not going to be affected by grinding and polishing before it was examined in the microscope. The result of the microscopical inspection of **Coating 1** is presented in Figure 6.48. The coating is visible as free hanging with a cavity of 0,514mm length under. The cavity is formed by corrosion of the steel. The same result is visible in Figure 6.49 of **Coating 2**, but the length of the cavity is 0,385mm. The Figure 6.50 of **Coating 3** is difficult to analyse. The rubber is black and makes it difficult to obtain good pictures of the coating. The length of the cavity under Coating 3 is 0,612mm. In Figure 6.51 of **Coating 4**, there are no visible cavity underneath the coating. The other samples exhibits the same result.

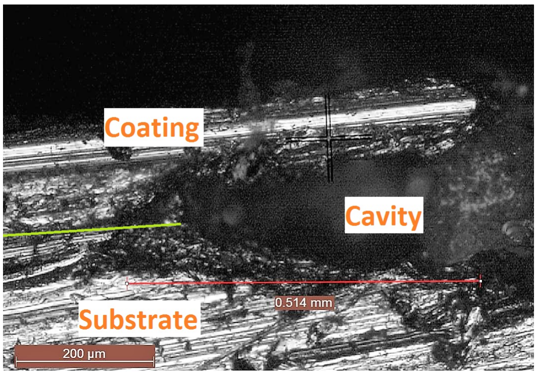


FIGURE 6.48: Coating 1, Corrosion underneath the coating

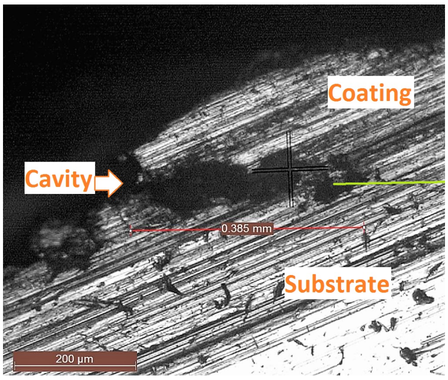


FIGURE 6.49: Coating 2, Corrosion underneath the coating

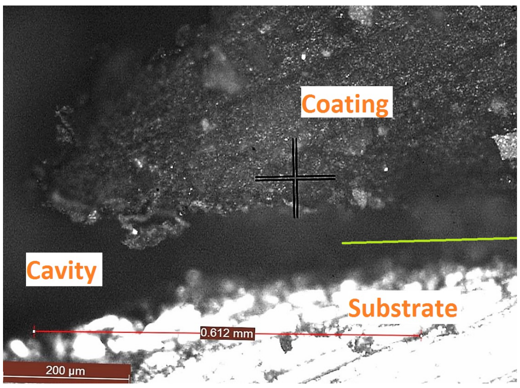


FIGURE 6.50: Coating 3, Corrosion underneath the coating

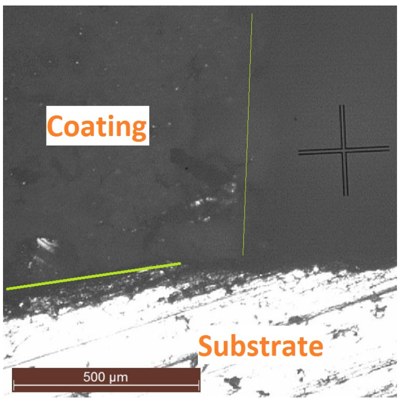


FIGURE 6.51: Coating 4, no corrosion underneath the coating

Other defects

The only coating that shows damages beyond the aperture is Coating 1. The type of defects on this coating are formation of corrosion pits. Three samples of Coating 1 that were tested for 720 h in the salt spray test. After the test, a total number of 8 pits were visible on the samples surface. Figure 6.52 shows the highlighted corrosion pits on sample 3.

FIGURE 6.52: Coating 1 after 720 hours in the salt spray test, with highlighted defects

Chapter 7

Discussion

7.1 Thickness

The thickness of the coatings deviate a lot when they are compared, but the deviation is The thickness of Coating 1, Coating 2 and Coating 3 is measured to be as specified from the suppliers. Coating 4 have a thickness twice as big as specified from the supplier. This was reported to the supplier and they answered that it was caused by an error in the thickness measurement apparatus in the application process.

The microstructure of the coatings are different. Coating 1 have a uniform structure where the Ni matrix is the main element There are particles of SiC visible in the cross section, and black spots. The black spots indicates pores and voids in the coating. The pores are formed in the coating process which is electrochemical deposition.

In the microstructure of Coating 2 there are several features visible; hard phases, soft phases, pores and voids. The pores formed between the substrate and the coating are large. These pores are most likely formed due to the roughness of the grit blasted steel surface. Roughness peaks may provide a shade where the coating do not adhere. In the coating there are several smaller pores, formed by carbides due to bad spraying parameters.

The microstructure of Coating 3 is uniform through the whole thickness. When the rubber is vulcanized the polymer is cross-binding, and the rubber becomes very dense and without pores and voids. When the coating is free of pores it indicates that the vulcanizing process is performed in a good manner.

In the cross section of Coating 4, there are three layers. The microstructure of the top layer and the middle layer, both have a large amount of pores. The middle layer have an uneven thickness and have a wave structure. This is caused by the application process, and it could be a problem with the application parameters. The top surface of the coating have a more even surface topography, but the deviation in the total thickness is still high.

7.2 Hardness

Due to the elastic behaviour of Coating 3 and Coating 4, are Vickers hardness measurements only carried out for Coating 1 and Coating 2. The low hardness and deviation in the results for Coating 1 can indicate that there are not a big amount of SiC particles in the coating. This corresponds good with the microstructure of the coating. A hardness of 750 HV was specified by the supplier. The measurements resulted in a hardness of 238 HV. This indicates that the coating have a much greater amount of Ni, than SiC.

The hardness measurements of Coating 2 was taken in the cross section of the sample. The larger deviation in the measurements can be explained by the difference in hardness of the phases in the coating. The maximum value of 815 HV is taken on the hard phase.

When Vickers hardness measurements were taken on Coating 3 and Coating 4, there were no indents to measure. This is caused by the elastic behaviour of these coatings.

There are no direct requirements to the hardness of the coatings. The hardness has a great influence on the wear properties of the coating, when the wear mechanism is pure abrasion or adhesion with two- or three-body contact. the wear mechanism of the train axle is mainly impacts, and other properties of the coating are important.

7.3 Roughness

The requirements to the roughness of the samples have great importance in the selection of coating. When all the samples were ordered, the requirement of a surface roughness not exceeding Ra=1,6μm, the most important requirement. The roughness was measured to be below the required value. For Coating 1 and Coating 4, the roughness was not changed during the coating process. For Coating 2 and Coating 3 the effect of the grit-blasting as pre-treatment had to be documented. The roughness for Coating 2 and Coating 3 is much higher than the requirement. The grit-blasting of the substrate surface is done to ensure good adhesion between coating and substrate.

7.4 Adhesion

The adhesion test for Coating 1 and Coating 2 showed promising results as none of the rupture areas went through the coating, but at the bonding agent. All the dummies showed the same location of the fracture. The high pressure required to pull-off the dummies and the low deviation in the results, indicate that the ultimate tensile strength of the adhesive was found. Due to the high hardness of Coating 2, problems arose when the isolation of the dummies were made. The cutting tool used to cut around the dummies failed. But this did not seam to affect the results.

Adhesion of Coating 3 was tested by the supplier. Two samples were provided to the supplier. One sample was pre-treated to the supplier specification with grit-blasting and chemical cleaning. The other samples was just pre-treated with chemical cleaning. The object of this was to control if the grit-blasting treatment affected the adhesion of the coating. The test exhibited the same force required to peel of the rubber on the grit-blasted samples and not-grit-blasted. However the location of the failure was different. While the grit-blasted sample exhibited a cohesive failure in the rubber, the not-grit-blasted sample showed adhesive failure between the coating primer and the substrate. Four pull-off tests were made on the same samples. These tests exhibited a lower tensile strength of the not-grit-blasted sample, than the grit-blasted sample. The location of failure occurred in the same areas as the previous test done by the supplier.

Adhesion test of Coating 4 was performed with large dummies. The location of failure on all 16 dummies were located in the epoxy primer at the same depth in the coating. The low force required to pull off the dummies indicate that the primer have weak cohesive bonds in the structure.

There are not any direct requirements to the adhesion of the coatings. As the PDS, in Table 2.5 state; the coating shall have satisfying adhesion to a surface with roughness Ra 1,6μm.

7.5 Resistance to impacts

The impacts were made on samples in different angles, energies and temperature. A large number of tests are conducted at different energies, angles and temperatures. And it can be difficult to figure out what cased the failure or defect of the impact. The failures can be caused by the impact enregy, impact angle, temperature or a combination of these factors.

In Table 6.9 Coating 1 has failed for all the impact tests at all temperatures. The visual inspection of the samples after testing was difficult to evaluate. There were no cracks or detachment of the coating. The impact zones both flat and inclined showed damages. After being subjected to the salt spray test, the samples showed corrosion in some of the impact zones, which means that the coating has been penetrated in the impact zones. The reason for the failure is the thickness of the coating which is significant smaller than the other. When the thickness is small and the hardness of the coating is low, the impact will cause penetration of the coating.

Coating 2 showed the same type of damages as Coating 1. No cracks or detachment of the coating was found during the visual inspection, which means that the toughness of the coating is good. The impacts at all the temperatures exhibits the same damages. From the salt spray test of the impacted sample, a large quantity of corrosion products were visible in the impact zones, which means that the coating had been penetrated in the impacts. Coating 2 have the highest hardness, and the failure can be caused by the low thickness of the coating.

Coating 3 passed all the impact tests at RT and -25°C. At RT the impact zones showed no defects such as cracks, detachments or deformation. At -25°C there were some deformation in the impact zone. After the salt spray test there were no signs of corrosion on the sample, which means that the coating is fully intact after the impacts. The toughness of the coating is high and with higher thickness the impacts could not penetrate the coating. However in the tests conducted at -65°C, there were severe damages in the coating. Cracks, detachments and deformation of the coating were visible. The reason for this is due to the reduction of the coating toughness. When the temperature is lower than the coating lower glass transition temperature, the coating becomes brittle. When the brittle rubber is impacted, it will shatter. An investigation of the surface of the exposed steel after the impact showed that the adhesion primer also failed, and detached with the coating. This shows that when the rubber looses its toughness, it will detach from the substrate, which can be explained by low adhesion to the substrate.

Coating 4 Showed the same results as Coating 3, and passed all the tests at RT and -25°C without any visible damages. In Table 6.9 Coating 4 is rated as ∼OK for the impacts at -65°C. The damages on the coatings are visible but the severity are much lower than in Coating 3. The characteristics of the damages are cracks propagating from the impact zones. The cracks are narrow but quite long. Of the 14 impacts made, there were cracks propagating from three of the impacts.

Other types of damages were visible on the tested sample. The propagation of cracks in the coating can be caused by the reduced toughness when the coating is cooled down to -65°C. The same principle is applicable to Coating 4 as Coating 3, where the coating is changing properties and become brittle at low temperatures. A cross cut section is cut out in the impact zone, and this shows that the top coat has cracked but the epoxy primer is still intact. Due to the elastic properties of the coating, there were no deformation of the coating surface nor the substrate. The reason for the good performance in the impact test can be explained with the high thickness of the coating. After the salt spray test of the impacted sample there were no visible corrosion in the impact zones, and therefore no penetration of the coating.

7.6 Salt spray test

The salt spay test was performed for 720 hours for all four coatings. The aperture in the coating surface of the samples was big, and the exposed steel had an area of 600mm^2. Corrosion of the bare steel in the aperture was expected for all coatings. The visual inspection showed that Coating 1 was the least corrosion resistant. The aperture was filled with corrosion products and there were several corrosion pits on the coating surface. This is due to the microstructural characteristics of the coating, where pores and voids in the coating makes it easier for water and corrosive media to penetrate the coating ans reach the substrate. The thickness have a significant role for the corrosion resistance for Coating 1, where the low thickness makes the path through the coating short, and the transportation of ions easy.

The visual inspection of Coating 2 showed sever build up of corrosion products in the aperture, but no signs of corrosion pits on the coating surface. The thickness and density of coating 2 is higher than Coating 1, and therefore there are no corrosion through the coating surface. The high amount of corrosion products in the aperture is caused by galvanic corrosion between the bare steel and the coating. The coating is composed by noble elements like Ni and Cr which act ass the cathode, while the bare steel act as the offer anode. This effect will cause accelerated corrosion of the bare steel.

Coating 3 and Coating 4 showed excellent performance in the salt spray test. There were a small amount of corrosion products in the aperture and no corrosion on the coating surface. These coatings act as a barrier to the corrosion media.

The investigation of the cross section of the aperture showed no severe corrosion underneath the coating. The largest cavity registered was on Coating 1. It was difficult to obtain good images of Coating 3 and Coating 4. By visual inspection of the cross section is was clear that there were no severe corrosion underneath these coatings either.

7.7 Grade of complexity

Coating 1 is applied by electrochemical process. This method of application is complex and demands equipment that have a high investment cost. The high investment coast can be justified by the low application cost. When the equipment is set up to the right process parameters, it can be performed as a continuous process and the cost of each component is decreasing by the increasing size of the batch. If the coating is damaged, the whole axle has to be recoated with the same process equipment. The grade of complexity is moderate.

Coating 2 is applied with special Thermal spray equipment, which demands a high qualified operator. The process parameters are very important in application of thermal spray coating. The equipment cost is high. If the coating is damaged, the whole axle has to be disassembled and the damage has to be recoated. The grade of complexity is high.

Coating 3 is applied by rolling the rubber lining on pre-treated axles, and then vulcanized in an owen. This method demands special equipment and a skilled operator. If the coating is damaged the, the axle has to be disassembled, stripped of the remaining coating and recoated. The grade of complexity is moderate.

Coating 4 is applied by special spraying process that can handle these types of coating. The process parameters are important in the application, but can easily be controlled. The application method used for coating 4 is similar to the method used for the existing coating solution 2.3. If the coating is damaged, the supplier can provide a reparation kit. The repair can be done on-sight while the axle is mounted. The grade of complexity is low.

7.8 Summary

The summary of the discussion is presented in Table 7.1.

TABLE 7.1: Summary

		Coating			
Test	**Requirement**	**1**	**2**	**3**	**4**
Thickness	~	100 μm	385 μm	3,2 mm	12,0 mm
Hardness	~	238 HV	678 HV	55 Shore	~
Roughness	OK/Not OK	OK	Not OK	Not OK	OK
Adhesion	OK/Not OK	OK	OK	OK	OK
Impact	11,3J	Not OK	Not OK	OK up to 57J @-65°C	OK
Salt Spray	2mm from aperture	OK	OK	OK	OK
Complexity	~	Moderate	High	Moderate	Low

Chapter 8

Conclusion

Coating 4 is the best solution for protection of the axles. There are no modifications of the substrate surface, and the adhesion is good. Coating 4 performs good in the salt spray test. The impact resistance of the coating is excellent. The coating had consistently the best performance throughout the test program, and are therefore the chosen coating system.

8.1 Future work

Coating 4 was delivered with the wrong thickness. This affects the impact resistance and corrosion resistance of the coating. New test specimens should be ordered and the impact resistance and the corrosion resistance should be tested.

Bibliography

[1] Lucchini RS. Presentation of lursak - copy for research purpose of anders opsahl bredesen. .

[2] Roy Johnsen. Protection against corrosion and wear - thorough the use of coating, 2013, Trondheim, Institutt for Produktutvikling og Materialer.

[3] European Standard. En 13261 - railway applications, wheelsets and bogies, axles, product requirements, 2009.

[4] NSB Materialer. Mr. espen ringnes, espen.ringnes@nsb.no, +4790503173.

[5] International Standard. *ISO 12944*. 1998.

[6] INTERNATIONAL STANDARD. Iso 2808 - determination of film thickness, 2007.

[7] INTERNATIONAL STANDARD. En iso 2409, 2007.

[8] INTENATIONAL STANDARD. Iso 4624 pull-off adhesion test, 2003.

[9] International Standard. Iso 9227 - corrosion tests in artificial atmospheres - salt spray tests, 2006.

[10] International Standard. Iso 5948 - railway rolling stock material - ultrasonic acceptance testing, 1994.

[11] AMS International. *Surface Engineering for corrosion and wear resistance*. 2001. ISBN 0-87170-700-4.

[12] V. C. Chandrasekaran. *Rubber as a Construction Material for Corrosion Protection: A Comprehensive Guide for Process Equipment Designers*, book section Chapter 3. 2010. ISBN 9780470625941.

[13] Anders Opsahl Bredesen. *Internal thermal spray coating in pipe.* Project thesis, 2014.

[14] Lucchini RS. Mr. dimitri sala, d.sala@lucchinirs.it, +39035963427, .

[15] Douglas K Louie. *"Elastomeres". Handbook of sulphuric acid manufacturing.* 2005. ISBN 978-0-9738992-0-7.

[16] Trelleborg Offshore AS. Mr. svein gabrielsen, svein.gabrielsen@trelleborg.com, +4732232115, .

[17] Aquamarine AS. Mr. roy liltvedt, rli@aquamarine.no, +4795196567, .

[18] A. Lanzutti S. Benoni P. Caoduro L. Fedrizzi M. Lekka, P.L. Bonora. Industrialization of ni-microsic electrodeposition on copper moulds for steel continious casting. *La Metallurgia Italiana*, 6, 2012.

[19] Benoni S.N.C. Mr. stefano benoni, beoni@benoni.it, +390303760266.

[20] Mitutoyo. Jis b 0601, geometric product specification (gps) - surface texture: profile method, 2001.

[21] ASTM. Astm b177 salt spray (fog), 2009.

[22] International Standard. Iso 6272 - rapid deformation (impact resistance) test, 2011.

[23] International Standard. Iso 813 (festetest), 2010.

Appendix A

Material Data Sheet - Trelleborg

Material Data Sheet
Date: 17.11.2014 Version no.: 7
Last edition date: 15.01.2010
Sign.:

TRELLEBORG

Compound 73181

Application: Bellows. Weather protection

Typical Material Properties*

Property	Typical value	Specification	Unit	Test standard
Hardness	55	-4/+3	°shore A	ISO 7619-1
Density	1,31	-0,01/+0,03	g/cm^3	ISO 2781
Tensile strength	19	min.13	N/mm^2	ISO 37
Elongation at break	650	min.500	%	ISO 37
Modulus 100%	1,7	min.1,4	N/mm^2	ISO 37
Modulus 300%	6,5	min.4,5	N/mm^2	ISO 37
Tear strength, Crescent	40	min.25	N/mm	ISO 34-1
Compression set, 24h 70°C		max.30	%	ISO 815-1

*Tests are performed on moulded samples prepared in laboratory. All samples are prepared according to ISO 23529:2010 Rubber – General procedure for preparing and conditioning test pieces for physical test methods.

As buildt properties tested on samples prepared from final products might have an increased variation

Other Material Properties

Property	Typical value	Unit	Test standard
Abrasion resistance	170	mm^3	ISO 4649
Volume resistivity	10^{10}	Ωcm	ISO 1853

Storage Stability

If kept at a temperature of 4-7°C this material has a shelf life of minimum 3 months.

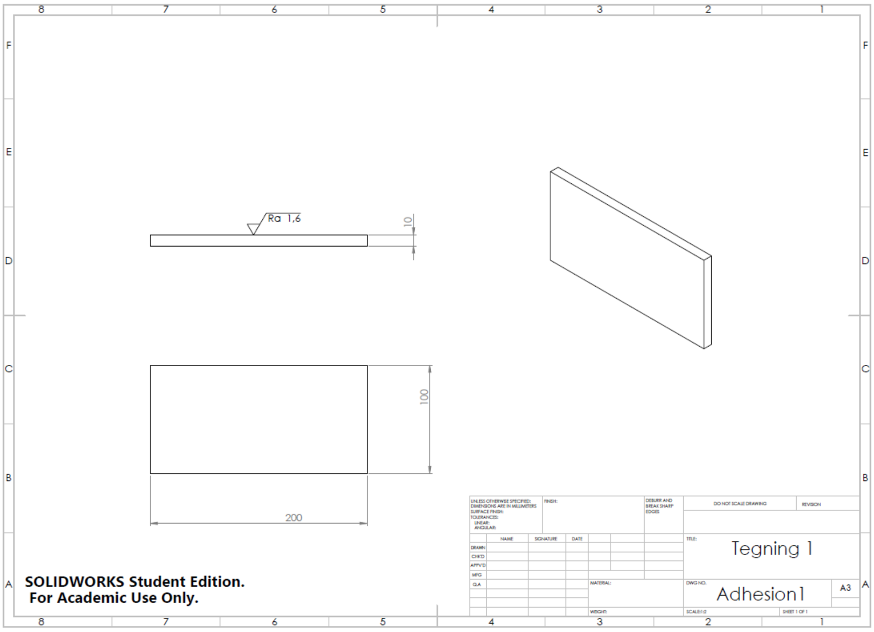
Material Safety

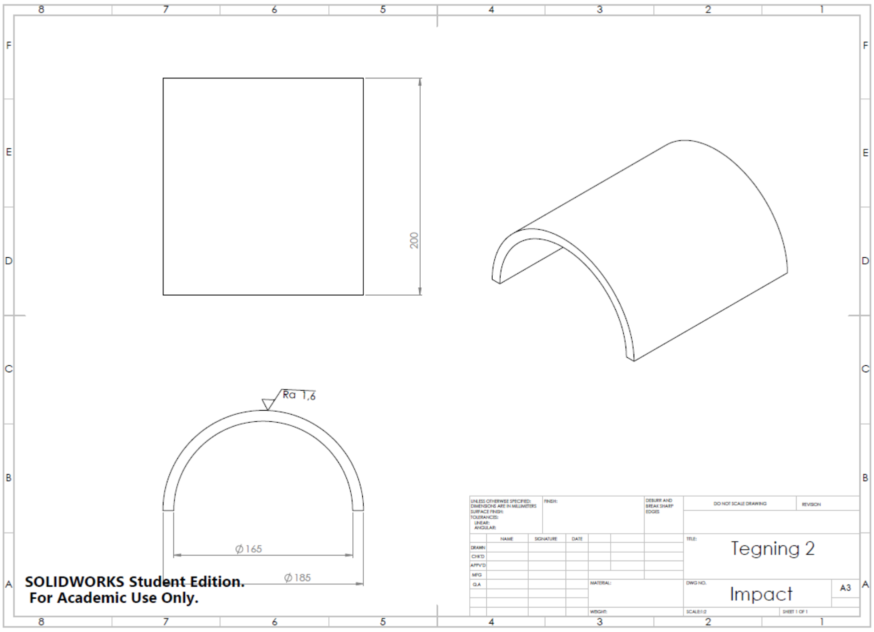
Relevant safety data and necessary warning labels are to be found in the material safety data sheet

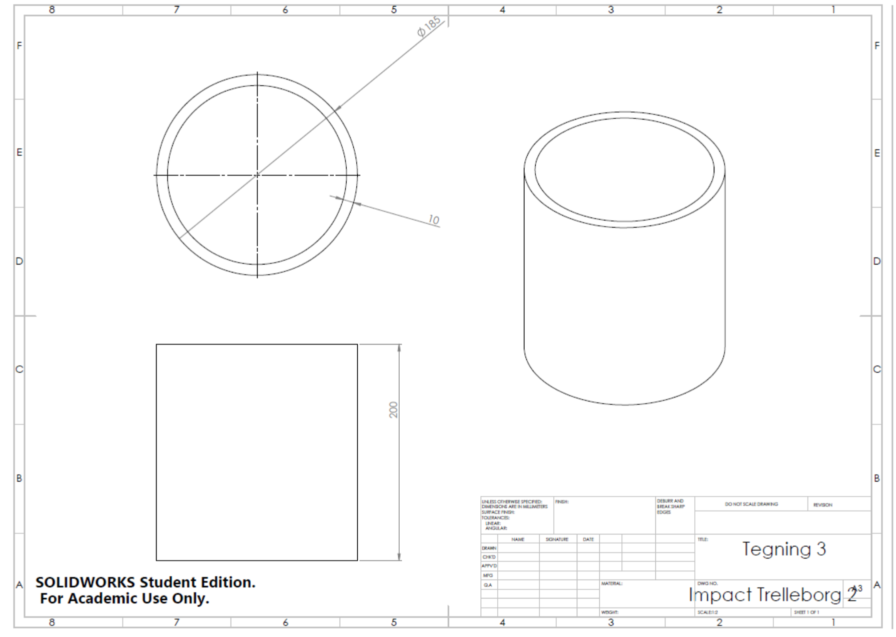
Trelleborg Offshore Norway AS
P.O Box A, N-3051 Mjøndalen, Norway, Visiting address: Kalosjegaten 15, NO-3051 Krokstadelva, Norway
Phone: +47 32 23 21 00. Fax: +47 32 23 22 00. Internet: www.trelleborg.com/offshore/no. E-mail: offshore.norway@trelleborg.com.
Registered No: NO 941 730 566 VAT

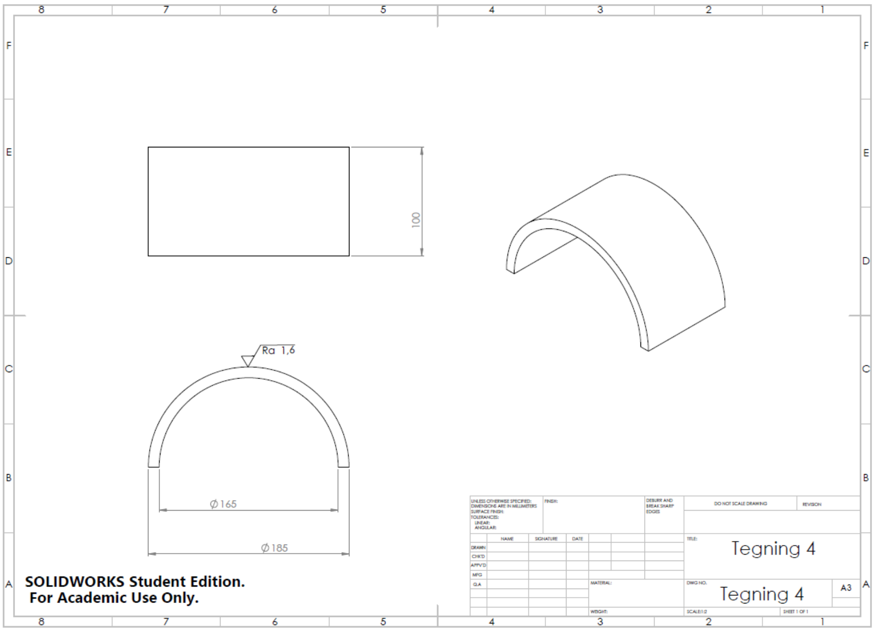
Appendix B

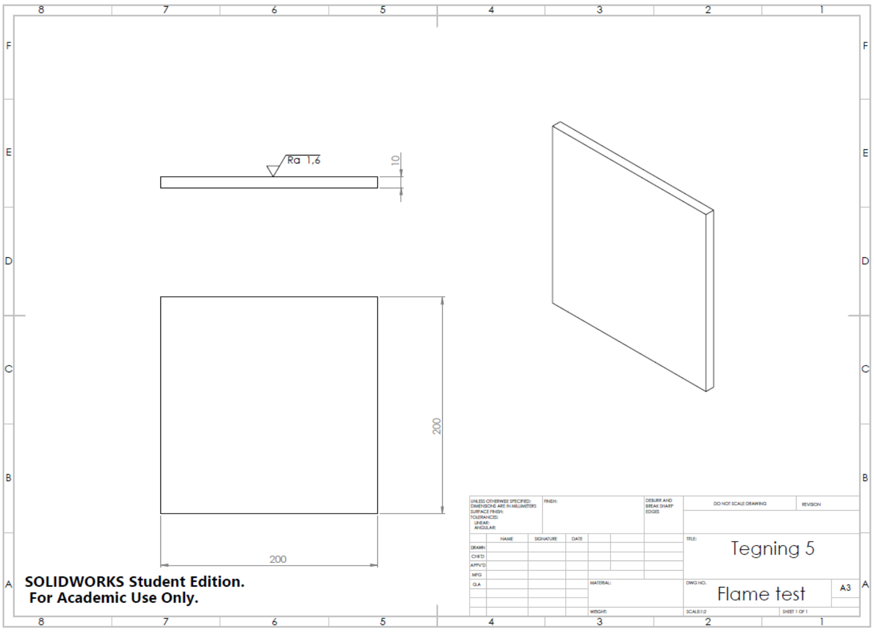
Samples for testing - Drawing

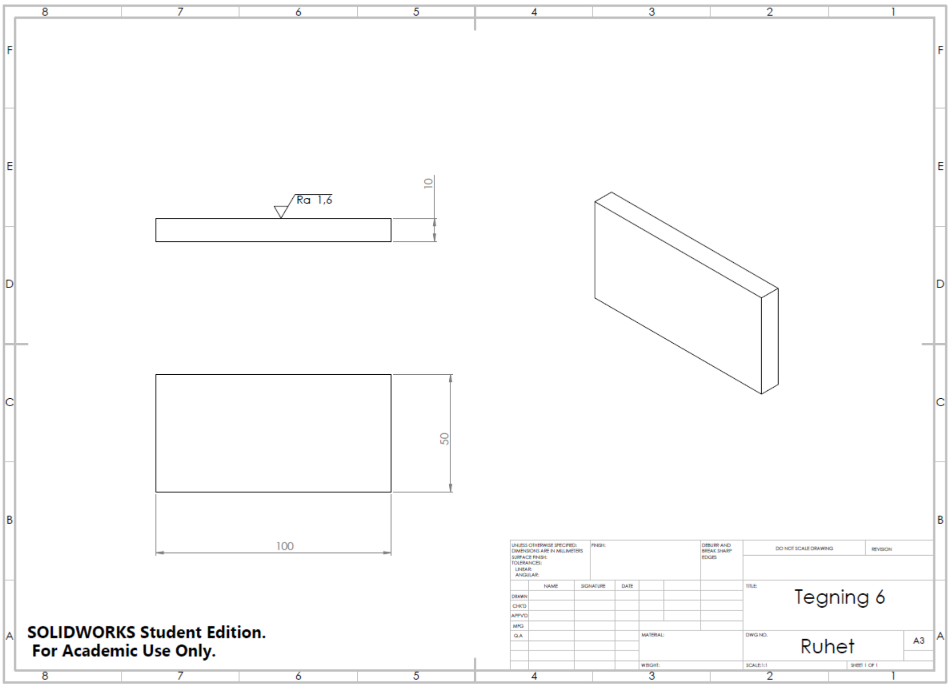



200
Ra 1,6
Ø 165
Ø 185
Tegning 2
Impact
A3
SOLIDWORKS Student Edition.
For Academic Use Only.


Ø 185
10
200
Tegning 3
Impact Trelleborg 2
A3
SOLIDWORKS Student Edition.
For Academic Use Only.

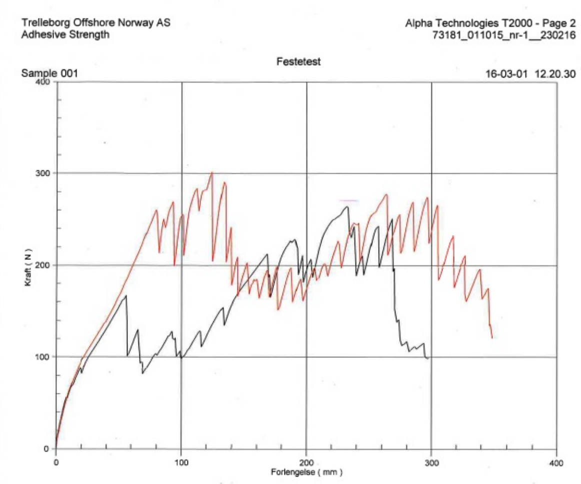

100
Ra 1,6
Ø 165
Ø 185
Tegning 4
Tegning 4
A3
SOLIDWORKS Student Edition.
For Academic Use Only.

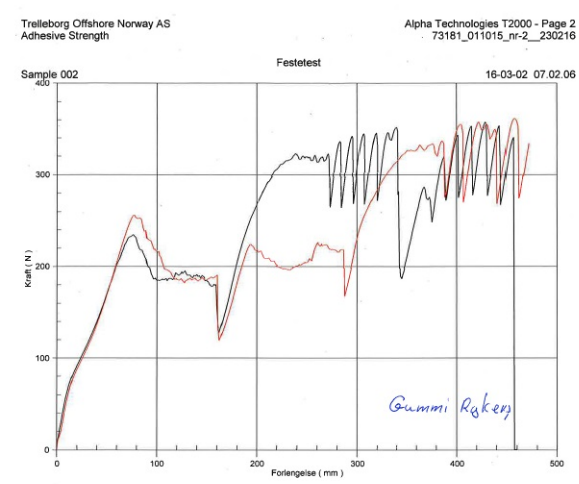

Ra 1,6
10
200
200
Tegning 5
Flame test
A3
SOLIDWORKS Student Edition.
For Academic Use Only.


Ra 1,6
10
50
100
Tegning 6
Ruhet
A3
SOLIDWORKS Student Edition.
For Academic Use Only.

Appendix C

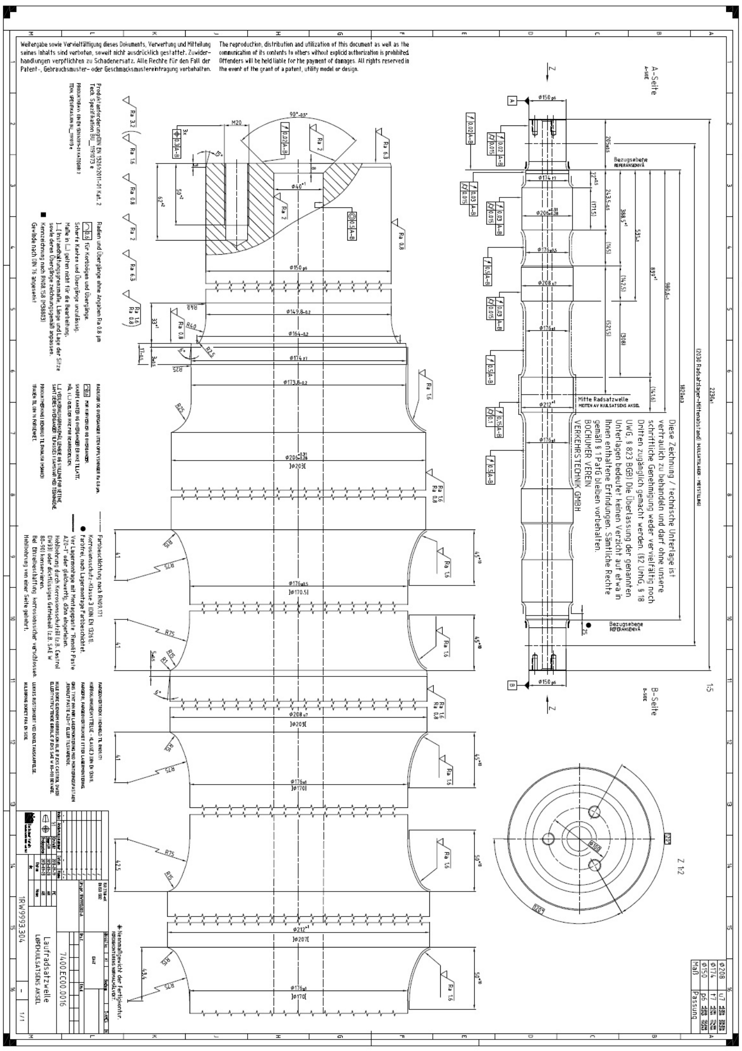
Adhesion Test Data - Coating 3





Appendix D

Technical drawing of axle



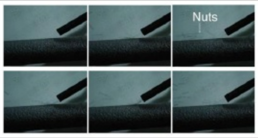
Appendix E

Test Data Lursak

LURSAK®- Test campaign

Official tests for Certification as protective coating Class 1 – EN 13261

LUCCHINI RS GROUP

Test	Requirements of Class 1 protective coating EN 13261	Test procedure	LURSAK® Results	Picture
Coating thickness	-		4.58 ÷ 4.99 mm (between 4.0 ÷ 8.0 mm according to [2])	
Coating adhesion	-	EN 13261 & EN ISO 4624	6.0 ÷ 11.5 MPa (higher than 2.0 MPa according to [2])	
Impact test @ R.T.	No hole in the coating, nor any alteration to the test piece surface	EN 13261	Requirement satisfied	
Impact test @ -25°C				
Gritting test	≤ Level 3	EN 13261	Requirement satisfied	
Resistance to salt Spray	No corrosion under the coating, nor any corrosion present at a distance of more than 2 mm from the edges or from the incisions in the coating	EN 13261 & ISO 9227 (1000 hours)	Requirement satisfied	
Coating resistance to cyclic mechanical stresses	Level 5	EN 13261	Requirement satisfied	

Thursday, June 04, 2015 7

LURSAK® - Test campaign

Internal tests at Lucchini RS Research & Development laboratories

Test	Requirements	Test procedure	LURSAK® Results	Picture
Impact test @ -40°C	No hole in the coating, nor any alteration to the test piece surface	EN 13261 @ lower Temperature	Requirement satisfied	
Impact test @ +150°C		EN 13261 @ higher Temperature		
Impact test @ -25°C		EN 13261 with higher impact energy (20 J)		
Impact test @ R.T.°C				
Thermal test – Ageing	No defect after test	Lucchini RS Internal procedure	Requirement satisfied	
Impact test @ R.T. after ageing	No hole in the coating, nor any alteration to the test piece surface	EN 13261	Requirement satisfied	
Braking tests on full-scale painted wheelset using BU300 test rig	No defect/detachment of LURSAK® during and after tests	Simulation of real high-speed track	Requirement satisfied	
		Braking stop from 150, 220 and 300 km/h	Requirement satisfied	
Fatigue test on full-scale painted axle	No defect/detachment of LURSAK® during and after fatigue test	Application of 180MPa for 10^7 cycles	Requirement satisfied	

LURSAK® - Test campaign

Official tests at Deutsche Bahn laboratories

Test	Requirements	Test procedure	LURSAK® Results	Picture
Coating thickness	-	Technical Instruction Deutsche Bahn	5.5 ÷ 7.0 mm (between 4.0 ÷ 8.0 mm according to [2])	
Impact test @ R.T., angle of impact 90°	No hole in the coating, nor any alteration to the test piece surface	EN 13261	Requirement satisfied	
Impact test @ -25°C, angle of impact 90°				
Gritting test @ R.T., angle of impact 45°	≤ Level 3	EN 13261	Requirement satisfied	
Flame test	DIN 5510-2	DIN 54873	Class of: . Fire resistance: S4 . Smoke emission: SR 2 . Drops production: ST 2 Requirement satisfied	
		EN ISO 5659-2		
Suitability to Ultrasonic Test by bore probe	Internal document Deuscthe Bahn	Technical Instruction Deutsche Bahn	Suitable	
Impact test @ R.T. & @-25°C, angle of impact 45°	No hole in the coating, nor any alteration to the test piece surface	EN 13261 & Technical Instruction Deutsche Bahn	Requirement satisfied	
Gritting test @ R.T. & @-25°C, angle of impact 90°	≤ Level 3	EN 13261 & Technical Instruction Deutsche Bahn	Requirement satisfied	
Gritting test @ -25°C, angle of impact 45°				
Resistance to corrosion	Sub-superficial rust lower than 2.0 mm (BN 918300)	Technical Instruction Deutsche Bahn	1.6 mm Requirement satisfied	

Thursday, June 04, 2015 9

LURSAK® - Test campaign

Official tests at CSI SpA laboratories

Test	Requirements	Test procedure	LURSAK®Results
Flame Test & Smoke emission	Hazard Level HL2, requirement R8	CEN/TS 45545-2:2009	MARHE: 74.28 kWm^{-2} (Maximum Average Heat Emission) D_s max :255 (Smoke density) CIT_G: 0.18

LURSAK® - Test campaign

Tests at "AkzoNobel Aerospace Coatings – division of International Paint Italia" laboratories

Test	Requirements	Test procedure	LURSAK®Results
Chemical resistance to de-icing agents	Compatibility of the coating to de-icing chemicals as heavy glycols	ASTM F 502-02	Hardness of the coating before exposure: 2B Hardness of the coating after exposure: 2B Defects after exposure: . No blister . No softening . No whitening . No other visible defects

Appendix F

Risk Assessment

NTNU HMS	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: **IPM** **Dato: 02.12.2015**

Linjeleder: Roy Johnsen

Deltakere ved kartleggingen (m/ funksjon): **Anders Bredesen, student**

(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Kort beskrivelse av hovedaktivitet/hovedprosess: Masteroppgave Anders Bredesen. Korrosjon og slitasjebeskyttelse for NSB.

Er oppgaven rent teoretisk? (JA/NEI): **Nei** *«JA» betyr at veileder innestår for at oppgaven ikke inneholder noen aktiviteter som krever risikovurdering. Dersom «JA»: Beskriv kort aktiviteteten i kartleggingskjemaet under. Risikovurdering trenger ikke å fylles ut.*

Signaturer: *Ansvarlig veileder:* *Student:*

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Ruhetsmåling	Anders	Interne prosedyrer for labarbeid på NTNU	Verneutstyr, Godkjent utstyr		
2	Slagtest	Anders	Interne prosedyrer for labarbeid på NTNU	Verneutstyr, Godkjent utstyr		
3	Adhesjonstest	Anders	Interne prosedyrer for labarbeid på NTNU	Verneutstyr, Godkjent utstyr		
4	Steinspruttest	Anders	Interne prosedyrer for labarbeid på NTNU	Verneutstyr, Godkjent utstyr		
5	Saltspray test	Anders	Interne prosedyrer for labarbeid på NTNU	Verneutstyr, Godkjent utstyr		
6	Tykkelsemåling	Anders	Interne prosedyrer for labarbeid på NTNU	Verneutstyr, Godkjent utstyr		

NTNU HMS	Risikovurdering	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: IPM **Dato: 02.12.2015**

Linjeleder: Roy Johnsen

Deltakere ved kartleggingen (m/ funksjon): Anders Bredesen

(Ansv. Veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Risikovurderingen gjelder hovedaktivitet: Masteroppgave Anders Bredesen. Korrosjon og slitasjebeskyttelse for NSB.

Signaturer: *Ansvarlig veileder:* *Student:*

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet	Vurdering av konsekvens:				Risiko-Verdi	Kommentarer/status Forslag til tiltak
			(1-5)	Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)		
1a	Ruhetsmåling	Skade på utstyr	2			B		B2	Utføre arbeid etter instruks
2a	Slagtest	Skade på finger/hender, klemsituasjon	3	B			B	B3	Sikre prosjektil og prøveemne før test
2b	Slagtest	Øyeskader	2	B			B	B2	Bruke vernebriller, sikker avstand
3a	Adhesjonstest	Skade på utstyr	1			B		B1	Utføre arbeid etter instruks
4a	Steinspruttest	Skade på hender/fingre	2	B			B	B2	Sikre muttre og prøveemne før testing
4b	Steinspruttest	Øyeskader	2	B			B	B2	Bruke vernebriller

NTNU HMS	Risikovurdering	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

5a	Saltspraytest	Skade på utstyr	2			C		C2	Utføre arbeid etter instruks
6a	Tykkelsesmåling	Skade på utstyr	1			B		B1	Utføre arbeid etter instruks

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E Svært Alvorlig	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans > 1 år.	Troverdighet og respekt betydelig og varig svekket
D Alvorlig	Alvorlig personskade. Mulig uførhet.	Langvarig skade. Lang restitusjonstid	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket
C Moderat	Alvorlig personskade.	Mindre skade og lang restitusjonstid	Drifts- eller aktivitetsstans < 1 mnd	Troverdighet og respekt svekket
B Liten	Skade som krever medisinsk behandling	Mindre skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1 uke	Negativ påvirkning på troverdighet og respekt
A Svært liten	Skade som krever førstehjelp	Ubetydelig skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1 dag	Liten påvirkning på troverdighet og respekt

NTNU	Risikomatrise	utarbeidet av	Nummer	Dato
HMS/KS		HMS-avd.	HMSRV2604	08.03.2010
		godkjent av		Erstatter
		Rektor		09.02.2010

MATRISE FOR RISIKOVURDERINGER ved NTNU

KONSEKVENS						
	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært stor
		SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge	Beskrivelse
Rød	Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul	Vurderingsområde. Tiltak skal vurderes.
Grønn	Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.