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Using the Hybrid Metal Extrusion & Bonding (HYB) Process for Butt Welding of 4 mm Plates of AA6082-T6

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Abstract. Hybrid Metal Extrusion & Bonding is a new solid state joining technique developed for aluminium alloys. By the use of filler material addition and plastic deformation sound joints can be produced at operational temperatures below 400 ℃. This makes the HYB process more flexible and less vulnerable to defects compared to conventional solid state processes. Here, we present the results form an exploratory investigation of the mechanical integrity of a 4 mm AA6082-T6 HYB joint, covering both hardness, tensile and Charpy V-notch testing of different weld zones. The joint is found to be free from internal defects like pores, cavities and kissing bonds. Still, a soft heat affected zone (HAZ) is present. The joint yield strength is 54 % of the base material, while the corresponding joint efficiency is 66%. Therefore, there is a potential for further optimization of the HYB process. This work is now in progress.

1 Introduction

The unique physical and mechanical properties of aluminium alloys, as the Al-Mg-Si alloys, makes them attractive for a wide range of structural applications and welded assemblies [1]. In particular, there is an increased use of aluminium alloys within the automotive industry as a result of the growing demand for more fuel efficient and lightweight vehicles. In fact, a full aluminium car body design permits weight savings up to 30-40% [2]. However, within the automotive industry welding is often required as part of the fabrication process. Even though the Al-Mg-Si alloys are readily weldable, a variety of weld defects may occur. For instance, the excessive heat generation associated with the traditional welding processes makes them vulnerable to heat affected zone (HAZ) softening due to the reversion of the hardening precipitates which form during artificial ageing [3]. Moreover, the material melting occurring during fusion welding makes the weld susceptible to pore formation, hot and liquation cracking as well as bond defects causing additional degradation of the joint [1, 4]. Therefore, solid state joining offers several advantages compared to traditional fusion welding when it comes to structural and mechanical integrity of the weldments.

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Over the years a variety of solid state joining processes have been developed, where friction stir welding (FSW) is among the more recent ones. Since its entry in 1991 the FSW process has continuously evolved due to systematic research and development, including parameter optimization and new tool design. This has brought FSW to the forefront of aluminium welding technology [5, 6]. Although FSW is approaching its ultimate technology maturity level, the frictional heat generated through the process is still large enough to cause HAZ softening. In addition, strict base plate and profile tolerances are required, as lack of filler material addition may result in insufficient material feeding and consequently undercuts and internal defects in the joint [7, 8]. These fundamental limitations need to be overcome in the future by new process developments.

Despite its recent introduction, the Hybrid Metal Extrusion & Bonding (HYB) process is deemed to have a great potential. By the use of filler material addition and plastic deformation sound joints can be produced in solid state employing this technique [9-11]. At the same time, the filler material addition makes the process more flexible and less vulnerable to undercuts and weld defects compared to other solid state joining processes. In order to illuminate the potential of the process, a more extensive analysis of the HYB joint mechanical performance will be conducted. This will be done by characterizing a 4 mm AA6082-T6 butt weld based on transverse hardness measurements, tensile testing and Charpy V-notch testing of different regions across the weld zone. The results will then be compared with corresponding test data reported in the scientific literature for gas metal arc (GMA) and FS welds.

2 CURRENT STATUS OF THE HYB TECHNOLOGY

The HYB PinPoint extruder is based on the principles of continuous extrusion [12]. The current version of the extruder is built around a 10 mm diameter rotating pin, provided with an extrusion head with a set of moving dies through which the aluminium is allowed to flow. This is shown by the drawing in Fig. 1A. When the pin is rotating, the inner extrusion chamber with three moving walls will drag the filler wire into and through the extruder due to the imposed friction grip. At the same time the wire is kept in place inside the chamber by the stationary housing constituting the fourth wall. The aluminium is then forced to flow against the abutment blocking the extrusion chamber and subsequently, owing to the pressure build-up, continuously extruded through the moving dies in the extruder head.

In a real joining situation, the extruder head is clamped against the two aluminium plates to be welded. The plates are separated from each other so that an I-groove is formed. The pin diameter is slightly larger than the groove width to ensure contact between the side walls of the groove and the pin. This is illustrated in Fig. 1B. Analogue to that in FSW, the side of the joint where the tool rotation is the same as the welding direction is referred to as the advancing side (AS), whereas the opposite one is referred to as the retreating side (RS). During pin rotation, some of the base material along with the oxide layer on the groove sidewalls will be dragged around by the motion of the pin. Hence, the surface oxide tends to mix with the filler material as it flows downward into the groove and consolidates behind the pin. The base and filler materials flow during processing are schematically illustrated in Fig. 1B. Typically, the temperature in the grove between the two base plates to be joined is between 350 and 400 °C.

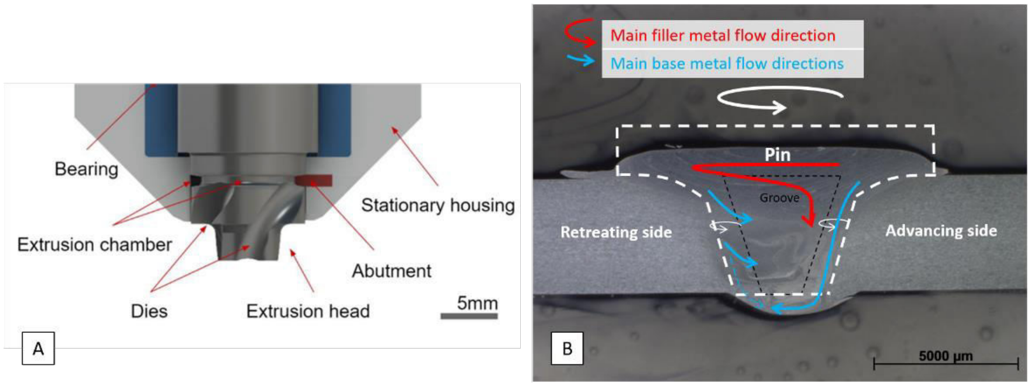

Fig. 1. (A) Schematic overview of the main components of the HYB PinPoint extruder [13]. (B) Cross sectional view of a HYB butt joint. Included is also a schematic illustration of the material flow pattern during joining.

3 Experimental

3.1 Materials and Welding Conditions

In the present welding trial, 4 mm rolled plates of aluminium alloy 6082-T6 were used as base material. The plates were bought from an external supplier. The filler material was a Ø1.2 mm wire of the AA6082-T4 type produced by HyBond AS. The wire was made from a DC cast billet, which then was homogenized, hot extruded, cold drawn and shaved down to the final shape. The chemical composition of both the base material (BM) and filler material (FM) can be found in Table 1. HYB single-pass butt welding was conducted by HyBond AS, using an I-grove with 3 mm root opening and the following welding parameters: pin rotation of 400 RPM, travel speed of 6 mm/s and a wire feed rate of 142 mm/s. This corresponds to a gross heat input of 0.34 kJ/mm.

Table 1. Chemical composition (wt.%) of the aluminium base and filler materials (BM and FM).

	Si	Mg	Cu	Fe	Mn	Cr	Zn	Ti	Zr	B	Other	Al
BM	0.9	0,80	0,06	0,45	0,42	0,02	0,05	0,02	-	-	0,03	Balance
FM	1.11	0,61	0,002	0,20	0,51	0,14	-	0,043	0,006	0,13	0,029	Balance

3.2 Mechanical testing

Transverse samples were cut from the HYB welded plates. Specimens used for tensile testing and Charpy V-notch (CVN) testing were located in different regions relative to the weld center-line, and subsequently flush-machined to remove contribution from the weld reinforcement. Details of specimen location and number of specimens tested can be found in Fig. 2 and Table 2, respectively. The subsize tensile specimens were prepared in accordance with ASTM standard E8/E8M-16a. The specimen thickness was 4 mm (corresponding to the plate thickness). Tensile testing was carried out at room temperature using an Instron hydraulic test machine (50 kN load cell) with a fixed cross-head speed of 1.5 mm/min. The applied gauge length was 25 mm. Similarly, the subsize CVN specimens were prepared in accordance with ASTM standard E23-12c (type A). The thickness of the specimens was 4 mm (corresponding to the plate thickness).

CVN testing was carried out at room temperature, using a Zwick impact test machine with a total impact energy absorption capacity of 450 J.

The specimens used for the microstructural analysis and hardness testing were prepared according to standard sample preparation procedures. To reveal the micro- and macro structure of the joint, the specimen was immersed in an alkaline sodium hydroxide solution (1g NaOH + 100 ml H_2O) for 3 to 4 min. The macro- and microstructure of the weld were analysed using a Leica DMLB light microscope and an Alicona Confocal Microscope. Transverse Vickers hardness measurements were performed both along the horizontal and vertical mid-sections of the joint (Fig. 2), using a Mitutoyo Micro (HM-200) Vickers hardness test machine and a constant load of 1 kg. The distance between each hardness indentation was 0.45 mm. In total, three test series were carried out for each of the two mid-sections. The base material hardness was established from ten individual hardness measurements being randomly taken on one separate base material specimen. Finally, selected fracture surfaces of the broken tensile specimens and CVN specimens were examined in a Quanta FEG 450 scanning electron microscope (SEM).

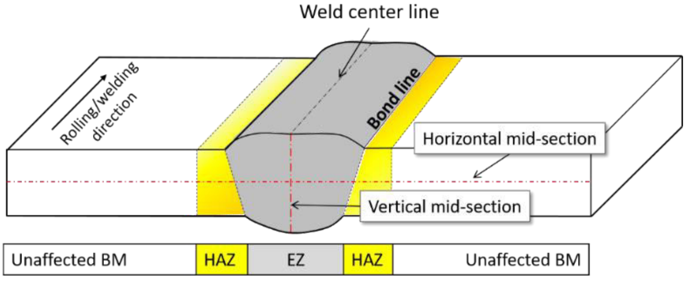

Fig. 2. Schematic illustration of different weld zones in the HYB butt joint. Included are also the welding and plate rolling directions. EZ: Extrusion zone (consists of a mix of FM and BM), HAZ: Heat affected zone, BM: base material.

Table 2. Number of specimens tested and their location.

	Base material	**HAZ**	**Bond line**	**Extrusion zone**	**Total**
Tensile	4	3	-	3	10
CVN	3	3	3	3	12

4 Results

4.1 Weld Macrostructure and Hardness Profile

The measured hardness profile along the horizontal mid-section of the HYB joint is presented graphically in Fig. 3A. Moreover, Fig. 3B shows an overview of different weld zones, from which the FM and the BM flow patterns in the groove also can be seen. Note that each hardness point represents the arithmetic mean of three individual measurements. The horizontal dotted line in Fig. 3A represents the hardness of the unaffected base material, measured to be 111 HV with a standard deviation of 2.2. The minimum hardness is found on the advancing side of the joint, yielding a value of 66 HV approximately 3 mm from the weld center-line. The total width of the HAZ is estimated to be 25 mm. The hardness measurements along the vertical mid-section of the joint revealed that the hardness was highest in the top region, where it reached a value of 93 HV. The hardness then dropped monotonically with increasing depths below the plate surface, finally approaching it lowest value of 51 HV at the weld toe.

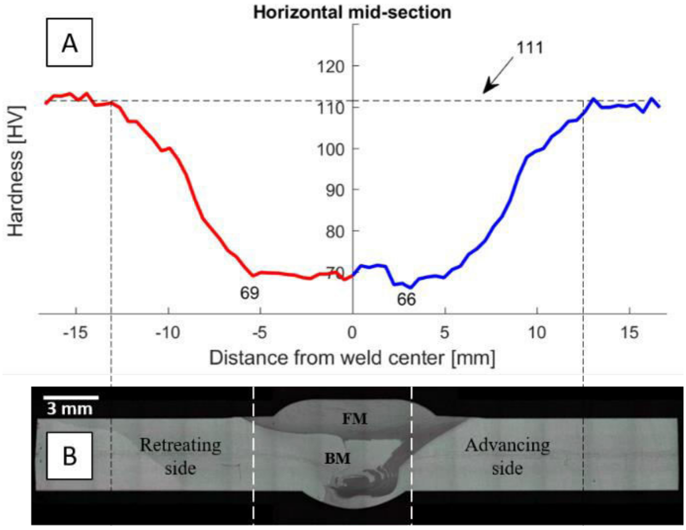

Fig. 3. (A) Measured hardness profile along the horizontal mid-section of the HYB joint. The graph represents the mean value of three individual measurements. (B) Optical micrograph showing the macrostructure of the HYB joint in the transverse direction.

4.2 Tensile Properties

The measures tensile properties of the HYB joint are graphically presented in Fig. 4. It is evident that welded specimens (EZ and HAZ) have significantly lower tensile properties compared to those of the base material. However, there is apparently no difference between the EZ and the HAZ. The weld yield strength, as indicated by the bars to the right in Fig. 4A, amounts to 54 % of the BM yield strength, while the corresponding joint efficiency (i.e. $\sigma_{UTS,HAZ}/\sigma_{UTS,BM}$ ratio) is higher and reaches a value of 66 %. The elongation at fracture of the different weld zones is presented in Fig. 4B. Owing to the necking effect caused by the HAZ softening the measured elongation of the welded specimens is seen to be significantly lower than that of the base material. Another consequence of the HAZ is also that fracture always occurs on the advancing side of the joint regardless of the sample location (i.e. whether it is located on the advancing side or not). This is in good agreement with the results from the transverse hardness measurements in Fig 3A, where the minimum HAZ hardness appears on the AS.

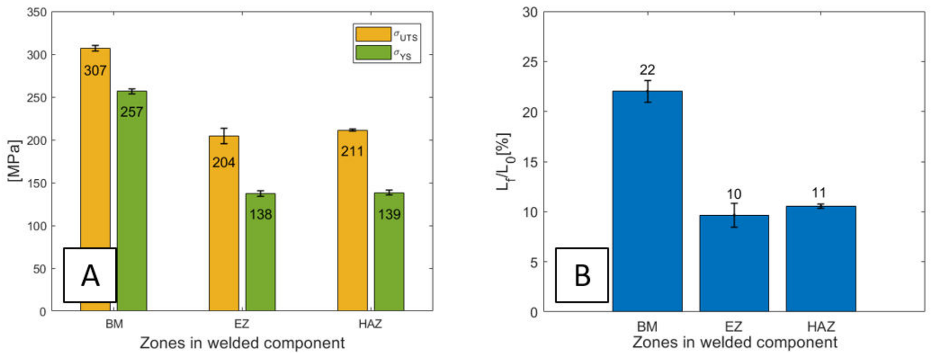

Fig. 4. Average tensile properties for specimens sampling different weld zones. (A) Offset yield strength and ultimate tensile strength. (B) Elongation at fracture. The error bars in the graphs represent the standard deviation of the measurements.

4.3 Impact Properties

The HYB joint response to high strain rates (>10^3 s^{-1}) was determined using CVN testing. The measured energy absorption (per unit area) for different weld regions is presented by the bar chart in Fig. 5. The base material displays a relatively low initial base material toughness, whereas all of the welded specimens show an increase in impact toughness relative to the base material. The highest energy absorption is found for the EZ specimens, which is almost three times larger than that of the BM. No difference is found between the bond line (BL) and HAZ when it comes to energy absorption.

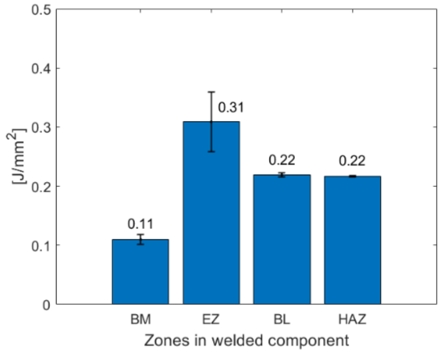

Fig. 5 Measured energy absorption for CVN specimens sampling different weld zones. The error bars in the graph represent the standard deviation of the measurements.

4.4 Microscopic Analysis

The HYB joint microstructure is shown by the micrograph in Fig. 6A. Obviously, the microstructure changes across the bond line, and the filler material reveals a much finer grain size compared to the HAZ. Close to the bond line strongly elongated and heavily deformed grains are visible. Fig. 6B shows a representative image of the fracture surface of a broken welded specimen. Extensive dimple formation is observed being characteristic of a ductile fracture. As a matter of fact, all tensile and CVN specimens examined in the SEM revealed the same type of fracture mode, and thereby excluding possible kissing bond formation. This means that full metallic bonding is achieved in the groove between the FM and the BM under the prevailing circumstances.

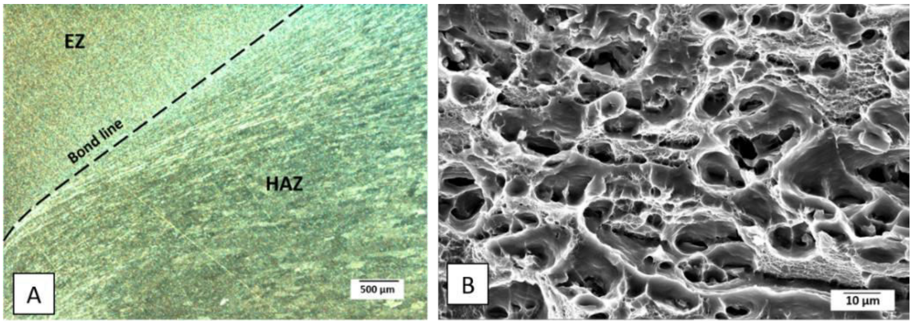

Fig. 6. (A) Optical micrograph showing the change in microstructure across the bond line between the base and the filler materials. (B) Representative SEM fractograph of a selected broken tensile specimen sampling the EZ.

5 Discussion

In order to evaluate the mechanical performance of the HYB joint, the properties achieved must be compared with corresponding results reported for conventional welding techniques as gas metal arc (GMA) welding and friction stir (FS) welding. Among others, the transverse hardness profile and tensile properties of AA6082-T6 have been determined by Moreira et al. [14, 15] and by Ericsson and Sandström [16]. In the work of Moreira et al. 3 mm thick rolled plates were used as base material, whereas in the work of Ericsson et al. 4 mm thick extruded profiles were used. In the GMA welds the total width of the HAZ varied between 35 mm and 50 mm. For the FS welds these values are found to be significantly lower, varying between 20 mm and 25 mm, highly dependent on the welding speed. The corresponding value for the HYB joint is measured to be 25 mm (revisit Fig. 3A). In order to completely eliminate problems with HAZ softening in the Al-Mg-Si weldments, the operational temperature needs to be kept below 250 ℃ [17]. This is physically feasible and within the reach of what is possible using the HYB process as demonstrated previously by Aakenes et al. [9, 18].

Moving on to the tensile properties, the GMA welds have a yield strength corresponding to about 50 % of the base material and a joint efficiency of 70 %. On the other hand, the FS weld reaches a yield strength of about 52 % of the base material and a joint efficiency of 80 %. In comparison, the HYB joint yield strength is 54 %, while the joint efficiency is 66 %. This indicates that the mechanical strength of the HYB joint is within the range of that reported for conventional welding technologies such as GMAW and FSW.

6 Conclusions

Here, the successful HYB joining of 4 mm AA6082-T6 rolled plates is presented. The joint is found to be free from internal defects like pores, cavities and kissing bond. Full metallic bonding is achieved between the filler and the base materials in the weld groove, as demonstrated by both tensile testing and Charpy V-notch (CVN) testing. Transvers hardness testing of the HYB joint disclosed evidence of significant HAZ softening, reaching a total HAZ width of 25 mm. This reduces both the yield strength and the joint efficiency to values well below those of the base material (54 % and 66 %, respectively). In contrast, the HAZ softening appears to have a positive effect on the CVN impact toughness, which is about three times larger for the welded specimens.

Moreover, to get an indication of the HYB joint mechanical performance a comparison with corresponding results reported for GMA and FS welds has also been made. This shows that the HYB joint mechanical properties are slightly better than the properties reported for comparable GMA welds, but do not fully match those of sound FS welds. Therefore, there is still a potential for further optimization of the HYB process in order to bring the method to the forefront of aluminium welding technology.

References

1. Ø. Grong, *Mechanical modelling of welding* (1997)
2. J. Hirsch, Mater. Trans **52**, 818 (2011)
3. J. E. Hatch, *Aluminum – Properties and Physical Metallurgy* (1984)
4. J. R. Davis, *Aluminum and Aluminum Alloys* (1993)
5. R. Nandan, T. DebRoy, H. K. D. H Bhadeshia, Prog. Mater. Sci. **53**, 980 (2008)
6. P. Threadgill, et al. Int. Mater. Rev. **54**, 49 (2009)
7. N. R. Mandal, *Ship Construction and Welding* 221-234 (2017)
8. Ø. Frigaard, Ø. Grong, O. T. Midling, Metall. Mater. Trans A **32**, 1189 (2001)
9. U. R. Aakenes, Ø. Grong, T. Austigard, Mater. Sci. Forum **794**, 339 (2014)
10. L. Sandnes, et al., Int. J. Adv. Manuf. Technol. (to be published)
11. Ø. Grong, Weld. J. **91**, 26 (2012)
12. Ø. Grong, United States Patent, US 7131567B2 (2006)
13. J. Blindheim, et al., Procedia. Manuf. (NAMRC46, to be published)
14. P. M. G. P. Moreira, et al., Theor. Appl. Fract. Mech. **48**, 169 (2007)
15. P. M. G. P. Moreira, et al., Theor. Appl. Fract. Mech. **50**, 81 (2008)
16. M. Ericsson, R. Sandström, Int. J. Fatigue **25**, 1379 (2003)
17. O. Myhr, et al., Acta Mater. **52**, 4997 (2004)
18. U. R. Aakenes, *Industrialising the Hybrid Metal Extrusion & Bonding (HYB) Method – From Prototype Towards Commercial Process.* PhD Thesis, Norwegian University of Science and Technology (2013)