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Using the Hybrid Metal Extrusion & Bonding (HYB) Process for Dissimilar Joining of AA6082-T6 and S355

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Abstract

Hybrid Metal Extrusion & Bonding (HYB) is a new solid state joining technique that uses filler material addition and plastic deformation to create sound joints. The filler material addition makes the HYB process more flexible and less vulnerable to weld defects compared to conventional solid state joining techniques. Moreover, the operational temperature during processing is even lower than that reported for conventional joining techniques, which reduces the width of the heat affected zone (HAZ) significantly as well as residual stresses and contaminants in the weld zone. Here we report the joining of the dissimilar materials aluminum alloy 6082-T6 and structural steel 355. The joint is found to be free from defects like pores and internal cavities and is fully characterized herein from a metallurgical point of view.

Keywords: Welding; Hybrid Metal Extrusion & Bonding (HYB); Solid State Process; Dissimilar Metals; Intermetallic Compounds.

1. Introduction

There is a growing demand for more fuel efficient vehicles in order to reduce the emission of greenhouse gasses. As a result, there is an increased interest in lightweight structures and the application of mixed materials, as the combined use of aluminum and steel. However, welding and fabrication of aluminum-steel products is challenging

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because of their large difference in physical and thermal properties (e.g. melting temperature, coefficient of thermal expansion, heat capacity and solidification shrinkage), which may give rise to a variety of weld defects (see Atabaki et al. (2014)). One of the major challenges in fusion welding of aluminum-steel products is the formation of brittle intermetallic compounds (IMC) along the bond line. Despite that the formation of intermetallic Fe_xAl_y-phases is necessary to achieve bonding, the high thermal input in fusion welding leads to an excessive formation of these phases resulting in brittleness of the bond, as reported by Agudo et al. (2007) and Bozzi et al. (2010). Therefore, solid state processes offer several advantages when it comes to welding of aluminum alloys to steel, as joining takes place below the melting temperature of both materials.

Over the years, a variety of solid state joining techniques have been developed. Among the more recent once is friction stir welding (FSW), which has successfully been used for joining of aluminum to steel, as reported among others by Hussein et al. (2015). Despite that the FSW process generates lower heat input, and thereby reduces the thickness of the IMC layer formed on the aluminum-steel interface, it still affects the joint strength (see Kundu et al. (2013) or Tanaka et al. (2009)). Moreover, the weld quality and strength of the joint is highly dependent on both the operational parameters and the position of the pin in the weld groove. For instance, both the welding speed, the pin rotational speed and its position relative to the weld center line will influence the amount of frictional heat generated during welding and thereby the thickness of the IMCs layer. In addition, these factors will also influence the material flow, the amount of steel fragments in the stir zone and the extent of wear on the pin (see Chen and Kovacevic (2004) or Watanabe et al. (2006)). Thus, a variety of factors may reduce the integrity of the joint. This opens up for more innovative joining technologies suitable for aluminum-steel products.

The Hybrid Metal Extrusion & Bonding (HYB) process is a new solid state joining technique which is deemed to have a great potential. By the use of filler material addition and plastic deformation, the HYB process can produce sound joints at even lower temperatures than that reported for conventional welding techniques, as reported by Grong (2012), Aakenes (2013) and Sandnes et al. (2018). Moreover, the filler material makes the process more flexible and less vulnerable to undercuts and weld defects compared to conventional solid state joining techniques, while the low operational temperature reduces the width of the heat affected zone (HAZ). In the present report, the usefulness of the HYB process for dissimilar joining of aluminum and steel is to be explored. Therefore, a full metallurgical characterization of a dissimilar butt weld of aluminum alloy 6082-T6 and structural steel 355 will be conducted. The experimental part will include both hardness measurements, tensile testing and simple microscopic analysis.

2. Principles of the HYB process for joining of dissimilar metals

2.1. Characteristic features of the HYB PinPoint Extruder

The HYB PinPoint extruder is based on the principles of continuous extrusion, as described in the patent by Grong (2006). The current version of the extruder is build up around a 10 mm diameter rotating pin, provided with an extrusion head with a set of moving dies through which the aluminum is allowed to flow. This is shown by the drawing in Fig. 1(a). When the pin is rotating, the extrusion chamber with three moving walls will drag the filler wire both into and through the extruder due to the imposed friction grip. At the same time, it is kept in place inside the chamber by the stationary steel housing constituting the fourth wall. The aluminum is then forced to flow against the abutment blocking the extrusion chamber and subsequently, owing to the pressure build-up, extruded through the moving dies in the extruder head.

2.2. Working principles during butt welding of dissimilar metals

In a real joining situation, the extruder head is clamped against the two metal plates to be joined. The plates are separated from each other so that a groove is formed between them, as can be seen from Fig. 1(b). Note that the groove side wall of the steel base material is machined to form a slope parallel to the pin to avoid physical contact between them. On the aluminum side the pin diameter is slightly larger than the groove configuration to promote direct contact with the pin and thus good oxide cleaning. 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 side is referred to as the retreating side (RS). During pin rotation some of the aluminum base material will be dragged around by its motion and mixed with the aluminum filler material, which simultaneously is extruded into the groove. Thus, most of the aluminum will flow from the top region of the weld and downwards along the steel side wall before it meets the steel backing and consolidates under the high pressure.

On the aluminum side of the joint, metallic boning is achieved through a combination of oxide dispersion, surface expansion, shear deformation and pressure. On the other hand, metallic bonding by shearing of valence electrons is not likely to occur between the aluminum alloy and the steel because of the pertinent differences in the atomic structure. However, based on previous work on dissimilar welding of aluminum alloys and steels (see Agudo et al. (2007), Hussein et al. (2015) or Jindal et al. (2006)), it is reasonable to believe that the formation of IMCs along the bond line also is the actual bonding mechanism in the HYB case.

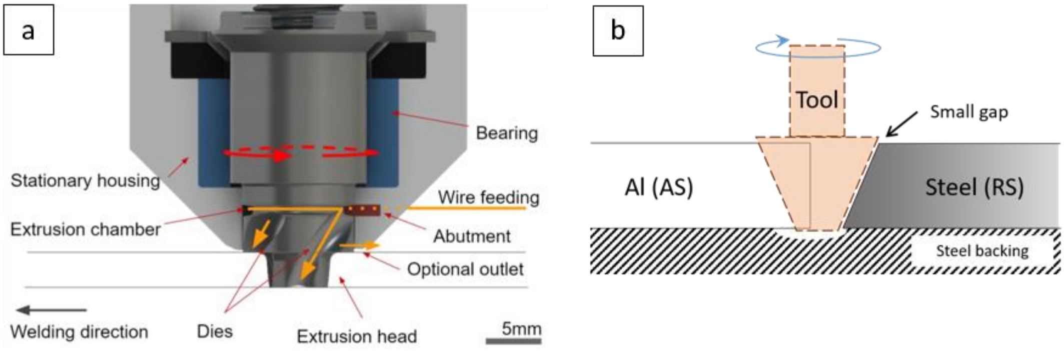

Fig. 1. (a) The HYB PinPoint extruder is built up around a rotating pin provided with an extrusion head with a set of moving dies through which the aluminum is allowed to flow; (b) Schematic illustration of the rotating pin and its location in the weld groove during HYB butt welding of aluminum to steel. Note the difference in shape of the groove on the aluminum side and the steel side.

3. Experimental

3.1. Materials and welding conditions

In the present welding trial, 4 mm rolled plates of aluminum alloy 6082-T6 and 4 mm rolled plates of structural steel 355 were used as base materials. Both plates were bought from an external supplier. The dimensions of the plates prior to welding was 240 mm x 55 mm. The filler material used 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 dimension. The chemical composition of the two different base materials (BM) and the filler material (FM) used can be found in Table 1 and Table 2.

Prior to welding, the steel side of the weld groove was machined to form a slope, whereas the aluminum plate was used as-received without any surface preparation. However, just before the joining operation both the aluminum and steel sides of the weld groove were cleaned in acetone. HYB single pass butt joining was carried out at room temperature by HyBond AS, using an I-groove with root opening of 2 mm and the following welding parameters: pin rotation of 400 RPM, travel speed of 6 mm/s and wire feed rate of 146 mm/s. This corresponds to a gross heat input of 0.37 kJ/mm.

Table 1. Chemical composition (wt. %) of the aluminum base material AA6082-T6 (Al BM) and the aluminum filler material AA6082-T4 (Al FM) used in the welding trial.

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr	Ti	B	Other	Al
Al BM	0.90	0.45	0.06	0.42	0.80	0.02	0.05	-	0.02	-	0.03	Balance
Al FM	1.11	0.20	0.002	0.51	0.61	0.14	-	0.13	0.43	0.006	0.029	Balance

Table 2. Chemical composition (wt. %) of the S355 structural steel used as base material (Steel BM).

	C	Si	Mn	P	Al	Nb	Cu	Cr	Ni	Other	C_{eq}
SS BM	0.067	0.02	0.69	0.010	0.040	0.014	0.028	0.05	0.05	0.028	0.20

3.2. Experimental procedure

Transverse samples were cut from the HYB welded plates and numbered, resulting in the final samples. The specimens used for tensile testing had a simple rectangular shape with final dimensions 25 mm x 100 mm x 4 mm. In total, four specimens were used for tensile testing. The specimens used for hardness measurements and microstructural analysis were prepared following standard sample preparation procedures. In order to reveal the macro- and micro structure of the dissimilar joint, the specimen was immersed in Baker's solution (5mL HBF_4 (48%) + 200mL H_2O) for 10-20 seconds. Then the weld macro- and microstructure were examined using a Leica DMLB light microscope and an Alicona Confocal microscope. The bond line between the aluminum and the steel was examined by energy dispersive x-ray spectroscopy (EDS) using a Quanta FEG 450 scanning electron microscope (SEM). Hardness measurements were taken transverse to the weld along the horizontal mid-section of the joint. In total, two test series were carried out, using a constant load of 1 kg with a distance of 0.5 mm between each indentation. For both aluminum and steel, the base material hardness was established from seven individual hardness indentations taken randomly on one separate specimen of the base material.

4. Results and discussion

4.1. Microstructure and hardness measurements

The measured hardness profile along the horizontal mid-section of the HYB Al-Fe joint is presented graphically in Fig. 2(a). Note that each hardness point in the figure represent the mean value of the two individual test series carried out along the horizontal mid-section of the weld. Moreover, Fig. 2(b) shows an overview of the HYB joint macrostructure with the different weld zones. As can be seen from the figure, both the Al BM and Al FM material flow patterns in the weld groove are clearly visible. The steel, on the other hand, is not deformed. The horizontal dotted lines in Fig. 2(a) represent the aluminum and steel base material hardness measured to be 111.5 HV and 157.2 HV, respectively. The minimum hardness of the joint is found on the aluminum side, approximately 2 mm from the weld center-line, reaching a value of 66 HV. The Al BM hardness is reached after 12 mm. On the opposite side, the minimum hardness value is found in the transition between the Al BM and Al FM, reaching a value of 68 HV. The steel seems to be unaffected by the joining operation and reaches the base material hardness immediately.

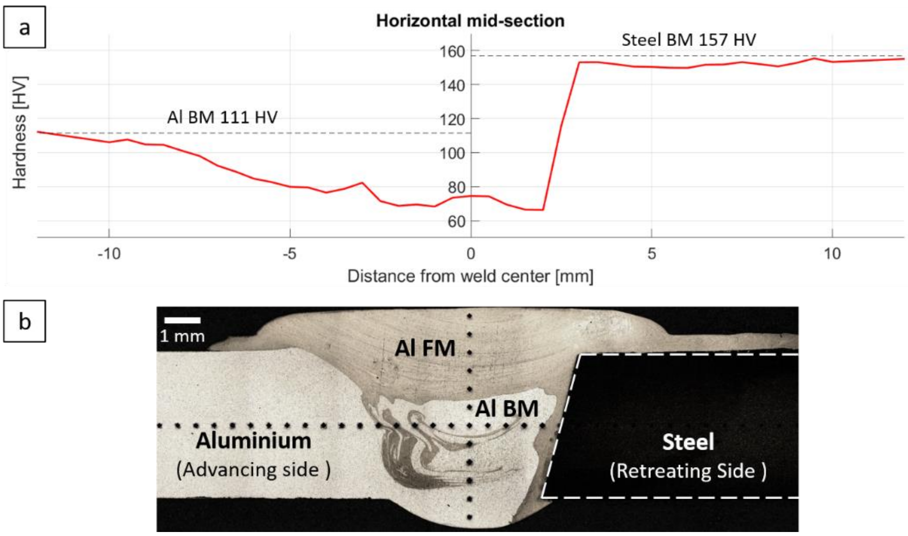

Fig. 2. (a) Measured hardness profile along the horizontal mid-section of the dissimilar AA6082-T6 and S355 HYB-welded joint; (b) Optical macrograph of the joint cross section. The material flow pattern of the aluminum base and filler material (Al BM and Al FM) are clearly visible.

4.2. Tensile properties and crack path

The tensile test results showed that specimens located in the center of the weld plate reached an ultimate tensile strength (UTS) of about 104 MPa, whereas specimens located at the end of the plate reached a UTS of about 140 MPa. The latter value corresponds to about 45 % of the base material tensile strength. It should be noted that a thick layer of aluminum was present on the steel fracture surface, as can be seen by the macrographs in Fig. 3. It follows from the figure that the fracture path starts along the bond line, but changes then direction and continues through the Al FM on the retreating side of the joint. This indicates that adequate bonding is obtained along most of the aluminum-steel interface. Note that the observed fracture path is in good agreement with the measured hardness profile in Fig. 2, where the weakest part of the weld is seen to be located in the Al FM to the left-hand side of the aluminum-steel interface.

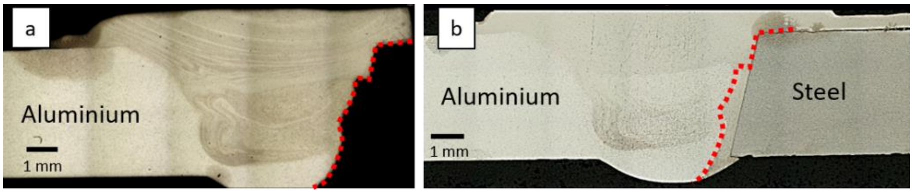

Fig. 3. Comparison of (a) the crack propagation path in a broken tensile specimen with its location (b) inside the weld zone. Obviously most of the fracture occurs within the Al FM and not along the bond line.

4.3. Microscopic analysis

In order to reveal possible IMC formation along the bond line between the aluminum and the steel one sample located in the middle of the weld cycle was examined at different magnifications in the SEM. The resulting SEM micrograph at high magnification is shown in Fig. 4. As can be seen from the figure, even at 8000 magnification, there is no sign of IMCs along the bond line. Note that the narrow white line observed in the figure is just an artefact arising from the sample preparation, which in this case is extremely difficult due to the pertinent difference in hardness between aluminum and steel.

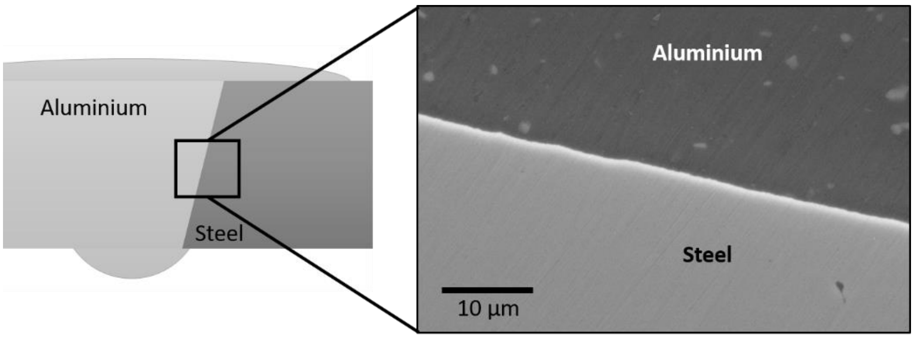

Fig. 4. SEM micrograph of the aluminum-steel interface at high magnification (8000x). Including also a schematic illustration of area analyzed.

It is worth noticing that for conventional fusion welding techniques, such as cold metal transfer (CMT) and tungsten inert gas (TIG) welding, the thickness of the IMC layer is commonly in the range of 2-5 µm, as reported by Agudo et al. (2007) and by Lin et al. (2010). For FSW, the IMCs thickness is found to be highly dependent on the tool rotation speed, but for a tool rotation of 600 RPM, the thickness is between 2-4 µm, as reported by Kundu et al. (2013). It should be mentioned that for FSW of aluminum alloy 6056-T4 to stainless steel 304, Lee et al. (2006) have reported a IMCs layer with thickness of 0.25 µm using a tool rotation of 800 RPM and a welding speed of 80 mm/min. Based on this, a magnification of 8000 should be sufficient to expose any significant formation of IMCs along the bond line if the layer thickness is comparable with that observed for conventional welding techniques. Thus, in the HYB case the IMC layer must be thinner than 0.1 µm, which is typically the lower limit of what can be detected in SEM.

5. Conclusion

Here, we present for the first time the successful application of the HYB process for joining of two dissimilar metals, i.e. aluminum alloy 6082-T6 to structural steel 355. The low operational temperature of this process makes it possible to achieve bonding without the presence of intermetallic compounds or oxides visible in standard SEM analysis. Moreover, from the tensile testing of the joint it was observed that fracture occurred mainly in the aluminum and not along the aluminum-steel interface. This is a promising result showing the potential of the HYB process for welding of challenging material combinations such as aluminum alloys and steel. Further characterization of the weld, together with further optimization of the welding geometry and the process parameters can certainly increase the bond strength and the mechanical properties of the HYB joints. Thus, this proof-of-concept will lay the foundation for a promising future research direction.

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