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ORIGINAL ARTICLE

Exploring the hybrid metal extrusion and bonding process for butt welding of Al–Mg–Si alloys

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Abstract
The hybrid metal extrusion and bonding (HYB) process is a new solid-state joining technique developed for aluminum alloys. By the use of filler material addition and plastic deformation sound joints can be produced at operating temperatures below 400 °C. The HYB process has the potential to compete with commonplace welding technologies, but its comparative advantages have not yet been fully explored. Here, we present for the first time the results from an exploratory investigation of the mechanical integrity of a 4-mm AA6082-T6 HYB joint, covering both hardness, tensile and Charpy V-notch testing. The joint is found to be free from defects like pores, internal cavities and kissing bonds, yet a soft heat-affected zone (HAZ) is still present. The joint yield strength is 54% of that of the base material, while the corresponding joint efficiency is 66%. The indications are that the HYB process may compete or even outperform conventional welding techniques for aluminum in the future after it has been fully developed and optimized.

Keywords Hybrid metal extrusion and bonding (HYB) · Solid state joining · Al-Mg-Si alloys · Mechanical properties

1 Introduction

Aluminum alloys, as the Al–Mg–Si alloys, exhibit unique physical and mechanical properties making them attractive for a wide range of structural applications and welded assemblies [1, 2]. Although the Al–Mg–Si alloys are readily weldable, the excessive heat generation associated with the traditional welding processes makes them vulnerable to HAZ softening due to reversion of the hardening precipitates which form during artificial aging [3]. Despite that some strength recovery may be achieved by natural aging or by applying an appropriate post-weld heat treatment, the mechanical integrity of the welded component is always poorer than that of the base material [1, 4]. Moreover, the material melting occurring during fusion welding makes the weld susceptible to pore formation, hot cracking, liquation cracking, and bonding defects causing additional degradation of the joint [1, 2].

Solid-state processes offer several advantages for joining of aluminum as material melting does not occur. Instead, metallic bonding is achieved through plastic deformation and diffusion taking place across the mating interface. Over the years a variety of solid-state joining processes have been developed, but most of them are limited to joining of certain materials with simple geometries [5, 6]. Among the more recent technologies, friction stir welding (FSW) is perhaps the most successful one. Since its entry in 1991 the process has continuously evolved thanks to successful parameter optimization and new tool design. Also modified versions of the process exist, as self-reacting friction stir welding (SR-FSW) [7] and filling friction stir welding (FFSW) [8, 9], aiming to increase the initial bond strength in different regions of the weld. The comprehensive research and technical development of the FSW process have brought it to the leading edge of aluminum welding technology [10, 11]. Still, FSW has some fundamental limitations. For instance, 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 to undercuts and internal defects in the joint [6, 12]. These limitations need to be overcome in the future.

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Although the hybrid metal extrusion & bonding (HYB) process is still technologically immature compared to FSW, it is deemed to have a great potential. By the use of filler material addition and plastic deformation the HYB process can produce sound joints in the solid state [13–15]. At the same time, the filler material addition makes the process more flexible and less vulnerable to undercuts and weld defects compared to conventional solid state joining processes. Moreover, except from cold pressure welding the operational temperature is lower than that reported for other solid state joining techniques, including FSW.

In order to illuminate the potential of the HYB process, we aim to put it to the test in its current development stage. This will be done by characterizing a 4-mm AA6082-T6 butt weld based on 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

2.1 Characteristic features of the HYB PinPoint extruder

The HYB PinPoint extruder is based on the principles of continuous extrusion [16]. 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 aluminum is allowed to flow. This is shown by the drawing in Fig. 1. When the pin is rotating, the inner 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 housing constituting the fourth wall. The aluminum is then

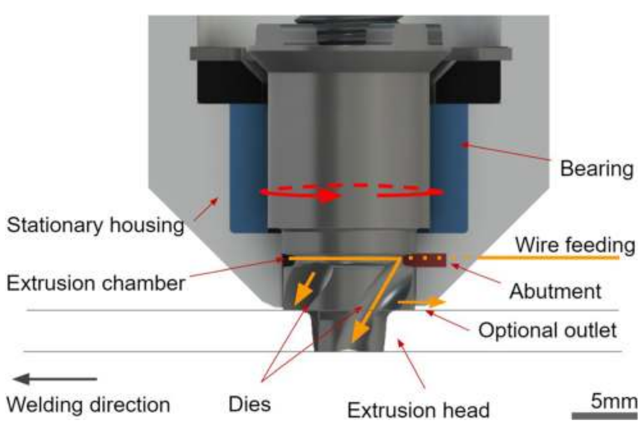

Fig. 1 The HYB PinPoint extruder is built around a rotating pin provided with an extrusion head with a set of moving dies through which the aluminum is allowed to flow

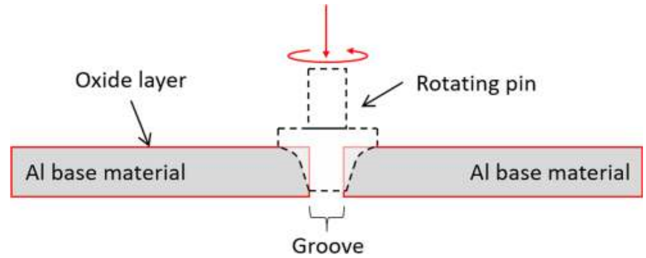

Fig. 2 Illustration of the rotating pin and its location in the groove during HYB butt welding of plates

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. They are, in turn, helicoid-shaped, which allow them to act as small "Archimedes screws" during the pin rotation, thus preventing the pressure from dropping on further extrusion in the axial direction of the pin. Furthermore, if the stationary housing is provided with a separate die at the rear, a weld face can be formed by controlling the flow of aluminum in the radial direction. In this case both the width and height of the weld reinforcement can be varied within wide limits, depending on the die geometry, ranging from essentially flat to a fully reinforced weld face. It is this flexibility that makes the HYB PinPoint extruder suitable for a number of other applications as well, including fillet joining, bead-on-plate deposition, plate surfacing, additive manufacturing [17], and welding of aluminum to steel [18].

2.2 Working principle during butt welding

In a real joining situation, the extruder head is clamped against the two aluminum plates to be joined. The plates are separated

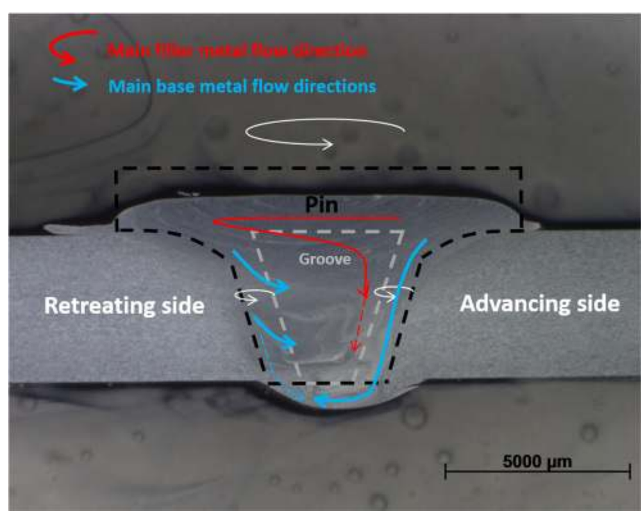

Fig. 3 Cross-sectional view of a HYB butt joint. Metallic bonding is mainly achieved by oxide dispersion and shear deformation along the groove side walls, whereas in the root region where the metal flows meet surface expansion and pressure contribute most to bonding

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

	Si	Mg	Cu	Fe	Mn	Cr	Zn	Ti	Zr	B	Other	Al
BM	0.9	0.8	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	0.13	0.006	0.029	Balance

from each other so that an I-groove forms in-between. The pin diameter is slightly larger than the groove width to ensure contact between the sidewalls of the groove and the pin (see Fig. 2). Analogous 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). Hence, the process is by definition asymmetrical, as the force transferred from the extruder head to the base plates during processing will be different on the AS compared to the 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. Because of that they tend to mix with the filler material as it flows downwards into the groove and consolidates behind the pin. Typically, the temperature in the groove between the two base plates to be joined is between 350 and 400 °C, which is below the operating temperature reported for FSW [12].

In the HYB case, metallic bonding is achieved through a combination of oxide dispersion, shear deformation, surface expansion and pressure, as shown in Fig. 3. This creates favorable conditions for metallic bonding between the filler metal and the base material when the new oxide-free interfaces (being formed following the re-shaping of the groove by the rotating pin) immediately become sealed-off by the filler metal under high pressure.

3 Experimental

3.1 Materials and welding conditions

In the present welding trial, 4-mm rolled plates of AA6082-T6 were used as base material. These were obtained from an external supplier. The dimensions of the base plates prior to welding were 120 mm × 60 mm. 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 dimension. The chemical compositions of the base and filler materials (BM and FM) are summarized in Table 1. From the table it can be seen that the FM contains Zr and larger amounts of Cr compared to the BM. These alloying elements have been added on purpose to the FM in order to increase its work hardening capacity by allowing dispersoids to form during homogenization. The HYB single-pass butt joining of the plates was carried out by HyBond AS, using an I-groove with 3 mm root opening and the welding parameters listed in Table 2. Note that these parameters are not considered to be optimal from a mechanical strength point of view, but represent rather a sensible compromise between a number of conflicting requirements to achieve a defect-free butt joint under the prevailing circumstances.

Table 2 Summary of welding parameters used in the HYB butt joining trial

Pin rotation (RPM)	Travel speed (mm/s)	Wire feed rate (mm/s)	Gross heat input (kJ/mm)
400	6	142	0.34

3.2 Mechanical testing

Transverse samples were cut from the HYB welded plates. The tensile and Charpy V-notch (CVN) specimens were located in different regions of the weld relative to the center-line. They were subsequently flush-machined to remove the contribution from the weld reinforcement. Details of the specimen locations and the number of specimens being tested can be found in Fig. 4 and Table 3, respectively. The flat specimens used for tensile testing had a reduced section length and width of 32 and 6 mm, respectively, a thickness of 4 mm (corresponding to the plate thickness), and a total length of 100 mm. The grip section width was 10 mm. 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 CVN specimens had a total length of 55 mm, a width of 10 mm and a thickness of 4 mm (corresponding to the

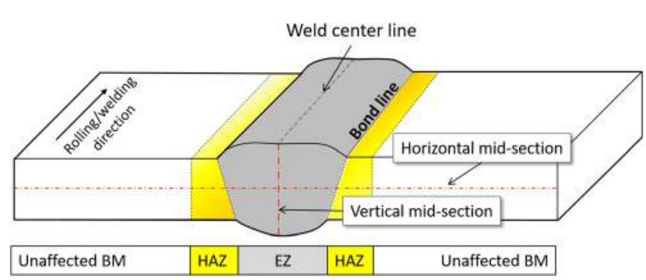

Fig. 4 Schematic illustration of different weld zones in the HYB butt joint. Also the welding and plate rolling directions are indicated in the sketch. EZ: Extrusion zone (consists of a mix of FM and BM), HAZ: (pure BM)

Table 3 Number of specimens tested and their location

	Base plate	HAZ	Bond line	EZ	Total
Tensile testing	4	3	–	3	10
Charpy testing	3	3	3	3	12

plate thickness). The depth of the V-notch being oriented in weld length direction was 2 mm and the flank angle was 45°. CVN testing was carried out at room temperature, using a Zwick impact testing machine with a total impact energy absorption capacity of 450 J.

Specimens used for microstructural analyses and hardness measurements were prepared according to standard sample preparation procedures. To reveal the micro- and macrostructure of the joint, the specimen was immersed in an alkaline sodium hydroxide solution (1 g NaOH + 100 ml H_2O) for 3 to 4 min. The macro- and microstructure of the weld were analyzed using a Leca DMLB light microscope and an Alicona Confocal Microscope. Transverse hardness measurements were performed along the horizontal and vertical mid-sections of the joint, see Fig. 4. The hardness measurements were made using a Mitutoyo Micro (HM-200 series) Vickers hardness testing machine at a constant load of 1 kg. The distance between each 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 measurements being randomly taken on one separate base plate specimen.

Finally, selected fracture surfaces of broken tensile and CVN specimens were examined in a Quanta FEG 450 scanning electron microscope (SEM). The fracture surface examination was performed at an acceleration voltage of 20 kV and a fixed working distance of 10 mm.

4 Results

4.1 Weld macrostructure and hardness distribution

The measured hardness profile along the horizontal mid-section of the HYB joint is presented graphically in Fig. 5a. Moreover, Fig. 5b shows an overview of the 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 vertical dotted line in Fig. 5a represents the hardness of the unaffected BM, 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 center-line. The total width of the HAZ is seen to be 25 mm, whereas the observed asymmetry in the hardness profile and FM and BM flow patterns is probably a reflection of the pertinent difference in the force acting on the AS and RS, respectively during pin rotation. The hardness measurements along the vertical mid-section revealed that the hardness was highest in the top region, where it reached a value of 93 HV. The harness then dropped monotonically with increasing depths below the

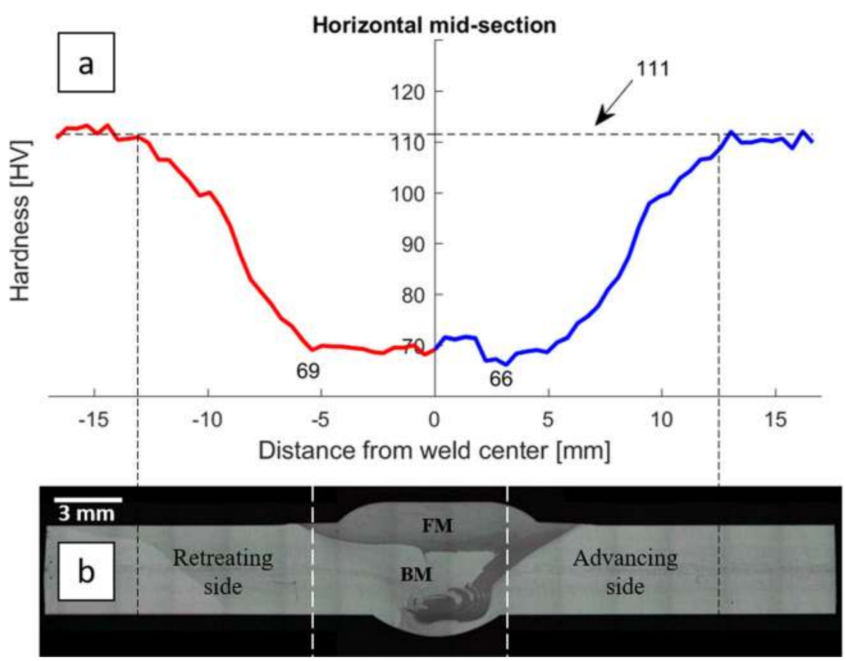

Fig. 5 **a** Measured hardness profile along the horizontal mid-section of the HYB joint. The graph represents the mean value of three individual measurements. **b** Optical micrograph showing the transverse macrostructure of the HYB joint

plate surface, finally approaching its lowest value of 51 HV at the weld toe.

4.2 Tensile properties

The measured tensile properties of the HYB joint are graphically presented in Fig. 6. It is evident that both the EZ and the HAZ have significantly lower tensile properties compared to the base material. However, there is apparently no significant difference in the properties between the EZ and the HAZ. The weld yield strength, as presented in Fig. 6a, amounts to 54% of the BM yield strength, while the corresponding joint efficiency (i.e. the $\sigma_{UTS,\ HAZ}/\sigma_{UTS,\ BM}$ ratio) is higher reaching a value of 66%. This means that the EZ has a higher work hardening capacity compared to the base plate. The latter observation is not surprising, considering the fact that the FM also contains the dispersoid-forming elements Zr and Cr, which are known to influence the work hardening behavior of Al–Mg–Si alloys.

The fracture strain of the different weld zones is presented in Fig. 6b. Owing to the necking effect caused by the HAZ softening the measured fracture strain of the welded specimens is seen to be significantly lower than that of the base material. Another consequence of the HAZ softening is also that fracture always occurs in the HAZ 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 found from the transverse hardness measurements, where the minimum HAZ hardness appears on the AS.

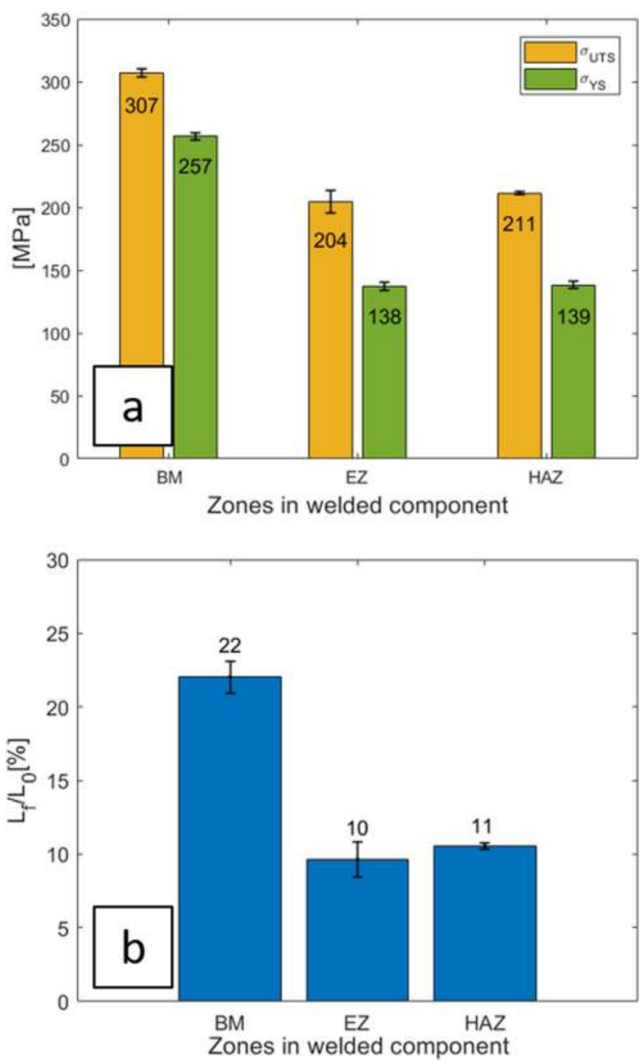

Fig. 6 Average tensile properties for specimens sampling different weld zones. **a** Offset yield strength and ultimate tensile strength. **b** Fracture strain. Note that the error bars in the graphs represent the standard deviation of the measurements

4.3 Impact properties

The joint response to very high strain rates (> 10^3 s^{-1}) was determined by the use of CVN testing. The measured energy absorption (per unit area) for the different weld regions is shown in Fig. 7. The base material displays a relatively low initial base material toughness, whereas all of the welded specimens show an increase in impact toughens 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 base material. No difference is observed between the bond line (BL) and the HAZ when it comes to energy absorption.

4.4 Microscopic analysis

The microstructure of the HYB joint is shown in Fig. 8a. Obviously, the microstructure changes across the bond line, and the filler material reveals much finer grains compared to the HAZ. Close to the bond line, strongly elongated and heavily deformed grains are visible. Figure 8b shows a representative image of the fracture surface of a broken weld tensile

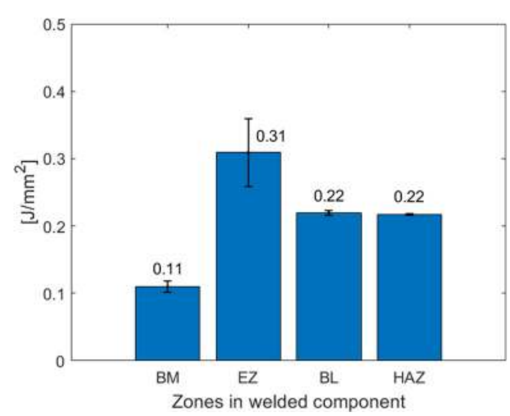

Fig. 7 Measured energy absorption for CVN specimens sampling different weld zones: base material (BM), extrusion zone (EZ), bond line (BL), and heat-affected zone (HAZ). The error bars in the graph represent the standard deviation of the measurements

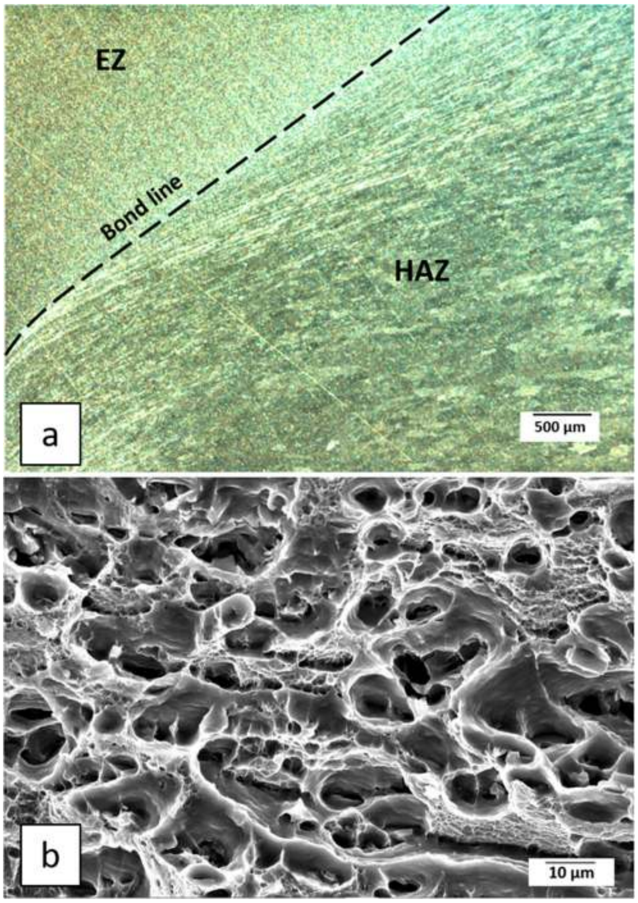

Fig. 8 **a** Optical micrograph showing changes in microstructure across the bond line between the base material and filler material. **b** Representative SEM fractograph of a selected broken tensile specimen sampling the EZ

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 fracture mode, 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.

5 Discussion

In order to evaluate the HYB joint mechanical performance, the properties achieved must be compared with corresponding results reported for conventional welding technologies such as gas metal arc welding (GMAW) and FSW. Among others, the transverse hardness profile and tensile properties of AA6082-T6 GMA and FS welded plates have been determined by Moreira et al. [19, 20] and by Ericsson and Sandström [21]. In the work of Moreira et al. 3-mm-thick rolled plates were used, whereas in the work of Ericsson and Sandström 4-mm-thick extruded profiles were used. In the GMA welds the total width of the HAZ varied between 35 and 50 mm. For the FS welds these values are significantly lower, varying between 20 and 25 mm, depending on the applied welding speed. The corresponding value for the HYB joint is 25 mm (revisit Fig. 5). To completely eliminate problems related to HAZ softening in Al–Mg–Si weldments, the operational temperature needs to be kept below about 250 °C [22]. This is physically feasible and within the reach of what is possible using the HYB process as demonstrated previously by Aakenes [13] and Aakenes et al. [23].

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 welds reach a yield strength of 52% with a joint efficiency of about 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.

In practice, a variety of factors may influence the properties of welded Al–Mg–Si components. The total width of the HAZ and subsequent strength loss in this region depend both on the base metal chemistry and the initial temper condition, as well as on the applied welding parameters which determine the HAZ *T-t* pattern [1, 4]. Thus, following further optimization the HYB process needs to be benchmarked against GMAW and FSW under otherwise comparable conditions using exactly the same base material and plate thickness. This work is now in progress.

6 Conclusions

For the first time 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 material and the base material in the groove, as documented both by tensile testing and Charpy V-notch (CVN) testing. Transverse 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 similar 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 aluminum welding technology. This work is now in progress.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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