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Progress in Solid State Joining of Metals and Alloys

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Abstract

In this overview, a new solid-state joining method for metals and alloys is presented, where the best features of gas metal arc welding, friction stir welding and cold pressure welding are combined. The invention, which is known as the Hybrid Metal Extrusion & Bonding (HYB) process, utilizes continuous extrusion as a technique to squeeze the aluminum filler material into the groove between the two plates to be joined under high pressure to achieve metallic bonding. Originally, the idea was to use the HYB process for simple butt joining of aluminum plates and profiles. However, over the years it has evolved into a multi-functional joining process handling a wide range of different joint configurations (butt, fillet and slot welds) and base metal combinations (Al, Fe, Ti and Cu). At present, up to four different metals can be joined together in one pass using the HYB PinPoint extruder and AA6082 as filler wire.

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Keywords: Solid state joining; continuous extrusion; aluminum alloys; dissimilar metals and alloys.

1. Introduction

Cold welding can be regarded as one of the oldest solid-state joining techniques, which dates back to the second or first millennium B.C. In ancient times it was used for joining of gold and silver, both separately and in combination, by the Greek Mycenaean civilization for decoration purposes (Haisma and Spierings, 2002). The first scientific study of cold pressure welding (CPW) of lead dates back to 1724 when Rev. J. T. Desaguliers, more or less accidentally, stumbled over the phenomenon as it was demonstrated to him by a Mr. Trievall in Newcastle and later in Edinburgh.

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Desaguliers repeated the experiment before the Royal Society in London the same year, and subsequently documented his experiment in the society's journal, Philosophical Transactions (Desaguliers, 1725).

Today, the term solid-state joining covers both CPW and a number of other processes as well such as diffusion welding, explosion welding, forge welding, conventional friction welding, friction stir welding (FSW), hot pressure welding, roll welding and ultrasonic welding (Mazar Atabaki *et* al., 2014). All these processes have that in common that they enable coalescence at temperatures essentially below the melting point of the base materials to be joined, without the addition of a brazing filler metal (Grong, 2012). Because there is no melting involved, the metals being joined will largely retain their microstructural integrity without forming a fusion zone (FZ) and a wide heat-affected zone (HAZ) with degraded properties, which is the main problem with traditional fusion welding (Grong, 1997). Also in dissimilar metals joining the solid-state methods offer considerable advantages compared to fusion welding due to the reduced risk of excessive intermetallic compound (IMC) formation and subsequent interfacial cracking - all being the result of large differences in chemical composition, crystal structure, thermal expansion and conductivity between the two components to be joined (Mazar Atabaki *et* al., 2014).

In this overview, a new solid-state joining method for metals and alloys is presented, where the best features of gas metal arc welding (GMAW), FSW and CPW are combined. The invention, which is known as the Hybrid Metal Extrusion & Bonding (HYB) process, utilizes continuous extrusion as a technique to squeeze the aluminum filler material into the groove between the two plates to be joined under high pressure to achieve metallic bonding (Grong, 2012, Sandnes *et* al., 2018, Grong *et* al., 2019a). Fig. 1 shows the experimental set-up during butt welding of two aluminum plates. The plates are separated from each other by a fixed spacing so that an I-groove forms between them. In a real joining situation, the extruder head slides along the joint line at a constant travel speed. At the same time the rotating pin with its moving dies is placed in a submerged position below. This allows the extrudate to flow downwards in the axial direction and into the groove under high pressure and mix with the base material. Metallic bonding between the filler metal (FM) and the base metal (BM) then occurs by a combination of oxide dispersion and severe plastic deformation. By proper adjustment of the wire feed rate (using the rotational speed of the drive spindle as the main process variable), the entire cross-sectional area of the groove can be filled with solid aluminum in a continuous manner.

Originally, the idea was to use the HYB process for simple butt joining of aluminum plates and profiles (Grong, 2012). However, over the years the method has evolved into a multi-functional joining process handling different joint configurations and groove geometries as well as base metal combinations, as illustrated in Fig. 2. The aim of the present overview is to provide an updated status report on the HYB process and its applications, starting with a brief review of the working principles of the HYB PinPoint extruder. Then, its performance during Al-Al and Al-Fe butt welding is described more in detail to shed light upon the complex material flow pattern in the groove and the underlying bonding mechanisms involved. Finally, some new ground-breaking results, emphasizing the multi-material joining capabilities of the extruder, are presented towards the end of the paper.

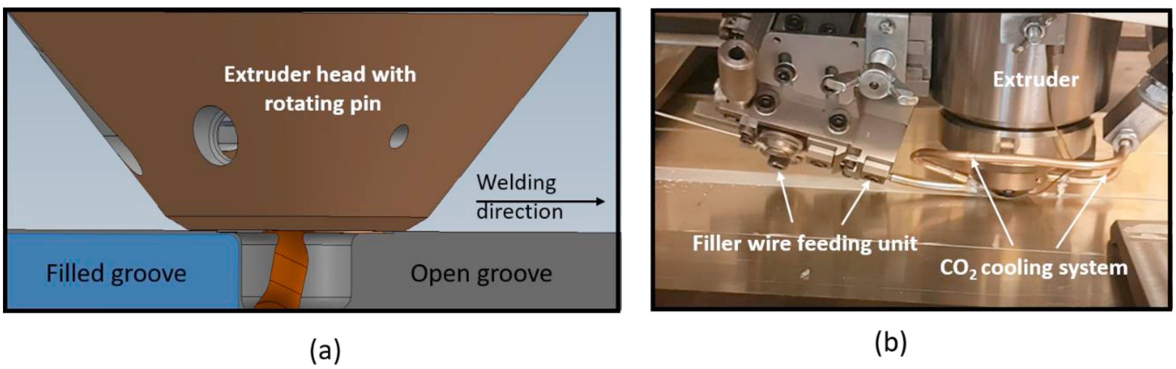

Fig. 1. Illustrations of the experimental set-up during butt welding of aluminum plates (Grong *et* al., 2019a); (a) Close-up of the "pin-in-groove" situation, (b) Snapshot of the HYB PinPoint extruder in operation.

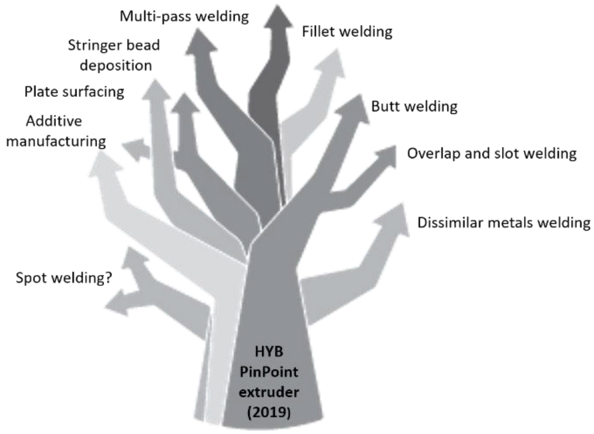

Fig. 2. Possible applications of the HYB PinPoint extruder (Grong *et* al., 2019a).

2. How the HYB PinPoint extruder works

As shown in Fig. 3, the HYB PinPoint 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. When the pin being attached to the drive spindle is rotating at a constant speed N_S, the inner extrusion chamber with its 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 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 pin head. They are, in turn, helicoid-shaped, thereby preventing the pressure from dropping on further extrusion of the FM in the axial direction of the pin and downwards into the groove. Furthermore, if the stationary housing also is equipped with a separate die at the rear, a weld face can be formed by controlling the flow of aluminum in the radial direction.

In a real welding situation, a vast number of process parameters are in play and will determine the final properties of the HYB joint. A more in-depth analysis of the essential HYB process parameters and how they are interrelated are reported elsewhere (Grong *et* al., 2019a).

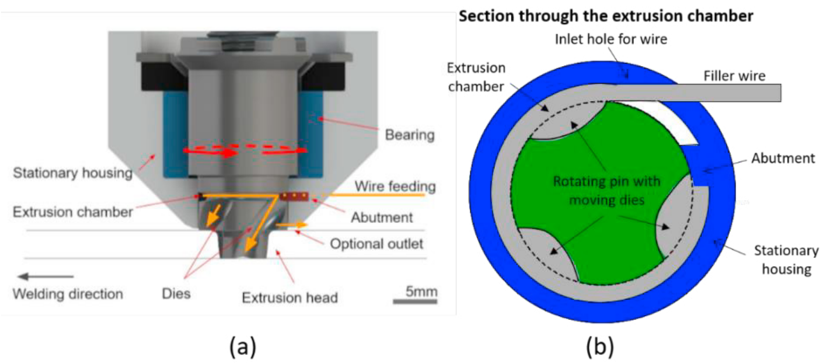

Fig. 3. The working principles of the HYB PinPoint extruder (Grong *et* al., 2019a); (a) Section through the extruder head, (b) Section through the extrusion chamber.

3. Status on Al-Al butt joining

During Al-Al butt joining the pin diameter is larger than the groove width to ensure good contact between the sidewalls of the groove and the pin (see sketch of a possible experimental set-up in Fig. 4). 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 HYB 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 (Sandnes *et* al., 2018). This type of asymmetrical behaviour is also observed in FSW (Liu and Ma, 2008).

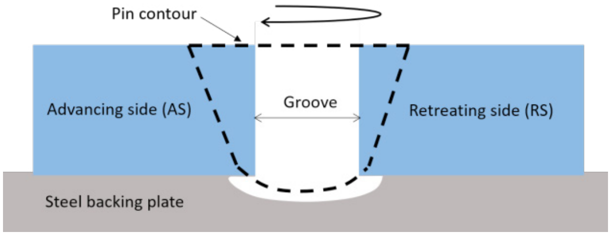

Fig. 4. Sketch of a possible experimental set-up during HYB butt welding of aluminum plates and profiles.

3.1. Material flow pattern in Al-Al butt joints

Fig. 5(a) shows a cross sectional macrograph of a 4 mm Al-Al butt joint made with a conically-shaped pin in combination with a grooved steel backing plate. The operational conditions employed are summarised in Table 1. The exact “pin-in-groove” situation is further elaborated in Fig. 5(b), where also the characteristic “ghost” interface appearing on the right-hand side in the image is indicated. Moreover, Fig. 6 shows a SolidWorks mockup of the same cross section following metallographic examination of all samples being extracted from the weld zone.

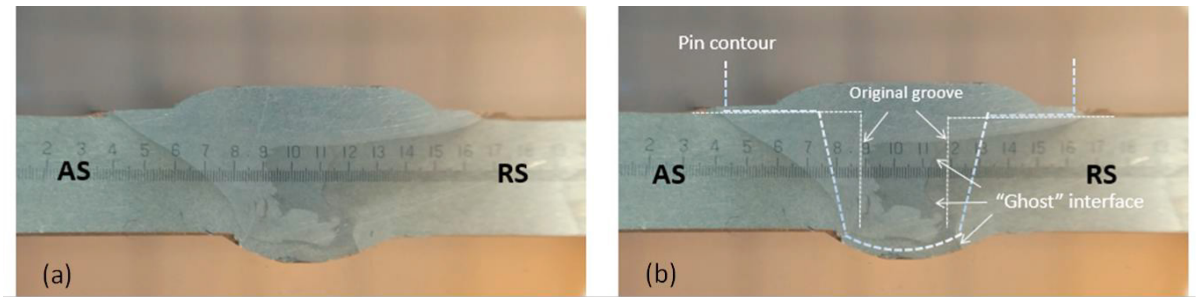

Fig. 5. Cross sectional macrographs of a 4 mm Al-Al butt joint made with a conically-shaped pin in combination with a grooved steel backing plate; (a) Overview, (b) “Pin-in-groove” situation.

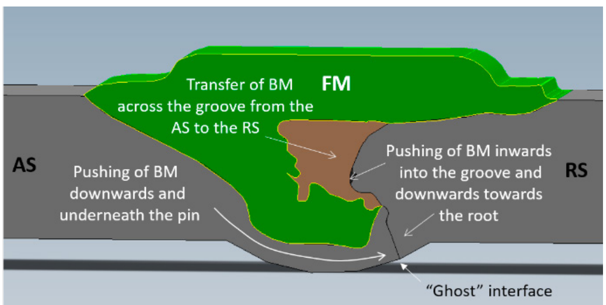

Fig. 6. SolidWorks mockup of the observed material flow pattern within the HYB butt weld shown in Fig. 5.

Obviously, the material flow pattern in this particular HYB weld is both complex and severe in the sense that the original I-groove becomes completely re-shaped during the welding operation. The re-shaping occurs as a result of the combined action of the rotating pin (and shoulder) crushing the groove walls and the directed down-flow of the FM from the upper part of the extrusion zone (EZ) towards the root region on the AS. As a matter of fact, the FM down-flow is so vigorous that big chunks of the BM on the AS actually become transferred across the entire groove, leading to the formation of the characteristic "ghost" interface on the RS following merging with the crushed groove wall on the opposite flank. Because the "ghost" interface reveals a bond strength exceeding that of the tensile strength of the joint (see Fig. 7), it does not represent a weak line segment within the weld zone being devastating for the mechanical integrity.

During Al-Al butt welding, the temperature in the groove between the two base plates to be joined is typically between 350 and 450 °C. This is below the process temperature reported for FSW (Frigaard *et* al., 2001).

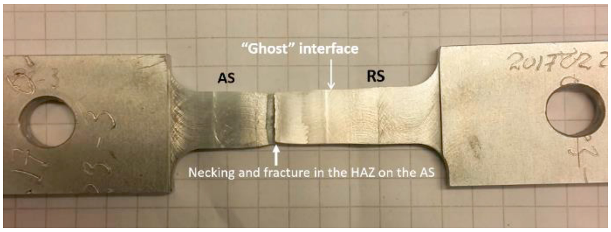

Fig. 7. Results from tensile testing of the "ghost" interface shown in Fig. 5 documenting its superior bond strength.

Table 1. Materials combinations and welding parameters used in the different case studies referred to in the text.

Case study	Materials combinations	Welding parameters N_s (RPM)	v_w (mm/s)	v (mm/s)	E (kJ/mm)
Al-Al butt joining (Figs. 5-7)	BM: AA6082-T6 (plate thickness: 4 mm) FM: AA6082-T4 (wire diameter: 1.2 mm)	400	150	6	0.35
Al-Fe butt joining (Fig. 11)	BM1: AA6082-T6 (plate thickness: 4 mm) BM2: S355 steel (plate thickness: 4 mm) FM: AA6082-T4 (wire diameter: 1.2 mm)	400	146	6	0.37
Al-Fe butt joining (Fig. 12)	BM1: AA6082-T6 (plate thickness: 4 mm) BM2: S355 steel (plate thickness: 4 mm) FM: AA6082-T4 (wire diameter: 1.4 mm)	400	155	9	0.30

N_s: Spindle rotational speed, v_w: wire feed rate, v: welding speed, E: gross heat input.

3.2. Bonding mechanisms and tensile strength levels achieved in Al-Al butt joints

In the HYB Al-Al butt welding case, metallic bonding is achieved through a combination of oxide dispersion, shear deformation, surface expansion and pressure, as shown in Fig. 8. This creates favorable conditions for metallic bonding between the FM and the BM when the new oxide-free interfaces (being formed following the re-shaping of the groove walls by the rotating pin) immediately become sealed-off by the FM under high pressure.

At present, the best 4 mm AA6082-T6 HYB butt joints produced reveal tensile strengths matching those of corresponding friction stir welds, as shown by the data presented in Fig. 9. In the future, the ambition is to surpass FSW when it comes to joint strength by further optimization of the HYB process.

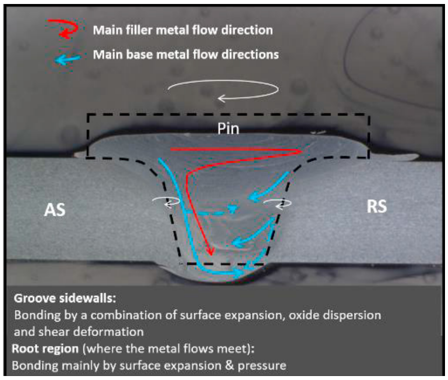

Fig. 8. Material flow pattern and bonding mechanisms in Al-Al HYB butt welds made with a conically-shaped pin in combination with a grooved steel backing plate (Sandnes *et* al., 2018).

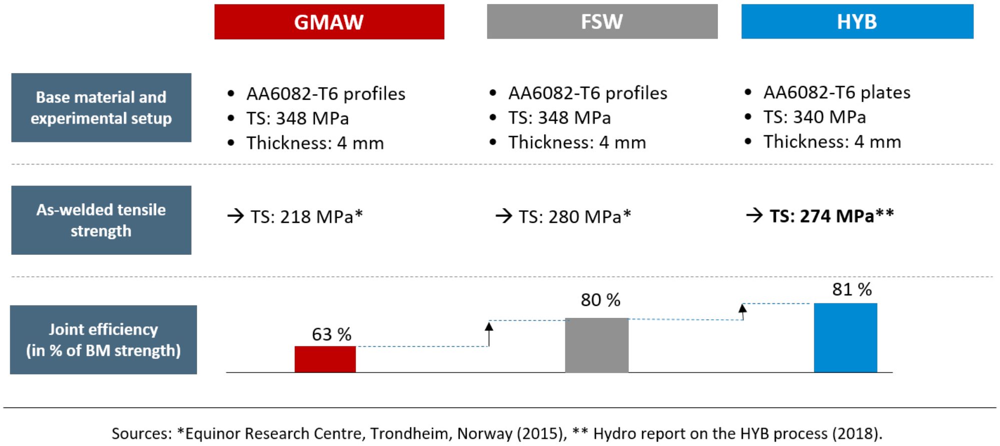

Fig. 9. Benchmarking of the HYB process against GMAW and FSW based on a comparison of tensile test data obtained for 4 mm thick Al-Al butt welds.

4. Status on Al-Fe butt joining

During HYB Al-Fe butt joining the aluminum and the steel plates are separated from each other by a groove to enable filler metal addition (Grong *et* al., 2019b). Hence, there is no need for the tool pin to machine the steel, as shown by the schematic drawing in Fig. 10. The opposite situation exists in FSW, where the two plates are firmly pressed together at the same time as the tungsten carbide (WC) tool pin is forced to machine the steel plate during the joining operation (Ramachandran *et* al., 2015). This is the main reason why the welding speed must be kept low and the weld heat input becomes correspondingly high during FSW of aluminum to steel.

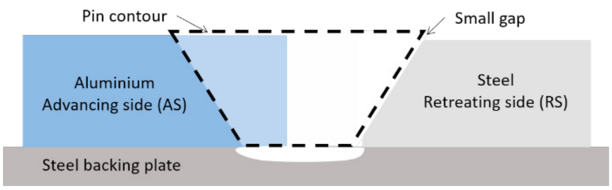

Fig. 10. Sketch of a possible experimental set-up during Al-Fe HYB butt welding.

4.1. Material flow pattern in Al-Fe butt joints

Fig. 11 shows a cross sectional macrograph of a 4 mm Al-Fe butt joint made with a conically-shaped pin in combination with a grooved steel backing plate. The operational conditions employed are summarised in Table 1. Because the aluminum plate in the present experimental set-up is located on the AS, the down-flow of the FM from the upper part of the EZ towards the root region is most extensive on this side. As a result, big chunks of BM are transferred across the entire groove from the AS to the RS similar to that observed during Al-Al butt joining. Moreover, a secondary down-flow of FM is also observed on the RS along the entire Al-Fe interface, as indicated by the broken arrow in Fig. 11. This creates favorable conditions for intermetallic compound (IMC) formation between aluminum and steel during the joining operation, which is the main bonding mechanism in Al-Fe weldments (Grong *et* al., 2019b).

Neither a change in the position of two base plates with respect to the pin rotation direction nor the use of a cylindrical pin in combination with a straight edge on the steel side appear to change the overall material flow pattern, as shown in Fig. 12. Nevertheless, having the steel plate located on the AS means that the down-flow of the FM from the upper part of the extrusion zone (EZ) towards the root region will be most extensive along the Al-Fe interface where bonding occurs by IMC formation. Under such conditions the aluminum-steel interaction is so strong that the interface actually becomes wavy and about 50% longer compared to that of a straight groove face, thereby providing additional bond strengthening through mechanical interlocking. This is considered to be a great advantage and a key to obtain a highest possible joint strength. Further details about the experimental conditions employed in the case study are provided in Table 1.

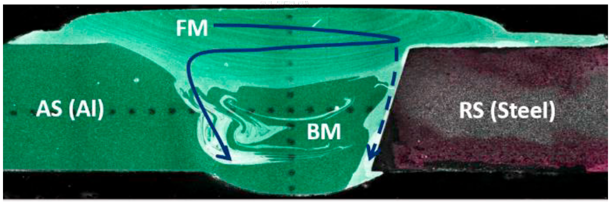

Fig. 11. Material flow pattern in an Al-Fe HYB butt weld made with a conically-shaped pin in combination with a grooved steel backing plate (Berto *et* al., 2018).

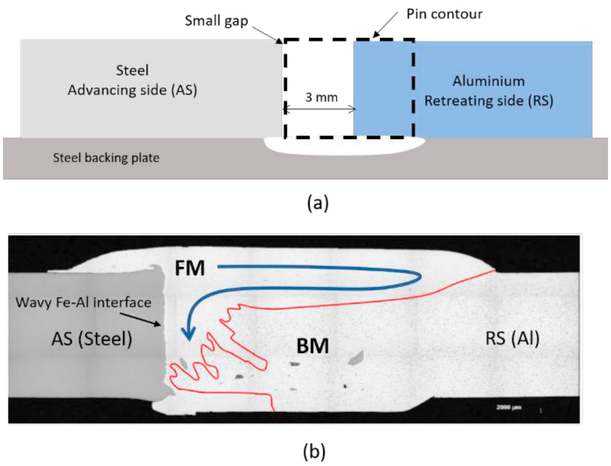

Fig. 12. Alternative experimental set-up during Al-Fe HYB butt joining using a cylindrically-shaped pin and a straight steel edge in combination with a grooved steel backing plate; (a) "Pin-in-groove" situation, (b) Observed material flow pattern in the groove, based on the image contrast provided by the pertinent difference in size between endogenous Mg_2Si particles present in the BM and the FM, respectively.

4.2. Bonding mechanism and tensile strength levels achieved in Al-Fe butt joints

It follows from the data presented in Fig. 13 that the tensile properties achieved for the 4 mm Al-Fe HYB butt joint shown in Fig. 12 surpass those reported for comparable friction stir welds. The superior bond strength can be attributed to the formation of a 20 to 40 nm thin IMC layer along the Al-Fe interface composed of adjoining Al-Fe-Si nanocrystals, as shown by the high-resolution transmission electron microscope (TEM) image in Fig. 14. This is opposed to the situation existing in FSW, where the IMC layer is typically one to two microns thick and may contain flaws as well in the form of cracks (Ramachandran *et* al., 2015). Obviously, the HYB nanolayer film is thick enough to create a very strong bond and at the same time thin enough to prevent it from cracking during tensile loading (Grong *et* al., 2019b).

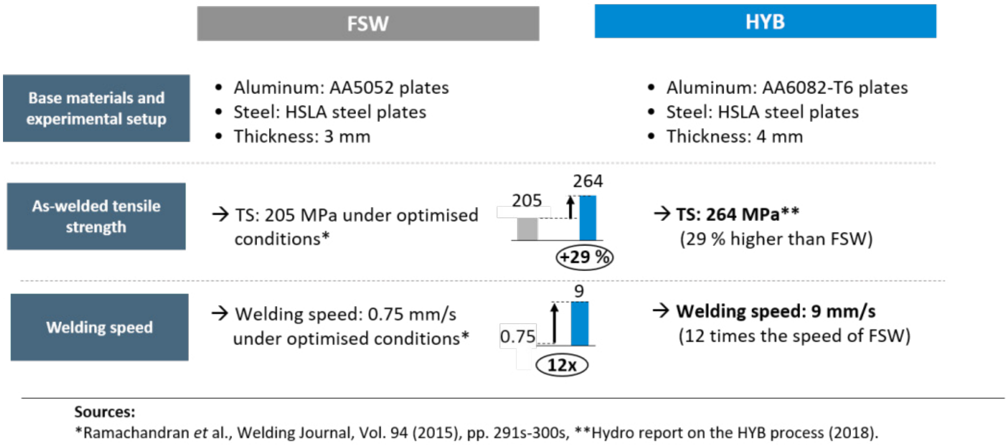

Fig. 13. Benchmarking of the HYB process against FSW based on a comparison of tensile test data obtained for different Al-Fe butt welds.

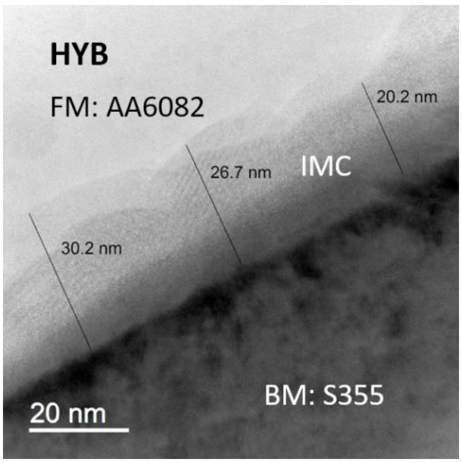

Fig. 14. High resolution TEM image of the HYB Al-Fe interface. The characteristic high bond strength of the HYB Al-Fe joints can be attributed to the formation of a 20 to 40 nm thin IMC layer containing the elements Fe-Al-Si along the entire interface (Grong *et* al., 2019b).

5. Recent advances in similar and dissimilar metals joining

Fig. 15 shows a selection of welds that have been produced using the HYB PinPoint extruder (Grong *et* al., 2019b). More detailed information about the applied metal combinations and welding conditions is provided in Table 2. Because the shift from butt and slot welding to fillet welding only requires minor modifications of the pin and steel housing geometries, the PinPoint extruder is very flexible when it comes to handling various joint configurations. In addition, it exhibits unique multi-material joining capabilities by allowing welding of up to four different metals in one pass. In the four metals (Al-Cu-Ti-Fe) butt welding case the role of the aluminum FM is to act as a solder, which bonds the other three metals together in a butt joint configuration. To the authors knowledge this has never been reported before. Work is now in progress to characterise these weldments, both mechanically and microstructurally, using advanced materials testing in combination with high-resolution transmission electron microscopy.

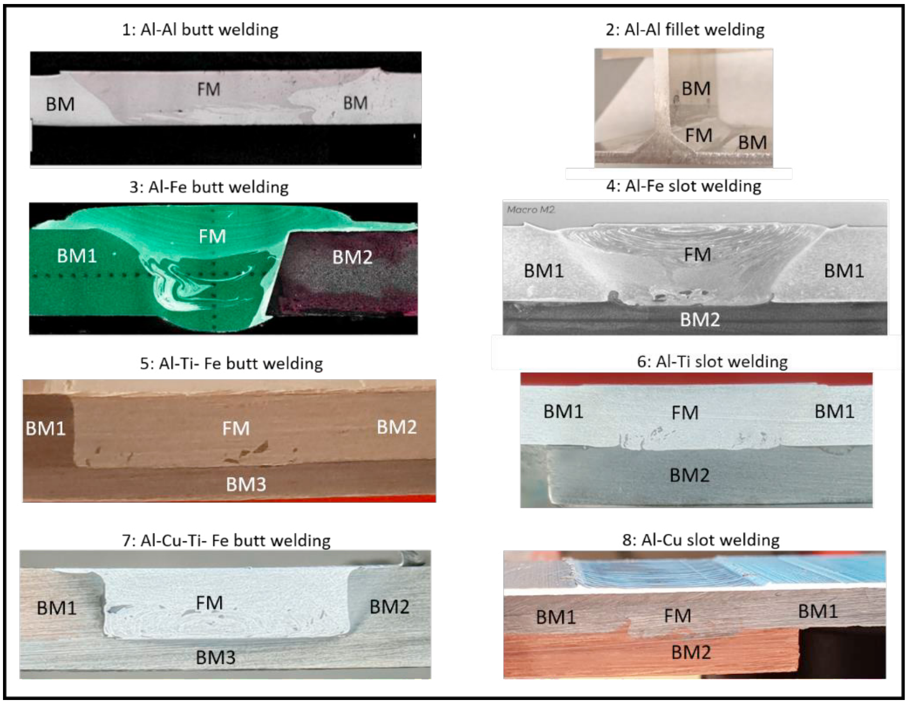

Fig. 15. Cross-sectional macrographs of welds that have been produced using the HYB PinPoint extruder. Details of the applied metal combinations and welding conditions are given in Table 2 (Grong *et* al., 2019b).

6. Conclusions

Established solid-state joining techniques for metals like cold pressure welding (CPW) and friction stir welding (FSW) offer considerable advantages compared to conventional fusion welding processes such as gas metal arc welding (GMAW) when it comes to energy efficiency and joint properties. On the other hand, CPW and FSW suffer from the lack of flexibility and the disadvantage of heavy and less versatile equipment. In the HYB case, the best features of GMAW, FSW and CPW are combined in one process to enable solid-state joining with filler metal addition. This makes the HYB method very flexible when it comes to handling different joint configurations and weld geometries as well as base metal combinations.

In dissimilar aluminum-steel welding bonding occurs via intermetallic compound (IMC) formation. The results presented for the HYB process show that a thin continuous IMC layer in the nanometer range will be most crack-resistant and thus provide the highest joint strength following welding. This is opposed to the situation existing in FSW, where the IMC layer is typically one to two microns thick and may contain flaws as well in the form of cracks. Obviously, the HYB nanolayer film is thick enough to create a very strong bond and at the same time thin enough to prevent it from cracking during tensile loading.

Finally, the characteristic low HYB process temperature also explains the unique multi-material joining capabilities of the method by allowing welding of up to four different metals in one pass. In the four metals (Al-Cu-Ti-Fe) butt joining case the role of the aluminum FM is to act as a solder, which bonds the other three metals together in a butt joint configuration. This kind of achievement has never been reported before for any other technique.

Table 2. Summary of the experimental conditions employed in the multi-material HYB joining trials.

Weld No.	Materials combinations	Welding parameters N_s (RPM)	v_w (mm/s)	v (mm/s)	E (kJ/mm)
1	BM: AA6060-T6 (plate thickness: 2 mm) FM: AA6082 (wire diameter: 1.2 mm)	250	122	8	0.28
2	BM: AA1050 (plate thickness: 4 mm) FM: AA1070 (wire diameter: 1.2 mm)	400	167	5	0.60
3	BM1: AA6082-T6 (plate thickness: 4 mm) BM2: S355 steel (plate thickness: 4 mm) FM: AA6082 (wire diameter: 1.2 mm)	400	146	6	0.37
4	BM1: AA6082-T6 (plate thickness: 4 mm) BM2: SS316 steel (plate thickness: 2 mm) FM: AA6082 (wire diameter: 1.2 mm)	400	163	7	0.33
5	BM1: Ti - Grade 2 (plate thickness: 3 mm) BM2: AA6082-T6 (plate thickness: 3 mm) BM3: HTC590 steel (plate thickness: 1.5 mm) FM: AA6082 (wire diameter: 1.4 mm)	350	125	8	0.24
6	BM1: AA6082-T6 (plate thickness: 3 mm) BM2: Ti - Grade 2 (plate thickness: 3 mm) FM: AA6082 (wire diameter: 1.4 mm)	350	125	8	0.24
7	BM1: Cu - 0.5 H (plate thickness: 3 mm) BM2: Ti - Grade 2 (plate thickness: 3 mm) BM3: HTC590 steel (plate thickness: 1.5 mm) FM: AA6082 (wire diameter: 1.4 mm)	350	115	6	0.33
8	BM1: AA6063-T6 (plate thickness: 3 mm) BM2: Cu - 0.5 H (plate thickness: 3 mm) FM: AA6082 (wire diameter: 1.4 mm)	350	125	8	0.24

N_s: Spindle rotational speed, v_w: wire feed rate, v: welding speed, E: gross heat input.

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