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A First Approach on Modelling the Thermal and Microstructure Fields During Aluminium Butt Welding Using the HYB PinPoint Extruder

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Abstract

Hybrid metal extrusion & bonding (HYB) is a new solid-state joining method for metals and alloys that utilizes continuous extrusion as a technique to enable aluminium filler metal additions. In the HYB case, heat is generated by friction between the rotating tool and the workpiece and by plastic deformation of the base and filler materials. To get further insight into how the PinPoint extruder behaves during aluminium butt welding, a finite element (FE) model for the HYB process has been developed by exploiting the framework provided by the numerical code WELDSIM. The model allows the thermal and microstructure fields along with the resulting HAZ hardness profile to be calculated from knowledge of the net power input. In the present investigation the FE model is used to determine the energy efficiency of the HYB process following calibration against thermal data being obtained from dedicated *in-situ* thermocouple measurements. In the future the FE element model will be extended to enable predictions of both residual stresses and global distortions by taking full advantage of the opportunities that the numerical code WELDSIM offers.

Keywords: FE modelling; WELDSIM; HYB; Aluminium welding; Thermal fields, Mictrostructural fields

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1. Introduction

Mechanical properties of components subjected to welding depend upon the characteristics of the microstructure. This applies in particular to structural parts of age hardening aluminum alloys, which are used to an increasing extent within the transport and automotive industry because of their high strength, good formability, low density and good resistance to general corrosion Myhr *et* al. (1998). In many cases, the application of aluminum is limited by a low heat-affected zone (HAZ) strength level due to softening reactions occurring during welding Myhr *et* al. (1998). In other cases, cracking resistance, fatigue strength or global distortions becomes the limiting factor, depending on the design criterion Myhr *et* al. (1998).

The term solid-state joining covers a vast number of processes such as cold pressure welding, diffusion welding explosion welding, forge welding, conventional friction welding and friction stir welding, hot pressure welding, roll welding and ultrasonic welding AWS Welding Handbook (2007), ASM Metals Handbook (1993). All these processes 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 and a wide 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 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 et al. (2014).

Recently, a new solid-state joining method for metals and alloys has appeared on the horizon, known as the Hybrid Metal Extrusion & Bonding (HYB) process Grong (2012), Sandnes *et* al. (2018), Berto *et* al. (2018), Blindheim *et* al. (2018), Grong *et* al. (2019), Leoni *et* al. (2020a), Leoni *et* al. (2020b), Leoni *et* al. (2020c), Grong *et* al. (2019). The HYB method utilizes continuous extrusion as a technique to enable aluminum filler metal (FM) additions. Figure 1 highlights the most important HYB PinPoint extruder tool parts.

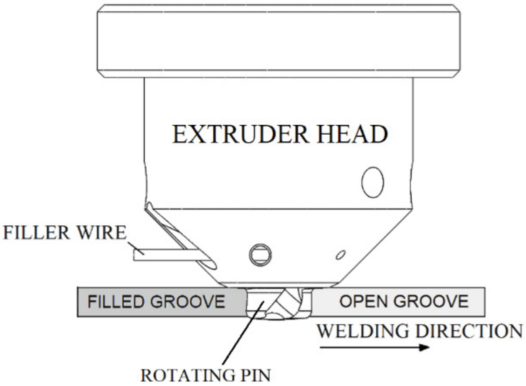

Figure 1: Schematic representation of the main parts of the HYB PinPoint extruder.

In a real butt-welding situation, the plates to be joined are separated from each other by a fixed spacing so that an I-groove forms between them. During the welding operation the extruder head shown in Figure 1 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 metal (BM). Metallic bonding between the FM and the BM then occurs by a combination of oxide dispersion and severe plastic deformation Sandnes *et* al. (2018), Sandnes *et* al. (2019), Grong *et* al. (2019). 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 aluminium in a continuous manner Grong *et* al. (2019).

In the present investigation attempts will be made to develop a finite element (FE) model for butt welding of aluminium plates and profiles using the HYB PinPoint extruder. As a starting point, the well-established numerical code WELDSIM is employed as a basis for the model development Fjær *et* al. (2005), Perret *et* al. (2011a), Perret *et* al. (2011b), Tang *et* al. (2015). This numerical code allows both the thermal, microstructure and residual stress fields along with the resulting HAZ harness profiles and global distortions in corresponding fusion welds to be calculated from knowledge of the net power input. In the HYB case, the energy efficiency of the PinPoint extruder is not known. Therefore, at first the FE model is used to determine the net power input during butt welding of 4 mm thick profiles of the AA6082-T6 type using a matching filler wire (FW). This will be done by calibrating the model against thermal data being obtained from dedicated *in-situ* thermocouple measurements. Then its ability to predict the resulting HAZ hardness profile in similar types of weldments will be evaluated by comparison with experimental hardness data being reported in the literature.

2. Weld preparation and location of thermocouples

The 4 mm thick AA6082-T6 butt weld referred to above was made using the HYB PinPoint extruder and the welding conditions summarized in Table 1. The experiment was carried out in HyBond's research laboratory at the Norwegian University of Science and Technology (NTNU). The pilot HYB machine at NTNU allows welds to be produced under controlled conditions, with full documentation of all relevant process parameters, e.g. temperature, torque, rotational speed, travel speed and wire feed rate as well as the main reaction forces acting on the extruder during welding Leoni *et* al. (2020a).

Table 1. Summary of operational conditions used in the HYB butt welding trial.

I-groove width	Pin rotation	Travel speed	Wire feed rate	Gross heat input†
3 mm	400 RPM	6 mm/s	142 mm/s	0.34 kJ/mm

† Value is not corrected for the amount of heat per second being removed by the CO_2 gas used to cool down the extruder.

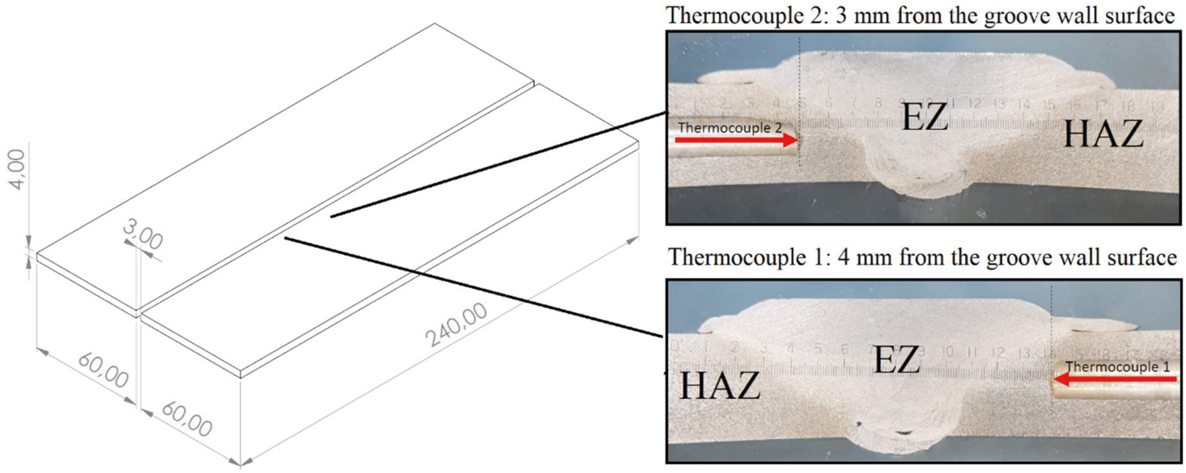

Figure 2: Workpiece dimensions and locations of thermocouples.

The dimensions of the base plates prior to butt welding are shown in Figure 2. The FM was a ϕ1.4 mm wire of the AA6082-T4 type produced by HyBond. Included in Figure 2 is also cross-sectional macrographs of the weld, revealing both the extrusion zone (EZ) and the HAZ as well as the location of the thermocouples. In this experimental set-up the first thermocouple is placed 110 mm from the start position of the weld and 4 mm from the groove wall surface, whereas the second one is placed 130 mm from the start position of the weld and 3 mm from the groove wall surface. In both cases the thermocouples were located on the advancing side (AS) of the weld.

3. Gross power output during welding and measured thermal cycles

Figure 3 shows how the torque acting on the drive spindle and the resulting gross power output, as calculated from the torque data, evolve with time during the joining operation. Moreover, the thermal cycles being recorded for the two thermocouple locations shown previously in Figure 2 are reproduced in Figure 4. These data are the starting point for the calibration of the FE model and provide a basis for calculating the energy efficiency of the HYB PinPoint extruder.

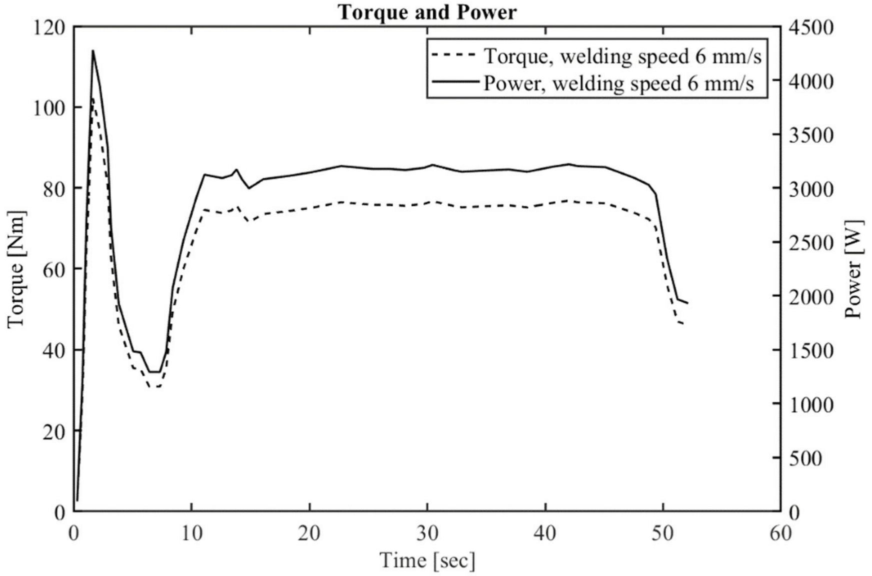

Figure 3: Plots showing how the torque acting on the drive spindle and the gross power output, as calculated from the same torque data, evolve with time during the welding operation.

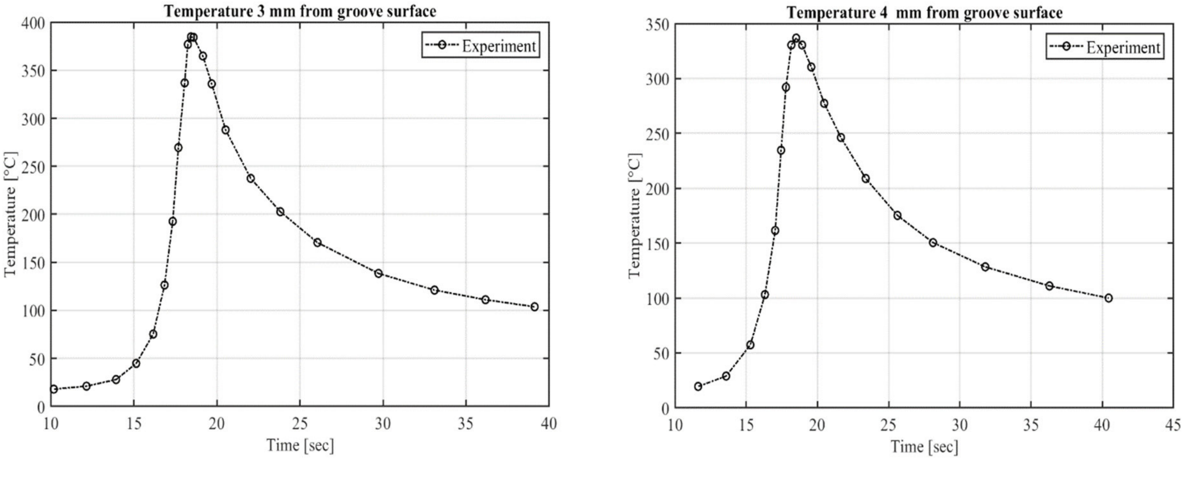

Figure 4: Recorded thermal cycles at the two different thermocouple locations shown in Figure 2.

4. Finite element modeling

To model the workpieces, a neutral file was first generated by using the CAE software Patran, where the domains were defined and then used to set the thermal boundary conditions in the numerical simulation code WELDSIM (see Figure 5). WELDSIM is a transient, nonlinear, three-dimensional finite element computer code for both heat transfer and solid mechanics analyses accounting for the evolution of the microstructure Fjær *et* al. (2005). Based on the modelling of the precipitation, growth and dissolution of hardening particles in 6xxx alloys, the softening of the HAZ during welding is estimated, and resulting fields of predicted yield stress and hardness after welding are provided Myhr *et* al. (2004), Myhr *et* al. (2009).

A double ellipsoid volume distributed heat source as proposed by Goldak *et* al. (1984), was placed in the middle the two workpieces to simulate the heat generation associated with friction and extrusion. This heat source moves along the weld line in the mid-thickness of the workpiece at the same speed as the tool, i.e. at 6 mm/s. To account for the metal deposition from the PinPoint extruder, elements that form the weld are continuously activated during welding as the heat source proceeds along the weld. Moreover, to account for the extra material that is present in the real joining operation with respect to the ideally smooth weld profile modelled, the density of the filler metal has been adjusted to obtain a correct heat capacity of the part. The boundary conditions are represented by heat transfer coefficients between the material and the environment. The top and bottom surfaces of the workpiece are assumed to have two different heat convection coefficients. At the top surface, a convective heat transfer coefficient of 20 $Wm^{-1}K^{-1}$ was used. The value is typical for natural convection between aluminum and air. At the bottom surface of the workpiece, a conductive heat transfer of 200 $Wm^{-1}K^{-1}$ was defined between the two domains. This is because the two base plates are clamped to a backup steel plate during the welding operation.

The heat being generated during the extrusion & joining operation leads to a temperature rise both in the two workpieces and the different extruder parts. However, how much of that heat which is actually absorbed by the base plates is not known and needs to be determined. Therefore, an iterative procedure was implemented to find the "best fit" value for the net power input. This was made possible by having WELDSIM to interact with Matlab, where Matlab first was set up to automatically generate different heat input values to WELDSIM. Then WELDSIM was used to calculate the resulting HAZ thermal fields. The whole process was repeated until a good agreement between measured and predicted thermal cycles for the two different thermocouple locations was obtained.

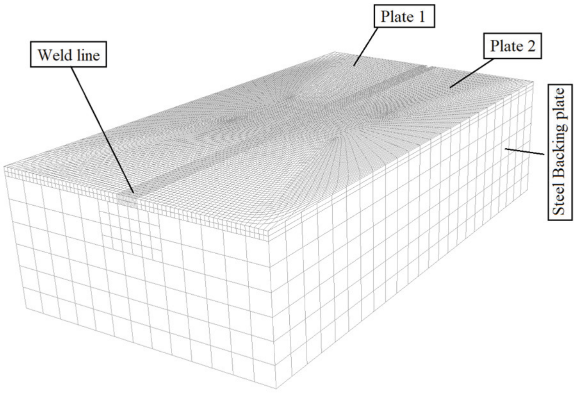

Figure 5: Finite element meshing of the different parts being modelled.

5. Results and discussions

Figure 6 shows a comparison between calculated and measured thermal cycles for the two thermocouple positions. It is evident that the numerical heat-flow model adequately predicts the HAZ temperature pattern following calibration. As shown in Table 2, the fine-tuned input value corresponds to a net power input of about 880 W, or a thermal efficiency factor of 0.28, as evaluated from a comparison with the listed value for the gross power output.

This means that only a minor fraction of the heat being generated is actually absorbed by the base plates in a real joining situation.

Table 2. Best-fit input values for the gross power output and the net power input during butt welding 4 mm thick plates of AA6082-T6 using the HYB PinPoint extruder.

Welding speed	Gross power output†	Net power input	Efficiency factor
6 mm/s	3135 W	880 W	0.28

† Value is not corrected for the amount of heat per second being removed by the CO_2 gas used to cool down the extruder.

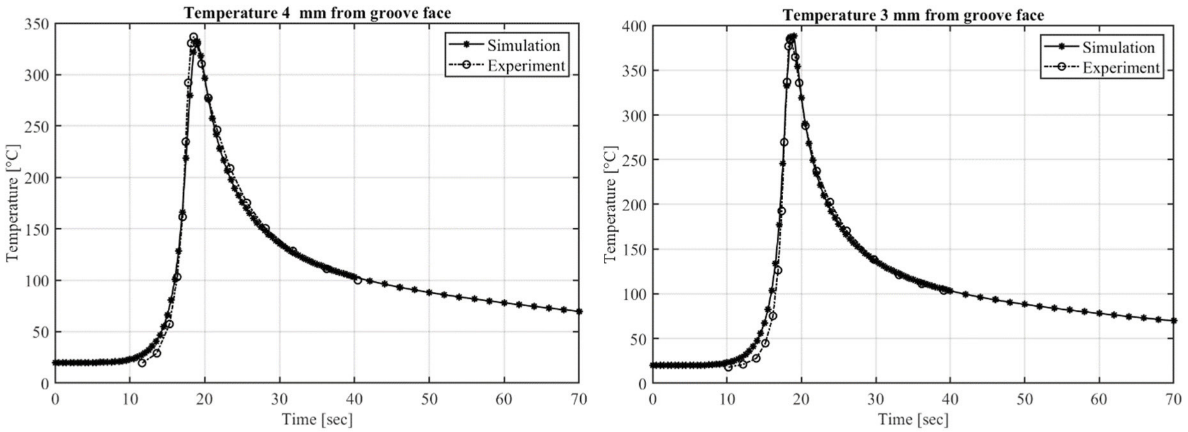

Figure 6: Comparison between predicted and measured thermal cycles following calibration of the FE model for the two thermocouple locations shown previously in Figure 2.

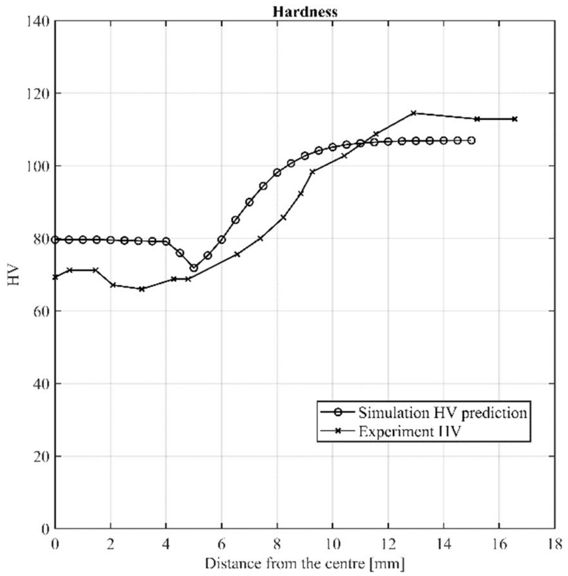

Figure 7: Comparison between predicted and measured cross-sectional hardness profiles for the 4 mm thick AA6082-T6 HYB butt weld referred to in the text.

Finally, by invoking the microstructure module being embedded in WELDSIM for calculating the resulting HAZ hardness distribution in Al-Mg-Si weldments Myhr et al (2004), Myhr et al (2009), the hardness profile in Figure 7 is obtained. This plot shows a comparison between predicted and measured hardness profiled in the cross section of a similar HYB aluminium butt weld 2 mm below the plate surface, where experimental hardness data are available (Sandnes *et* al. 2018). It follows that WELDSIM is capable of predicting the width of the HAZ quite well. Still, more work remains to be done when it comes to modifying the microstructure model to allow the absolute hardness level within the EZ to be calculated with a reasonable degree of accuracy.

6. Conclusions

The numerical code WELDSIM provides a good starting point for developing a finite element (FE) model for the HYB process.

- In a calibrated form the FE model allows the thermal and microstructure fields along with the resulting HAZ hardness profile to be calculated from knowledge of the net power input.
- Based on a best-fit comparison between predicted and measured thermal cycles for two different positions within the HAZ, a thermal efficiency factor of 0.28 is obtained for the HYB PinPoint extruder. This means that only a minor fraction of the heat being generated, as calculated from the torque acting on the rotating drive spindle, is actually absorbed by the base plates in a real joining situation.
- When the thermal efficiency factor of the HYB PinPoint extruder is known, it is possible to invoke the microstructure module being embedded in WELDSIM for calculating the resulting HAZ hardness distribution. It follows from a comparison with experimental hardness data that WELDSIM is capable of predicting the width of the HAZ quite well. Still, more work remains to be done when it comes to modifying the microstructure model to allow the absolute hardness level within the extrusion zone (EZ) to be calculated with a reasonable degree of accuracy.

7. Acknowledgements

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