FRICTION STIR WELDING OF ALUMINIUM HIGH PRESSURE DIE CASTINGS: PARAMETER OPTIMISATION AND GAP BRIDGEABILITY




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ABSTRACT

It is well established that friction stir welding (FSW) allows joining of aluminium alloys which can hardly be fusion welded. A well-known limitation of weldability in aluminium alloys is high hot crack sensitivity, such as encountered in Al-Cu and Al-ZnMgCu alloys. The weldability of cast alloys containing a significant amount of gases with MIG, TIG or laser welding is however also significantly compromised due to the occurrence of porosity, blowholes and cracks in the fused metal. In this study, the high pressure die cast aluminium alloy EN AC-46000-F, which belongs to the latter category of alloys with strongly reduced weldability, is successfully joined with the FSW technique. The selection of optimum welding conditions is discussed as function of the tensile properties and salient microstructural features. Moreover, the gap bridging ability of the FSW process is highlighted, by demonstrating the influence of weld gap on joint strength and the occurrence of weld flaws.

IIW-Thesaurus Keywords: *Aluminium alloys; Casings; Defects; Friction stir welding; Friction welding; Hardness tests; Joint preparation; Light metals; Mechanical properties; Mechanical tests; Microstructure; Process conditions; Process parameters; Reference lists.*

1 INTRODUCTION

It is well established that aluminium alloys have a large potential in many industrial sectors (automotive, aerospace, construction, general engineering, packaging) due to their interesting properties, e.g. low density, good mechanical properties, good corrosion resistance and high thermal/electrical conductivity [1]. However, the industrial use of certain aluminium alloys was somewhat inhibited, since these are considered non-weldable with conventional fusion welding techniques [2].

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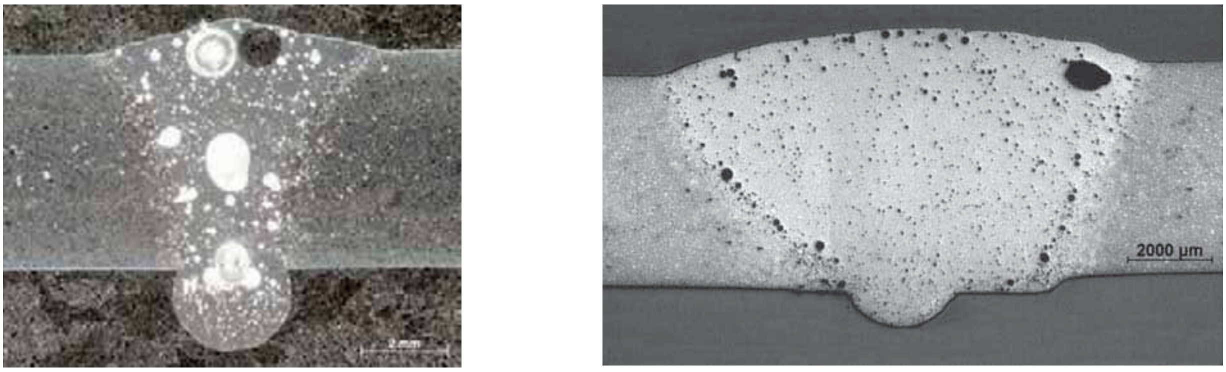
In the case of the high-strength Al-Cu (2xxx series) and Al-ZnMgCu alloys (certain 7xxx series alloys, such as 7075), the high tendency to hot cracking is problematic when conventional fusion welding processes are applied causing shrinkage and stresses in the welded zone. Successfully welding these alloys with MIG or TIG would require the use of filler material with a lower melting range than the base material, combined with a sufficiently high strength. Filler materials that meet both requirements are not commercially available (with the exception of 2319 for welding of alloy 2219 [3]).

Another factor compromising the weldability in certain aluminium alloys is the occurrence of blowholes in the weld metal of high pressure die castings when fusion welding techniques (such as MIG, TIG and laser welding) are used [4], unless restrictions on the gas content of the base material are imposed [5].



a) Nd:YAG laser welded b) Hybrid Nd:YAG laser-MIG welded

Figure 1 – Etched macrographs of fusion welds in EN AC-46000 alloy by Laser Center Flanders of VITO

The pores, which appear in fusion welds of die cast aluminium alloys, are due to the presence of nitrogen pores under high pressure as well as hydrogen trapped in hydrides in the base material microstructure. In Figure 1, the effect of two fusion welding processes is shown on the same castings as used for friction stir welding in this investigation.

Due to the reasons given above, hot crack sensitive aluminium alloys and die cast aluminium alloys are generally joined in a purely mechanical manner (such as bolting and riveting).

For these alloys in particular, “Friction Stir Welding” (FSW) provides a solution. This solid state welding technique was invented and patented in the early nineties by The Welding Institute (TWI, UK) [6].

The basic principle of this process is to soften the material by frictional heat generated between the material surfaces and a rotating tool. The components to be joined are rigidly clamped onto a backing plate. A rotating tool, consisting of a profiled probe and a shoulder, is forced down into the material until the shoulder meets the surface of the workpieces. The material in the close surrounding of the tool is thereby frictionally heated to temperatures where it is easily plasticised. As the tool moves forward, material is stirred from the leading to the trailing edge of the probe. Behind the probe, the joint is formed (Figure 2).

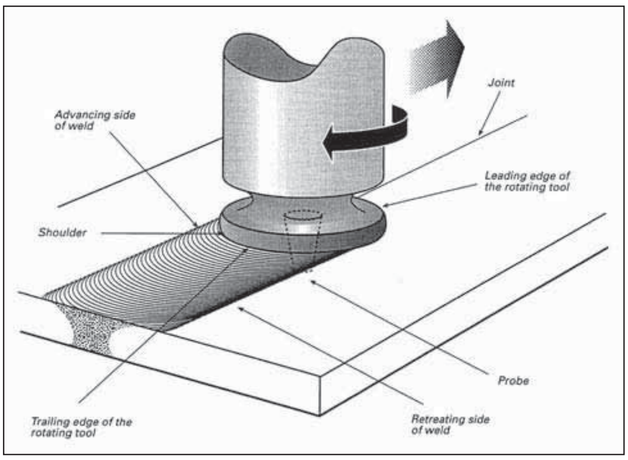


Figure 2 – Schematic representation of the friction stir welding process [9]

The high pressure die casting EN AC-46000 alloy was used in this study. This alloy contains gas in the microstructure which expands very rapidly and is set free during melting. This causes spattering, bad weld appearance, porosity and poor mechanical joint properties. The following research will prove that this alloy can be joined adequately by means of the friction stir welding technique (here executed on a conventional milling machine), due to the fact that no melting occurs at any stage of the FSW process. Therefore, it may be stated that FSW will revolutionise the welding of parts made of die cast aluminium alloys [7, 8].

Friction stir welding also allows the realisation of joints between aluminium die castings and aluminium wrought products, such as extrusion profiles. This type of joint receives special attention from the automotive industry for the realisation of space frames and suspension parts. It is shown in the literature that the mechanical properties of casting-to-extrusion friction stir welds are superior compared to TIG or laser welds [10].

Being able to friction stir weld a cast material may also present the advantage that welds can now replace permanent fasteners so that the casting itself becomes less complex (e.g. making holes in the casting is no longer necessary), and the amount of post-processing is reduced (it avoids the need for the threading of holes). In order to study the flexibility of the process, the tool geometry was chosen such that two-dimensional welds could also be performed. A complementary study on the weld gap tolerance of FSW applied to that alloy was executed.

2 BASE MATERIAL – EXPERIMENTAL PROCEDURES

2.1 Base material

The EN AC-46000 high pressure die casting aluminium alloy studied here is according to EN 1706 also indicated as EN AC-Al Si9Cu3(Fe) or 226D. Its standard chemical composition is given in Table 1.

This alloy has applications mainly in the transportation sector (complex machine and motor parts) and in

Table 1 – Chemical composition of EN AC-46000 according to EN 1706

Si	Fe	Cu	Mn	Mg	Cr
8.0-11.0	0.6-1.1	2.0-4.0	< 0.55	0.15-0.55	< 0.15
Ni	**Zn**	**Pb**	**Sn**	**Ti**	**Other**
< 0.55	< 1.2	< 0.35	< 0.25	< 0.2	< 0.25

electrical engineering (casings, housings). This alloy was supplied as high pressure die castings in as-fabricated condition, 152 mm long and 140 mm wide, with a thickness of 5 mm. Top and bottom side of the original castings are shown in Figure 3.

The tensile properties of 2 castings (2 tensile tests each) are given in Table 2 mentioning also the indicative mechanical properties of this alloy according to EN 1706 Informative Annex A. This material is clearly very brittle. It must be noted that the base material yield and tensile strengths (determined following EN 10002-1) are lower than mentioned in the standard. However, it is not customary to perform standard tensile tests on an actual casting, since its mechanical properties are varying substantially from location to location.

In the fracture surface of the tensile specimens, brittle glittering features were noticed, (Figure 4). Features noted in the base material microstructure are pores and abrupt changes in solidification direction along with oxide films (Figure 5).

These observations led to decide that tensile strength values obtained in friction stir welds in this material are of minor importance compared to the fracture location (i.e. in the weld or in the base material).

2.2 Experimental set-up

The friction stir welding process was executed by UCL-PRM using a displacement controlled 12 kW HERMLE

a) Top of the casting **b) Bottom of the casting**

Figure 3 – Photographs of the castings subjected to FSW in this study

Figure 4 – Fracture surface of a tensile test specimen in EN AC-46000 base material

Table 2 – Mechanical properties of EN AC-46000-F base material, compared with the requirements stated in Informative Annex A of EN 1706

	Yield strength $R_{p0.2}$ (MPa)	Tensile strength R_m (MPa)	Elongation after fracture (%)
EN 1706 Annex A	> 140	> 240	< 1
Base material (1)	137	167	0.6
Base material (2)	135	232	0.9

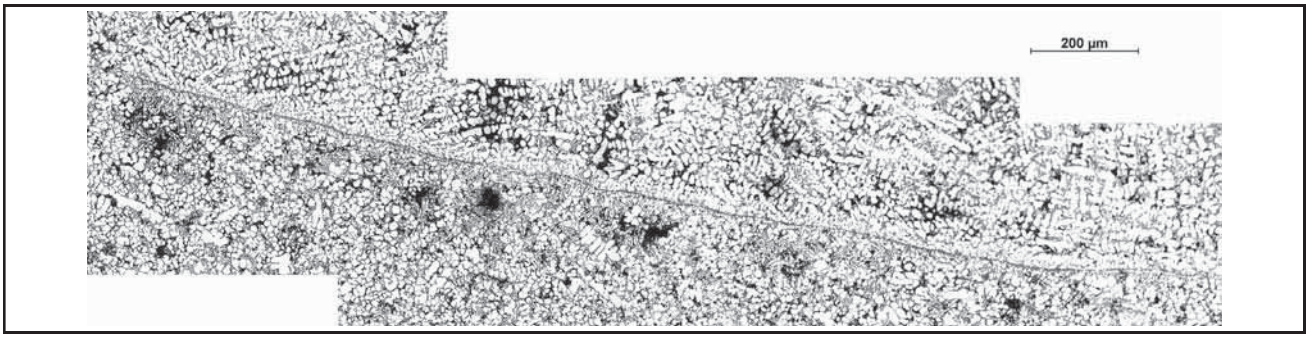


Figure 5 – Etched micrograph of a typical base material discontinuity

3-axis CNC milling machine (UWF 1001 H) equipped with appropriate clamping devices and home-made tools – see Figure 6.

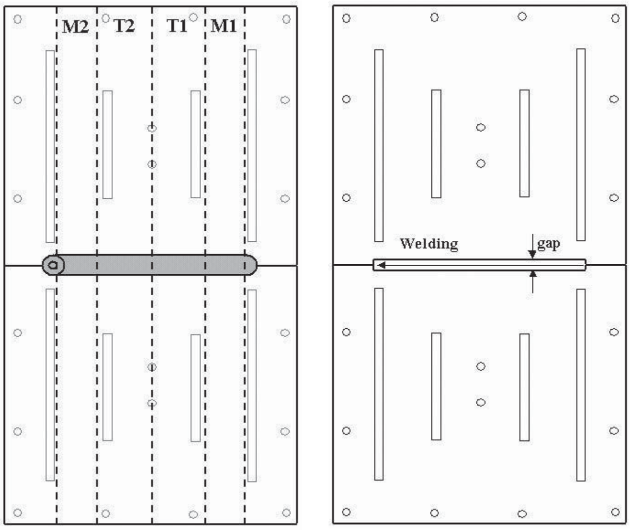
Due to the finite stiffness of the machine, there is a difference between the programmed plunge depth and the actual plunge depth with respect to the base material surface.

The welding direction ran parallel with the shortest dimension of the castings. The width of the castings to be welded was reduced by 12 mm, in such a way that the bolting holes present in the casting would not interfere with the welding process – see Figure 7 a). The casting edges were milled to limit the occurrence of unintentional weld gaps.

The joint geometry used to obtain a constant weld gap (0.2 mm, 0.5 mm or 1.0 mm), is shown in Figure 7 b): each of the two castings were partially milled over half the gap width prior to welding.

An example of the tool is shown in Figure 8. In order to maintain the plasticised material under the tool shoulder with a 0° tilt angle configuration, and therefore to achieve sound welds, a specially designed tool shoulder was used, see Figure 8. Two semi-spirals, 0.5 mm deep, were grooved into the shoulder surface which contains the plasticised material during welding. The tool itself had a shoulder diameter of 15 mm, a probe diameter of 5 mm, and a probe length of 4.7 mm. The probe was provided with an M5 left-hand screw thread and had a rounded-off end. It was made from H13 steel (X40CrMoV5-1), hardened to 50 HRC.

Figure 6 – Experimental FSW equipment at UCL-PRM used within this research



a) b)

(T: tensile test samples; M: sample for metallography)
In both cases, the welding direction is from right to left.

a) Sketch of the joint geometry, with indication of the sample extraction
b) Sketch of the preparation for constant weld gap friction stir welding

Figure 7

Transverse tensile testing of welds was executed on a 100 kN servo-hydraulic Instron 1342 universal testing machine at ambient temperature, in accordance with EN 895. The tensile test samples were machined up to the base material thickness. All mentioned tensile test data are based on at least two tensile tests – the

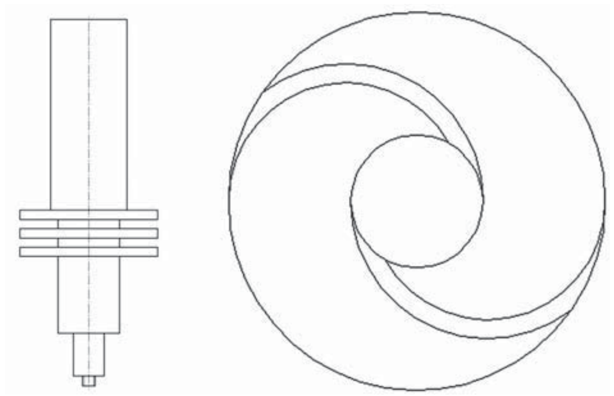
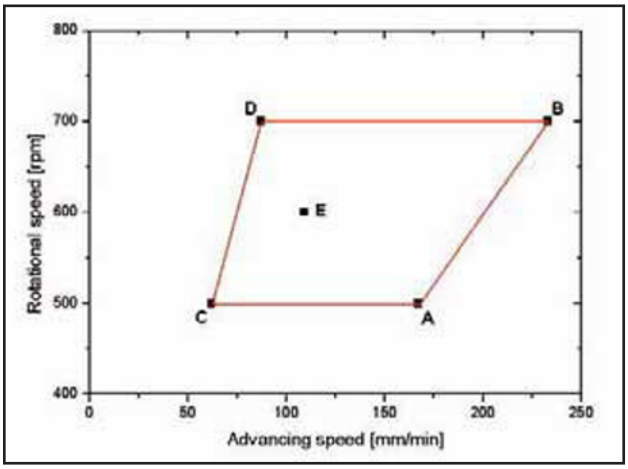


Figure 8 – FSW tool used at UCL-PRM (shoulder diameter: 15 mm; probe diameter: 5 mm), with a detail of the semi-spirals on the tool shoulder

extraction location of the test specimens is indicated in Figure 7 a).

Microscopic examination of parent material and welded joints was performed on a Zeiss-Axioskop 2 optical microscope, equipped with an AxioCam Mrc5 digital colour camera and the AxioVision image processing programme. Metallographic samples [two from each weld, see Figure 7 a)] were examined in both unetched and etched condition. In the latter case, Poulton's etchant was used. Microhardness testing was performed at mid-thickness on an Instron Wolpert TESTOR 4042 hardness indenter under a load of 4.903 N (HV0.5) with an indentation time of 30 s. On macrographs and microhardness profiles of friction stir welds, the advancing side (see Figure 2) is always displayed on the left.



The letters indicate the position of the welding parameters described in Table 3.

Figure 9 – Parameter window of EN AC-46000 alloy

3 RESULTS AND DISCUSSION

3.1 Welding parameter optimisation

The tilt angle of the tool was set at 0°. A zero tilt angle has the advantage that curvilinear (two-dimensional) welding can easily be performed, which is of course an advantage given the generally higher complexity of castings compared to wrought products.

The method of the present study takes into account the influence of the three main friction stir welding parameters (in the case of displacement controlled FSW equipment) for a given tool geometry, namely the rotational speed, the advancing speed and the plunge depth.

The first step of the research is based on literature, previous studies and a large number of pilot test welds. The latter were subjected to visual inspection of the weld face, weld root and exit hole. The next step consists in plotting a temporary welding parameter window, with the plunge depth kept constant. The plotted parameters are the advancing speed and the rotational speed.

Characterisation of welds at the parameter window corner conditions is then performed by means of tensile testing, metallography and microhardness measurements. The execution of transverse bend tests was considered to have little significance due to the previously mentioned brittleness of the base material itself.

Based on the weld characterisation results, the next step is either to investigate a new parameter window (larger or smaller), or to perform a weld with parameters corresponding with the welding parameter centre, in order to complete the data and confirm the study.

Figure 9 shows the final welding parameter window, while Table 3 summarises the principal welding parameters for these welds.

A typical macrograph of a friction stir weld in this material is shown in Figure 10. The interface between the nugget zone (central) and the parent material is relatively diffuse on the retreating side, but quite sharp on the advancing side of the tool.

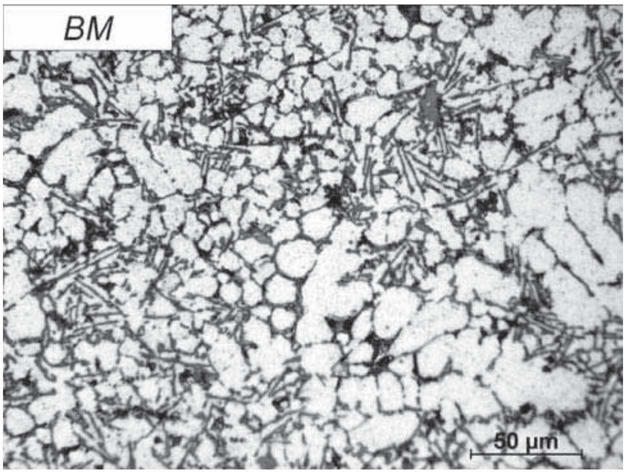
The microstructure of the distinct zones is given in Figure 11. The microstructure of the base material (BM) consists of primary aluminium dendrites separated by relatively coarse acicular silicon particles. There appears to be no large microstructural change in the heat-affected zone (HAZ) compared to the base material. An important refining effect of the microstructure is however readily observed in the thermomechanically affected zone (TMAZ), and certainly in the weld centre (the so-called "nugget").

This refinement is caused by breaking up and mixing of the heterogeneous base material microstructure due to the stirring motion of the FSW tool in the plasticised material. In these zones, the brittle silicon phase is broken and dispersed to a large extent. Therefore, the weld zone influenced by both heat and especially deformation has a more favorable microstructure. The

Table 3 – Numbering and welding parameters of EN AC-46000 friction stir welds (0 mm weld gap and 0° tilt angle in all cases)

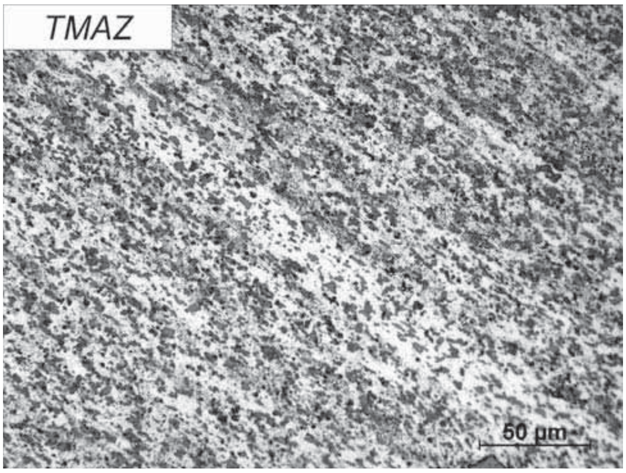
Weld	Rotational speed [rpm]	Advancing speed [mm/min]	Weld pitch [rev/mm]	Plunge depth [mm]
A	500	167	3	4.9
B	700	233	3	4.9
C	500	62	8	4.9
D	700	87	8	4.9
E	600	109	5.5	4.9

Figure 10 – Etched macrograph of a typical friction stir weld in EN AC-46000 (corresponding with weld E in Table 3)

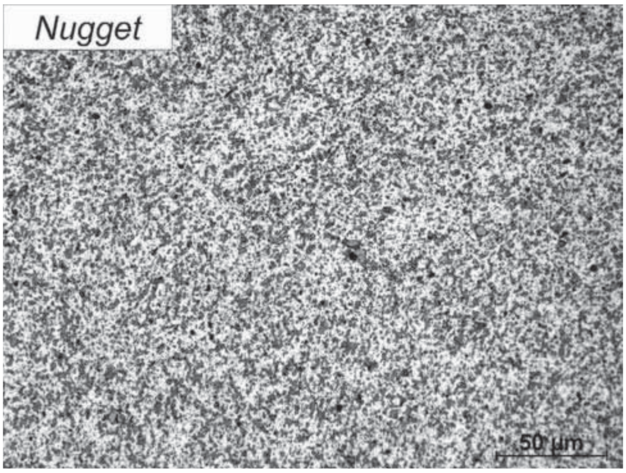


a) Base material (BM)

b) Heat-affected zone (HAZ)



c) Thermomechanically affected zone (TMAZ)



d) Weld nugget of weld E

Figure 11 – Etched micrographs

observation of this phenomenon in prior studies has led to the development of Friction Stir Processing, which no longer focuses on FSW as a joining technique, but rather as a microstructure modifying process [11, 12].

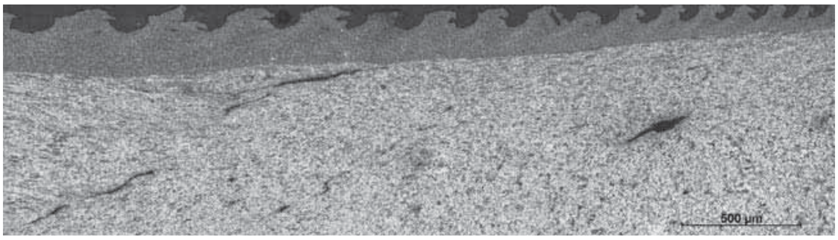
No significant difference in terms of microstructural refinement was observed in the weld nugget as a function of the advancing speed, contrary to [13], which might be due to a smaller range in advancing speed in the present study.

Typical welding defects encountered during the welding parameter optimisation phase were:

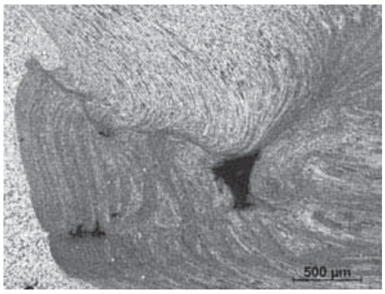
– cracks appearing in the TMAZ on the retreating side: this phenomenon can be explained as the result of the presence of flaws (pores) in the base material microstructure in combination with its very low deformability, see Figure 12 a);

– voids or tunnel defects in the weld nugget on the advancing side [Figure 12 b)]: this second feature is common in friction stir welding with non-optimised welding parameters due to inappropriate material flow or insufficient downward force.

In the welds from the parameter window shown in Figure 9, significant weld flaws were only present in



a) Cracks and voids in the TMAZ on the retreating side



b) Voids in the weld nugget on the advancing side

Figure 12 – Etched macrographs of weld flaws encountered in friction stir test welds

welds A and B, in the form of tunnel defects. The occurrence of tunnel defects might be explained by the higher advancing speeds, which negatively influence the material flow on the advancing side, as there is insufficient time to flow around the tool and fill the cavity left by the tool. An alternative explanation might be a decrease of the downward force, which increases the probability of generating tunnel defects. However, force measurements were not carried out during the welding experiments.

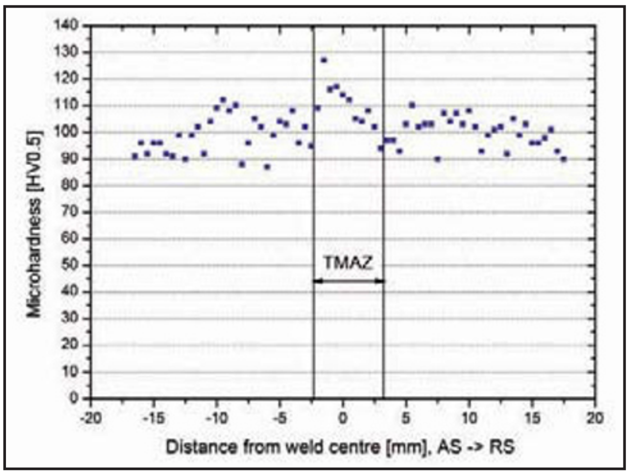
As shown in Figure 13, there is a large variation between individual microhardness measurements in the base material. With different welding conditions, similar profiles were obtained. As the microhardness values encountered in the weld zone are comparable to those of the base material, it can be stated that no softening occurred in the weld zone for these welding conditions. This was expected, since the base material was in a non heat treated, as-cast condition. In age hardened castings however, it is reported that a hardness decrease occurs in the weld zone [14]. Consistent hardness increase in the TMAZ or nugget due to microstructural refinement could not be confirmed.

During tensile testing of these welds, fracture always occurred outside the weld region. This indicates that the tensile strength of the weld zone is at least as high as that of the weakest point of the base material. Taking into account the fact that all tensile test specimens fractured outside the weld region, and considering the metallographic and microhardness results, the following can be derived:

– the microstructural imperfections present in the base material are greatly diminished in size in the TMAZ due to the mixing and breaking up feature of friction stir welding, which makes these features less detrimental with respect to static strength;

– there is neither significant hardening nor softening in the weld zone;

– any type of weld flaw encountered at this stage in the weld zone is less harmful for the strength than porosity or oxide inclusions initially present in the base material.



The vertical lines indicate the TMAZ width (including the nugget)

Figure 13 – Microhardness profile of weld E at mid-thickness

3.2 Gap tolerance investigation

When friction stir welding, the welding gap is usually set as closely to zero as possible by milling the edges. In this study, it was however also attempted to investigate the weld gaps that can be tolerated by the process with the present equipment, in order to judge the weld seam preparation needed for the present material – see Figure 7 b). The welding parameters are given in Table 4. In order to optimise the stirring of the material, a 2° tilt angle was used to perform this study (except in the case of L2*). The number in the weld designation addresses the constant weld gap (in mm) multiplied by 10.

Welds H2, H5 and H10 were executed with a relatively high (H) heat input, while welds L2 and L5 were executed with a relatively low (L) heat input. Actual heat input values are not mentioned in Table 4, as weld power was not determined. However, given the large difference in weld pitch (8.3 rev/mm compared to 3.5 rev/mm) while maintaining a comparable rotational speed, it is considered justified to state that the "H" welds are indeed executed at significantly higher heat input than the "L" welds.

Welds L2*, L5* and L10* were also executed with the lower heat input; however, the settings for the plunge depth were changed (L5* and L10*). In the case of L2*, both plunge depth and tilt angle were adapted.

Macrographs of transverse sections of the welds H2, L2, H5, L5 and H10 are shown in Figure 14.

The average tensile strength is shown in Figure 15. In this case, given the differences in tensile strength between the various welds, both the fracture location and

Table 4 – Numbering and welding parameters of EN AC-46000 friction stir welds performed with a constant weld gap

Weld	Rotational speed [rpm]	Advancing speed [mm/min]	Weld pitch [rev/mm]	Plunge depth [mm]	Tilt angle [°]	Gap [mm]
H2	500	60	8.3	4.9	2	0.2
L2	700	200	3.5	4.9	2	0.2
H5	500	60	8.3	4.9	2	0.5
L5	700	200	3.5	4.9	2	0.5
H10	500	60	8.3	4.9	2	1.0
L2*	700	200	3.5	5.1	0	0.2
L5*	700	200	3.5	5.2	2	0.5
L10*	700	200	3.5	5.2	2	1.0

a) Weld produced with a weld gap of 0.2 mm

b) Weld produced with a weld gap of 0.2 mm

c) Weld produced with a weld gap of 0.5 mm

d) Weld produced with a weld gap of 0.5 mm

e) Weld produced with a weld gap of 1.0 mm

See Table 4 for the actual welding parameters.

Figure 14 – Etched macrographs of EN AC-46000 friction stir welds

the tensile strength (if fracture occurs in the weld zone) become relevant.

The following observations were made:

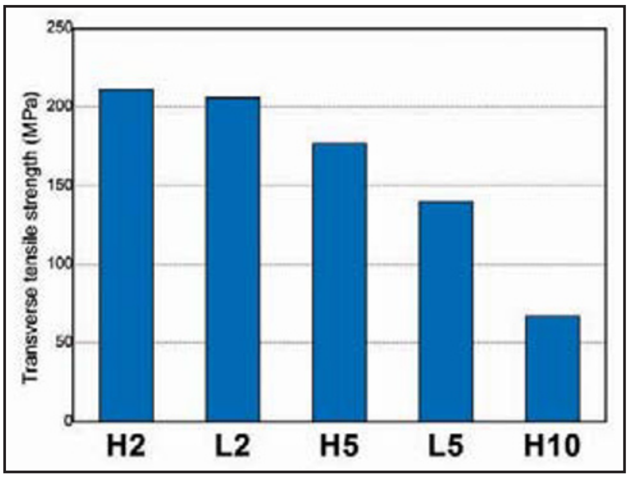


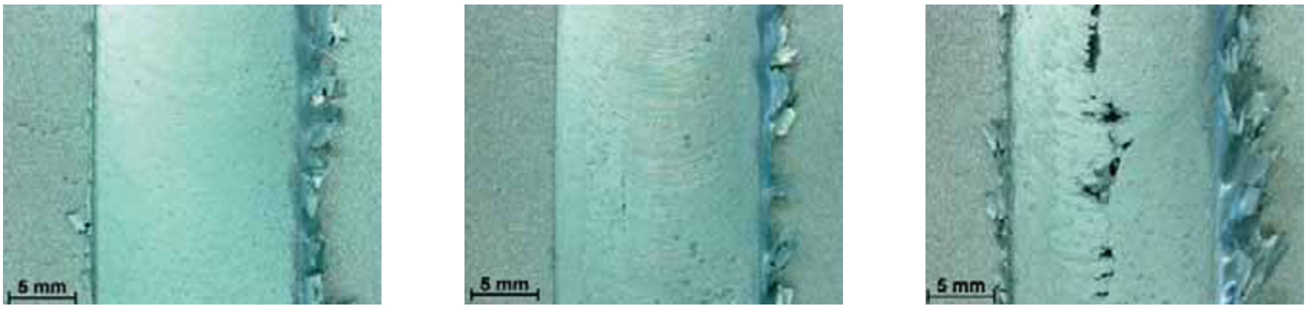
Figure 15 – Average tensile strength of EN AC-46000 friction stir welds produced with different weld gaps

– In weld H2, the weld zone is flawless, contrary to the intrinsically heterogeneous base material. Therefore, fracture during tensile testing logically occurred in the base material.

– In weld L2, a small tunnel defect on the advancing side is observed. However, since the defect size is smaller than flaws present in the base material, it is not surprising that fracture also occurred in the base material.

– In weld H5 a large tunnel defect on the advancing side is observed. Furthermore, small defects on the advancing side close to the weld surface can be noticed. As the flaws are located in the relatively strong, refined weld zone, the tensile strength of this weld remains quite comparable to that of the base metal, even though fracture now occurred in the weld nugget on the advancing side.

– In welds L5 and H10, the tunnel defect becomes larger. While the surface is quite smooth for all the previous welds (for example weld H5 in Figure 16), shallow and small surface-breaking flaws become visible



a) Weld H5 **b) Weld L5** **c) Weld H10**

Advancing side is always on the left.

Figure 16 – Macrograph of the weld face

at some places on the advancing side of weld L5. In weld H10 however, surface-breaking flaws are clearly appearing. Due to the important area reduction at the flaw locations (refer to Figure 14), the welds L5 and H10 fractured in the weld nugget, with a significant drop in tensile strength. Especially in weld H10, the thickness reduction of the weld zone is pronounced: the weld face is devpressed by 300 µm compared to the base material surface.

It is evident that the size of the defect plays an important role in failure location and tensile behaviour. However in this case, more than the size itself, the distribution of flaws and homogeneity of the base material are important to the tensile behaviour of the welds tested. For example, several small porosities or oxide inclusions close to each other (for instance, with sizes smaller than the tunnel defect) in the base material are much more detrimental to the tensile behaviour than the size of the tunnel defect. In the case of larger tunnel defects (H5, L5 and H10), surface flaws or thickness reduction are also present which negatively influence the final tensile behaviour.

From these observations, it can be derived that a higher heat input (more revolutions of the tool per mm weld length) is beneficial with respect to gap bridging.

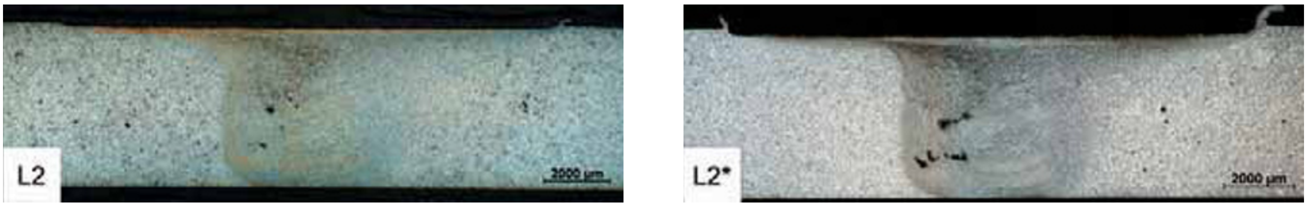
That the selection of a 2° tilt angle was justified is shown in Figure 17. Compared to weld L2, L2* was executed at 0° tilt angle. Even though a higher plunge depth was applied, larger volumetric flaws are present in L2* compared to L2. However, fracture during tensile testing still occurred in the base material.

It was attempted to further increase the gap bridgeability of the process for the lower heat input conditions towards 0.5 and 1.0 mm weld gap, using the same FSW tool. In order to achieve that, for two new welds (L5* and L10*) a higher plunge depth was programmed during welding (5.2 mm instead of 4.9 mm).

Macrographs of these welds are shown in Figure 18. No volumetric weld flaws are present in the microstructure. During tensile testing, fracture occurred in the base material. Therefore, it can be stated that a constant weld gap of 1.0 mm – 20 % of the base material thickness – is bridged successfully with these welding parameters. This is a good result compared to the allowable weld gap of 10 % of the base material thickness sometimes mentioned [15].

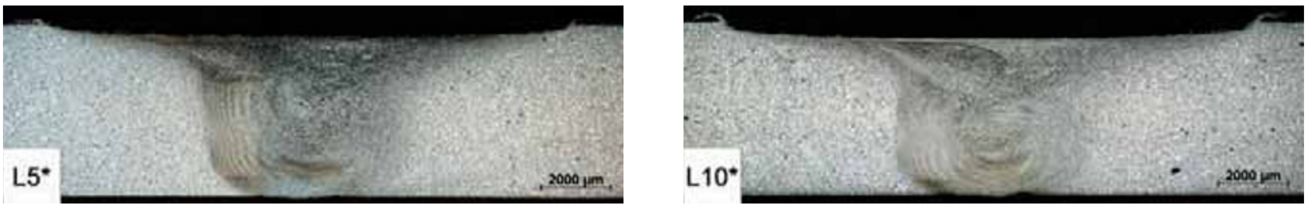
4 CONCLUSIONS

Friction stir welding of the high pressure EN AC-46000-F die cast aluminium alloy was performed, and a parameter window to perform sound welds was determi-



a) Weld L2 **b) Weld L2*(executed with higher plunge depth and 0° tilt angle instead of 2°)**

Figure 17 – Etched macrographs of welds



a) Weld L5* (weld gap of 0.5 mm) **b) Weld L10*(weld gap of 1.0 mm)**

Figure 18 – Etched macrographs of friction stir welds in EN AC-46000 executed with a constant weld gap, with 5.2 mm plunge depth

ned. Two advantages were clearly distinguished by using FSW:

– sound joints can be obtained in a material which is considered – with good reason – unsuitable for fusion welding;

– the refined microstructure of the weld zone appears much more favourable than that of the base material.

Two types of flaws were encountered in the welds of this material: cracks near the weld face on the retreating side, and – more commonly – voids on the advancing side. The weld in the middle of the process window (E) did not show any microstructural flaw.

As none of the zero gap butt welds fractured in the weld region during tensile testing, it is concluded that any flaw observed in the weld zone is less detrimental to the mechanical properties than the pores or oxide inclusions initially present in the base material. Indeed, the refined microstructure of the nugget and the TMAZ is at least as resistant and tough as the base material. No hardness decrease took place in the HAZ, and therefore, the mechanical properties of the welds remained at least as good as that of the base material. A better resistance in the weld zone is obtained because heterogeneous irregularities in the weld zone are reduced in size compared to the base material, due to the mixing feature of friction stir welding.

It was found that the gap bridging ability is somewhat higher when FSW is executed with higher heat input. More tool revolutions per mm seem to lead to less chance for discontinuities (voids / tunnel defects) appearing in the microstructure.

Using a combination of a 2° tilt angle and higher plunge depth resulted in successfully bridging a constant weld gap of at least 1.0 mm (20 % of the base material thickness) with the lower heat input welding parameters.

Further work on FSW of this alloy could consist of the following:

– extension of the parameter window towards higher advancing speed (hence higher productivity) could be achieved by changes in other welding parameters such as plunge depth and tool geometry;

– deeper investigation of the separate influence of plunge depth and tilt angle (together with tool geometry) with respect to weld gap bridging of FSW;

– investigation of bridging ability of the FSW process in the case of continuously varying welding gaps;

– realisation of casting-to-extrusion dissimilar friction stir welds;

– friction stir welding of EN AC-46000 alloy in age hardened condition – this however requires further developments in the casting process in order to allow the material to be heat treatable (this implies a low gas content).

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