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FSW Welding of Aluminium Casting Alloys

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Abstract

The article contains basic information associated with the impact of the FSW process parameters on the forming of a weld while friction welding of aluminium casting alloys. Research was conducted using specially made samples containing a rod of casting alloy mounted in the wrought alloy in the selected area of FSW tool acting. Research has thrown light on the process of joining materials of significantly dissimilar physical properties, such as casting alloys and wrought alloys. Metallographic testing of a weld area has revealed the big impact of welding conditions, especially tool rotational speed, on the degree of metal stirring, grain refinement and shape factor of a weld. As the result of research it has been stated that at the high tool rotational speed, the metals stirring in a weld is significantly greater than in case of welding at low rotational speeds, however this fails to influence the strength of a weld. Plastic strain occurring while welding causes very high refinement of particles in the tested area and changing of their shape towards particles being more equiaxial. In the properly selected welding conditions it is possible to obtain joints of correct and repeatable structure, however in the case of the accumulation of cavities in the casting alloy the FSW process not always eliminates them.

Keywords: Product development, Casting defect, FSW, Aluminium

1. Introduction

Aluminium casting alloys are difficult to weld using known arc welding techniques and their wide application in automotive, household appliances production and other industrial branches induce searching for the new methods of their joining. For joining aluminium and its alloys a relatively new method of welding in solid state, i.e. FSW can be applied [1].

In FSW process for heating, plasticising and joining the rotating tool with a pin is used most often, which penetrates weld zone along the joint line. The heated and plasticised materials of the components being welded are extruded around the tool pin backwards, where before cooling down they are upset by the shoulder. The scheme of the process is shown in Fig. 1 [1].

The shape and dimensions of a weld depend on the shape and dimensions of the stirring tool and applied welding parameters. In case of aluminium casting alloys welding, the microstructure of a weld is associated both with the processes of deforming, recovery and recrystallization and also with phase transformations of microstructure components, e.g. with precipitation or dissolving of intermetallic phases. Welding conditions influence also the degree of metal stirring in the faying area [2, 3]. While selecting welding conditions it is essential to obtain a weld free from defects and meeting the required functional quality.

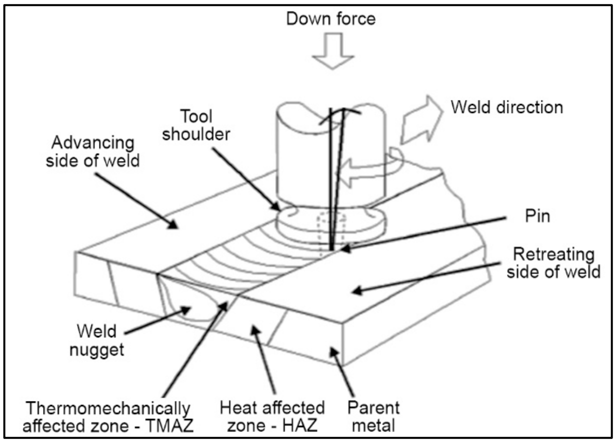


Fig. 1. The scheme of the FSW process [1]

The aim of this research was finding the impact of FSW process conditions on a weld structure and the joint quality during friction welding of aluminium casting alloys.

2. Description of the station, tools and materials

The investigation into FSW process was conducted on the friction welding machine constructed basing on FYF32JU2 vertical milling machine equipped with special clamps fixing the parts being welded. The station for testing linear butt welding of aluminium sheets and plates is shown in Fig. 2.

Fig. 2. Station for FSW welding process testing

During the research tools with the conventional pin and the Triflute pin were used having a shoulder diameter D = 20 mm, pin length l = 5,8 mm and pin diameter d = 8 mm (Fig. 3). The tool tilt angle was 1,5°. In testing of FSW process the samples cut out from 6.0 mm thick plates of EN AC-43200 casting material and EN AW-6082 wrought aluminium were used. Chemical composition of materials used during investigations are presented in Table 1.

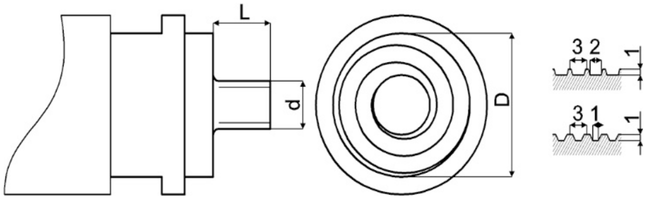


Fig. 3. Structure of a working part of FSW process tool

3. Testing of the process of the FSW weld forming

During FSW process, i.e. rotating and translational motion of a tool, the material is extruding around the tool pin on the retreating side and is subjected to the stresses and significant strains in this region. Behind the tool the compact weld is being formed of displaced and stirred materials as the result of the upsetting by the shoulder. (Fig. 4). In order to select correct conditions for friction welding of casting alloys the impact of welding conditions, mainly of rotational speed, on the process of the structure forming behind the tool has been tested. To this end a rod of EN AC-43200 casting alloy, having the dimensions of 3.0 x 3.0 mm was mounted in the material of EN AW-6082 alloy, see Fig. 5.

a) b)

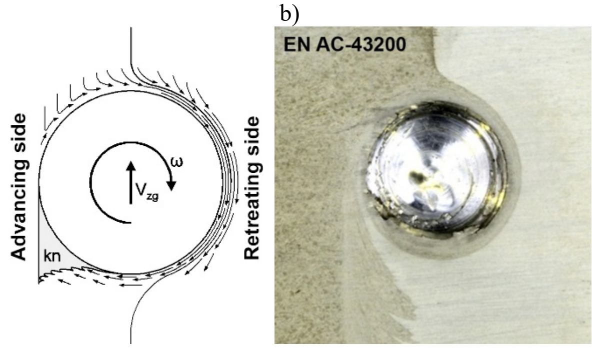


Fig. 4. Schematic image of the metal motion around the tool pin (a) and cross-section of the joint perpendicular to tool axis, in the place of retracted tool pin (b); *kn* – place of possible forming of wormhole discontinuities

Table 1.
Chemical composition of aluminium alloys used during studies [6, 7]

No.	Alloy denotation		Content of elements, %									
	numerical symbol	chemical symbol	Si	Cu	Mg	Mn	Fe	Ti	Zn	Ni	Cr	Al
1	EN AC-43200 (AK9)*	EN AC-AlSi10Mg(Cu)	9,00-11,00	0,35	0,20-0,45	0,55	0,65	0,20	0,35	0,15	-	rest
2	EN AW-6082 (PA4)**	EN AW-Al Si1MgMn	0,70-1,30	0,10	0,60-1,20	0,40-1,00	0,50	0,10	0,20	-	0,25	rest

Notes:
* Aluminium casting alloy, ** Wrought aluminium alloy

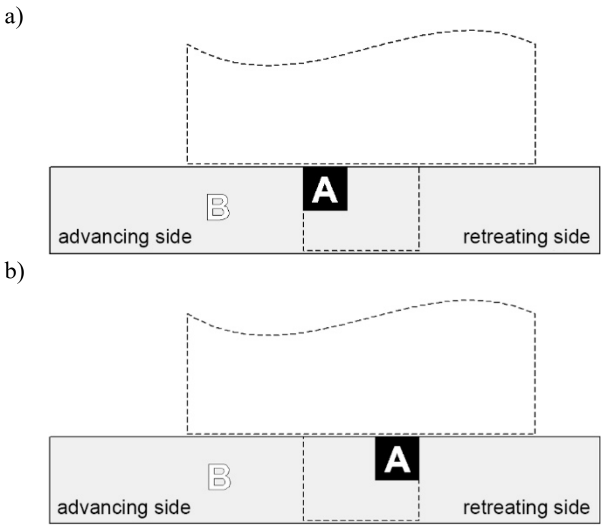


Fig. 5. Diagram of location of the rod of EN AC-43200 alloy (A) in the material of EN AW-6082 alloy (B) before welding with FSW process, a) from the advancing side; b) from the retreating side

As results from Fig. 4 the zone associated with the possible occurrence of discontinuities in a weld is not so much connected with faying surfaces of metals being joined but with stresses behind the tool. In the large majority of cases metals from the retreating and advancing sides modified and pressed against each other on the retreating side while displacing backwards join together and form the continuous structure. Possible lacks of continuities however occur in a weld zone on the advancing side (Fig. 4). Depending on the process parameters and type of used tools as well as thickness of welded plates the area of limited coherence of metal may be located closer to the tool shoulder, i.e. in the vicinity of the weld face or closer to the tool pin end, i.e. in the root area.

The testing of weld structures in samples with mounted rod of EN AC-43200 obtained during FSW process has revealed that after friction welding process the rod is located in specific regions of a weld, which can be seen in the cross-sections. The structure of a weld zone after the tool passage, depending on the process conditions, more or less resembles the arrangement before welding.

In the case of locating the rod with EN AC-43200 alloy on the advancing side before welding (Fig. 5a), during welding process the material is deformed and displaced around the tool pin and after welding it is located in the weld also on the advancing side, as in Fig. 6. The deformed material of EN AC-43200 alloy (material A) is more or less in the same weld area as before the process.

In the case of locating a rod on the retreating side before welding (Fig. 5b), during welding process the material is displaced around the tool pin and analogically is located in the weld on the retreating side, as in Fig. 7.

In the case of welding at twice as high rotational speeds the stirring of metals is significantly greater. In the whole welding area and particularly in the central region, called weld nugget, is the fine-grained structure mixture of many times dynamically recrystallized metals (Fig. 8 and 9).

Fig. 6. Structure of FSW weld in the case of locating the rod of EN AC-43200 (A) on the advancing side. Welding parameters: $\omega = 450$ min^{-1}, $V = 224$ mm/min. Triflute pin. Etching: Keller

Fig. 7. Structure of FSW weld in the case of locating the rod of EN AC-43200 (A) on the retreating side. Welding parameters: $\omega = 450$ min^{-1}, $V = 224$ mm/min. Triflute pin. Etching: Keller

Fig. 8. Structure of FSW weld in the case of locating the rod of EN AC-43200 (A) on the advancing side. Welding parameters: $\omega = 900$ min^{-1}, $V = 224$ mm/min. Triflute pin. Etching: Keller

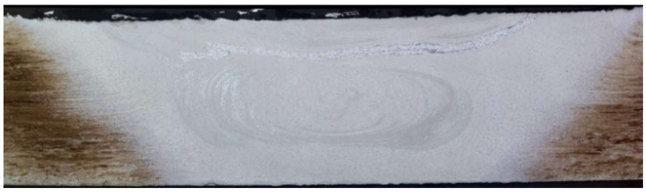


Fig. 9. Structure of FSW weld in the case of locating the rod of EN AC-43200 (A) on the retreating side. Welding parameters: $\omega = 900$ min^{-1}, $V = 224$ mm/min. Triflute pin. Etching: Keller

In spite of the fact that in welding process at low rotational speeds of a tool the implemented material was also very strongly heated and deformed while extruding around the tool pin (Fig. 6 and 7), the previous localisation of separate parts of metals was successfully reproduced. Dissimilar physical properties of the materials in this case did not prove any significant obstacles. Some small particles coming from the material being mounted could move in a random way and be inserted in the material matrix, but in its whole mass the significant part of mounted material does not change its location relative to the tool axis after FSW process. The photograph of the structure, Fig. 10, shows the well visible boundary between material of EN AC-43200 alloy and the material matrix of EN AW 6082 alloy.

Despite the lack of stirring of the individual metals in their contact area, due to the strong upsetting a good connection and metallic continuity along the joint line can be observed. In the photograph of the structure (Fig.11) good metallic bonding between a layer of EN AC-43200 alloy (from the top) and the matrix material of EN AW-6082 alloy is visible. The SEM-EDS analysis was conducted for numerous locations in weld cross-cuttings from Figs. 6-9. Exemplary results of the analysis are presented in Figs. 12-15.

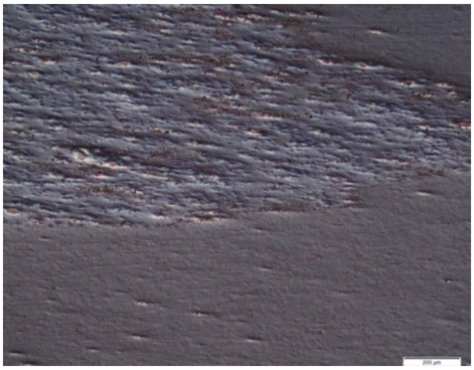


Fig. 10. Fragment of a structure from Fig. 6. EN AC-43200 alloy (from top) located on the advancing side after friction welding process (Nomarski contrast)

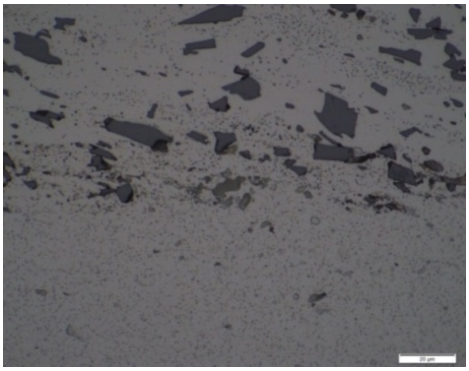


Fig. 11. Fragment of the structure from Fig. 6. Joining of EN AC-43200 metal layer (from top) with EN AW-6082 alloy

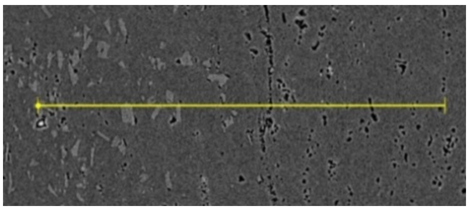


Fig. 12. Fragment of the structure from Fig. 6. The boundary between EN AC-43200 alloy (from the left side) and EN AW-6082 alloy (from the right side). Welding parameters: ω = 450 min^{-1}, V = 224 mm/min. Triflute pin. SEM-EDS chemical composition analysis was conducted along the marked line (Fig. 13)

Good metal stirring in the central part of a weld occurs especially in the case of welding at high rotational speeds of a tool. This however fails to unambiguously influence the quality of the joint between metals being welded. While strength testing using the pressure test any difference have not been revealed: the test pieces (radiators) with welds obtained both with low and high rotational speed of a tool proved leakproofness at the pressure of 10 MPa.

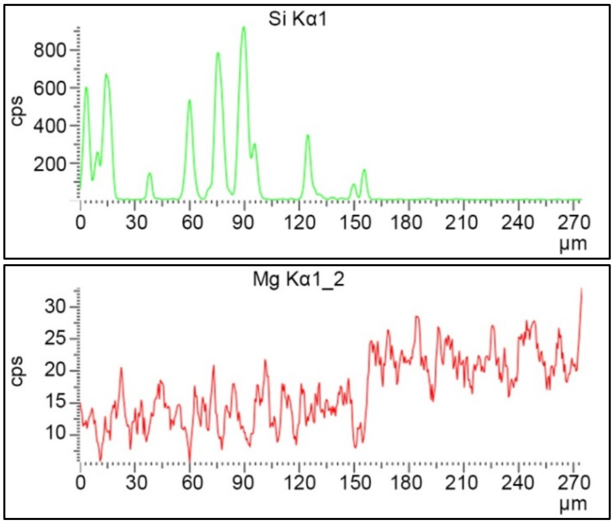


Fig. 13. Concentration of Si and Mg along the measuring line from Fig. 12

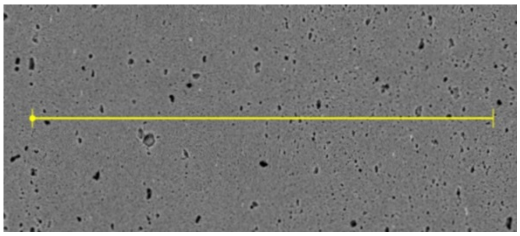
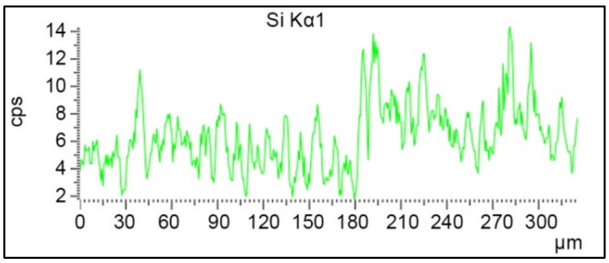


Fig. 14. Fragment of the structure from Fig. 8. Welding parameters: ω = 900 min^{-1}, V = 224 mm/min. Triflute pin. SEM-EDS chemical composition analysis was conducted along the marked line (Fig. 15)



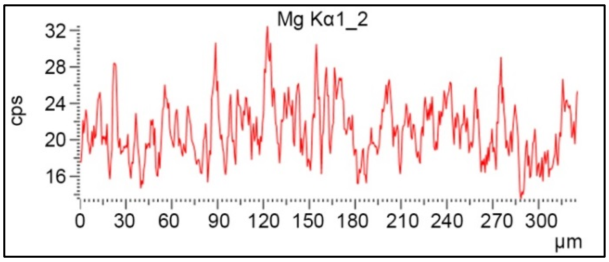


Fig. 15. Concentration of Si and Mg along the measuring line from Fig. 14

The tests of the structures of FSW welds have revealed that FSW process significantly influences two additional phenomena being observed in the weld area: refinement of grains of a structure and elimination of defects/cavities occurring in a casting. As can be seen in Fig. 16 the weld structure is compact and free from discontinuities, even in the case of occurring of substantial number of cavities in the parent material.

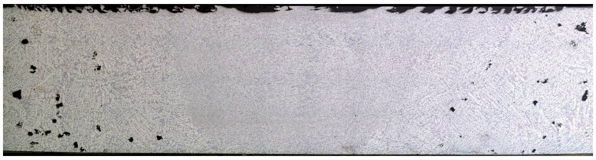


Fig. 16. Macrostructure of FSW weld (in the central zone) in the EN AC-43200

Research conducted in various research centres have proved that the size of grains is significantly reduced after FSW process [3, 6, 7]. Testing of grain size in the central area of a FSW weld have confirmed that the grains undergo substantial refinement and unification. The calculated medium size of a material particle is 80.2 μm^2. In turn average size of a particle in a weld is significantly smaller and amounts to 12.4 μm^2. In Fig. 17 distribution of shape factor value basing on the data from EBSD is presented.

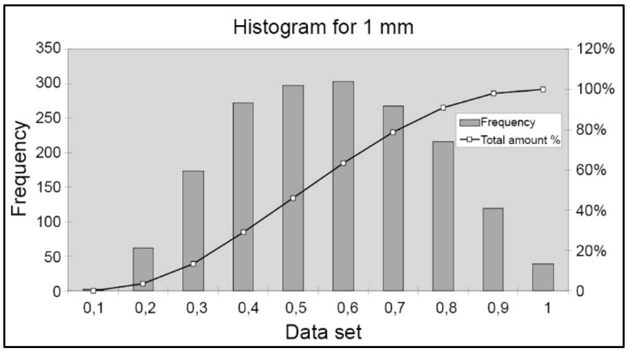


Fig. 17. Distribution of shape factor value basing on the data from EBSD [14]

Material from the welded area when is squeezed around the pin is subjected to strong stress and distortion. The intermetallic particles undergo fragmentation and deformation. In the Fig. 18 the fragmentation of the particles, probably of $Al_3(FeMn)$, during FSW process is visible. After welding the structure of the parent material (Fig. 18a) is clearly fragmented and intermetallic particles take shape more equiaxial (Fig 18 b).

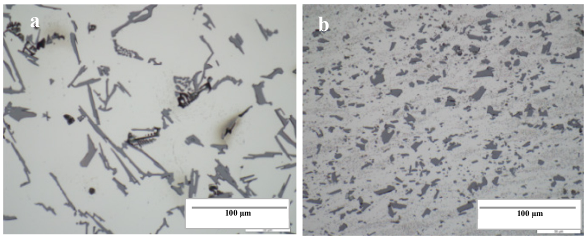


Fig. 18. Structures of casting alloy before FSW – a) and after FSW process – b) (SEM)

4. Summary

During friction welding, due to rotation and translational movement of a tool, around the tool pin in the layer being frictional modified the stress field occurs depending on the movement speed. Compressive stresses are present in a layer in the front of a tool on the retreating side, whereas tensile stress is behind the tool, on the advancing side. The calculations have revealed that these stresses are not very high, from several to several tens MPa and depend on temperature conditions of the weld area, i.e. on parameters of a tool movement and its dimensions. They are however sufficient to create the favourable conditions for joining of individual parts of the material, coming from different sides of a tool [9, 10]. Compressive stresses on the retreating side exert the pressure on metals in the contact area of heated layers, which enables a good contact of metals and joining of layers in the solid state after stopping their relative motion. In the faying surface due to friction and pressure induced by a tool movement, in practice metals are always well joined. Lacks in continuity in a weld may rather occur behind the tool, on the advancing side where the tensile stresses are present (area *kn* – Fig. 4). This observation is similar to the results quoted by various authors [3, 11]. In Fig. 4 the schematic metal motion around the pin and location of the possible occurrence of discontinuities is marked.

Testing of the weld structures of samples with mounted EN AC-43200 rod obtained in the FSW process has revealed that this rod is located the specific areas of a weld which is visible in the cross-sections. The structure of a weld zone after the tool passage, depending on the process conditions, more or less resembles the arrangement before welding. While conducting the process with low tool rotational speeds (450 min^{-1}) after welding the structure was rebuild like before the process: the material from mounted rod was located on the advancing or retreating side, depending on its previous location (Fig. 6 and 7). The process is not that clear in the case of welding with high tool rotational speeds (900 min^{-1}), which is visible in Fig. 8 and 9. At high tool rotational speeds in a weld, especially in its central areas, the zones of very distinct stirring of the separate parts of metal are present (Fig. 9).

Regardless of the rotational speed of the tool, the material in the FSW process is subjected to the thermal-plastic treatment. It depends on the distance between the material and the tool, the temperature and the degree of deformation [12, 13]. More about the influence of these factors on the forming of the FSW structure has been written in the article [14]. In each case of welding conditions analysis, a significant reduction in grain size was observed. Average size of a particle in a weld zone amounts to 12.4 μm^2 and is 6 times smaller than in parent metal. The material during squeezing around the pin is subjected to strong stress and plastic deformation, which causes particle fragmentation. This process is visible in the Fig. 4. The skeleton structure, visible in the parent metal, during this process has been broken and transformed in the small particles shaped more equiaxial. If the material contains porosity structure the FSW process can usually eliminate this imperfection. In the case of properly conducted welding process, defects in the cross-section are not visible (Fig. 16). Analysis of the results allowed to draw the following conclusions:

- FSW process can be used for joining elements of cast aluminium alloys. During FSW welding of cast aluminium alloy with wrought aluminium alloy the parameters should be carefully selected to avoid imperfections of the weld structure.
- Depending on the applied FSW process conditions, especially tool rotational speed, material of welded components may undergo higher or smaller stirring, which is neither associated directly with the quality of welding nor with mechanical properties of the joint.
- At low tool rotational speed the degree of stirring is not very high. High tool rotational speed caused the significant refinement of grains and stirring of welded metals.
- During the squeezing around the pin the material is deformed and the fragile particles are fragmented.
- The FSW process causes refinement of the particles. The particles size after FSW process is approximately 6 time smaller than in parent metal and they take shape more equiaxial.

Acknowledgements

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