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The influence of friction stir welding process on structure and mechanical properties of the AlSiCu/SiC composites

P. Kurtyka [a,*], I. Sulima [a], A. Wójcicka [a,b], N. Ryłko [a], A. Pietras [c]
[a] Institute of Technology, Pedagogical University,
ul. Podchorążych 2, 30-084 Kraków, Poland
[b] X-ray microtomography Lab, Institute of Computer Science,
University of Silesia, ul. 1. Pułku Piechoty 75, 41-500, Chorzów, Poland
[c] Institute of Welding, ul. Bł. Czesława 16/18, 44-100 Gliwice, Poland
* Corresponding e-mail address: pkurtyka@up.krakow.pl

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Properties

ABSTRACT

Purpose: The aim of this study was to explain the influence of the friction stir welding on the size and distribution of reinforcement particles in the composite AlSiCu/SiCp, as well as determine its mechanical properties.
Design/methodology/approach: Aluminium alloy reinforced with 10% vol. SiC particles with an average size of 15 microns has been joined using friction stir welding method. The joining process were carried out at rotation speed 560 rpm and linear velocity of 355 mm/min and the temperature was lower than 793 K. Microstructures of joined materials were observed according to the light and scanning electron microscopy. Changing of distribution of reinforcement particles were analysed by new RVE theory. The mechanical properties determined on the basis of compression tests. Tests were performed at room temperature at a strain rate $10^{-4}s^{-1}$.
Findings: In the resulting joints (welds) observed significant changes in the distribution of SiC particles, precipitation which was characterized by macro-heterogeneity. However, in micro scale, a few typical distributions and areas of fragmentation of the reinforcing particles were identified. Differences in the sizes of the ceramic particles were 15 microns in the initial material and 2-3 micron in the welded material, respectively. The analysis of these regions using the new RVE theory shows that the coefficient of mechanical properties anisotropy was varied from 0.500328 to 0.016961. Mechanical testing of selected parts of joints showed significant differences in the values of the plastic flow stress in advancing and retreating sides, approximately from 400 to 450 MPa.
Practical implications: The obtained results can be used to optimize the welding process composites by friction stir welding. In addition, the analysis results may be used to design new methods to modify aluminium matrix composites reinforced with ceramic particles.
Originality/value: The work provides information on the influence of the FSW process on the change distribution and fragmentation of reinforcing particles and mechanical properties of composites joints.
Keywords: Aluminium matrix composites; Friction stir welding; Mechanical properties

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1. Introduction

The dynamic development of many industries was possible as a result of technical progress in the creation of new materials, new technologies for their preparation and permanent welding. One of the many problems requiring urgent solutions is to develop effective technologies permanent welding to the aluminum alloys and aluminium matrix composites. Solving this problem requires an identical strength base material and weld material, so they require unchanged the reinforcing particle size and their distribution. In the case of non-fulfillment of this condition is expected reduce mechanical properties of joints, as well as other adverse effects on the physical and chemical properties of the weld. One of the modern methods of welding, solving this problem is the friction stir welding (FSW) method (Fig. 1). FSW method has proved to be particularly useful in the process of welding alloys and aluminum matrix composites in the aerospace and automotive industries [1,2].

The friction stir welding process is performed by the tool FSW which, performed simultaneously rotating and sliding in the direction of laying weld [3].

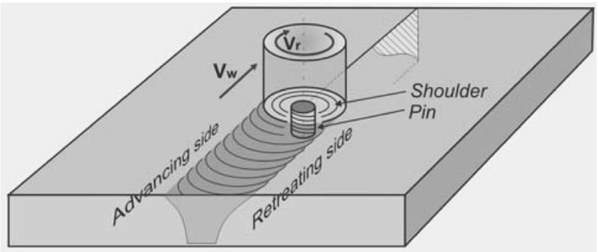


Fig. 1. A scheme of FSW (butt-welding) [4]

The tool consists of two, essential for the process of welding parts: shoulder and the pin. The shape of the pin and the resistance of which marks the contact surfaces (combined) may vary depending on the type of materials combined [2,5]. Research carried out on the selected composites reinforced with particles of oxides or carbides revealed that FSW process significantly affects the distribution of the reinforcing phase in the matrix material, it greatly improves [6-8]. It also leads to fragmentation of the particles [9]. At the same time it was found that the distribution of reinforcing phase in the stir zone is uniform. This has as a consequence, changes in mechanical and tribological properties, since the final number of particles of the reinforcing phase increases significantly, and the distribution is close to isotropic. In this study it was also found that the process of a very significant impact on the structure of the matrix material affecting the separation and homogenization of the silicon needles present in the cast material. [10-12].

Simultaneously, in other studies examined the impact of the process on the occurrence of a reaction between the particle and the matrix. It has been shown that during the process there are not relevant to the mechanical properties, adverse reactions at the interface, which is clearly advantage of these methods over traditional welding methods [1].

However, the test results for conventional alloys and aluminum matrix composites suggests that the distribution of particles and the size of the processed material by FSW may not always be uniform [13-15]. Hence, the study was carried out for an aluminum die-cast composite, reinforced SiC particles, to determine how the distribution of reinforcing phase particles and the size of the processed material, and what impact this has on the mechanical properties of the micro and macro levels.

2. Experimental procedure

For the tests used for the composite cast aluminium alloy matrix reinforced SiC particles with an average size 15 microns and a volume share of 10%. The composition of the matrix alloy according to the manufacturer certification are given in Table 1.

Table 1.
Chemical composition of aluminium matrix composites (wt. %)

Materials	Si	Cu	Ni	Mg	Fe	Ti	Other	Al
F3K.S10	9.5	2.8	1.0	0.8	0.3	0.2	0.03	balanced

The ingot was cut plate having a thickness of 6 mm. FSW welding process performed in accordance with the direction of the casting, rate of rotation speed of 560 rpm and a linear velocities of 355 mm/min. The process was carried out using conventional tools: pin diameter of 8 mm, with a standard thread, the angel between surface of the shoulder and the plates surface was 1.5 degree.

Weld lines was carried out by means of the surface between the welded plates. Welding was carried out at room temperature. A detailed description of the FSW process, provided in a number of publications [4, 13-16].

Observation of the microstructure on the surface of the weld section for light microscopy was performed OLYMPUS GX51 model equipped with Nomarski contrast and for scanning electron microscopy (SEM) JEOL 6610 LV with Energy Depressive Spectrometer EDS. The procedure of preparing the surface for observation consisted of mechanical grinding, the abrasive grit paper 180 to 2000, and after the gradation change paper samples were subjected to washing. Prepared samples were polished using the shields Struers grit diamond paste 9, 3 and 1 micron, and observations were made as to the not etched and etched with a solution of 2 ml of HF, 4 ml HNO_3, 94 ml H_2O.

The mechanical properties of the composite output and the weld were tested in the compression testing machine Instron TT-DM equipped with an electronic measuring circuit. Tests were performed on samples of cylindrical relation h / d of 1.5, cut out from the initial material and the weld at an angle of 0 and 90 degrees to the direction of movement of the pin. Also performed a series of tests on specimens cut out from different parts of the weld, including the advancing zone, weld nugget and retreating zone. Tests were performed at 293 K with an initial strain rate equal to $10^{-4}s^{-1}$.

3. Results and discussion

The starting material was analyzed by EDS to determine the main elements of the structure, including the reinforcing phase particles of SiC. The results of the analysis is given on Fig. 2.

The structure of two types of particles were observed, SiC and Si, and therefore require further analysis clearly distinguish them. The study began with the analysis of the surface structure of the weld cross section. Fig. 3 shows a cross-section of the weld seen on light microscopy, where the show is the presence of a number of different areas of the structure.

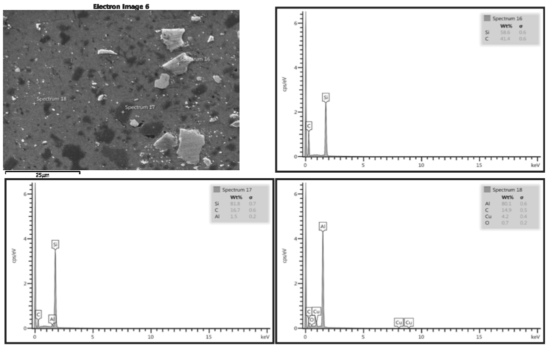


Fig. 2. Microstructure and EDS analysis of the F3K.S10 composites

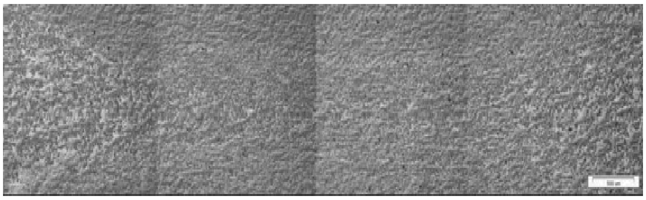
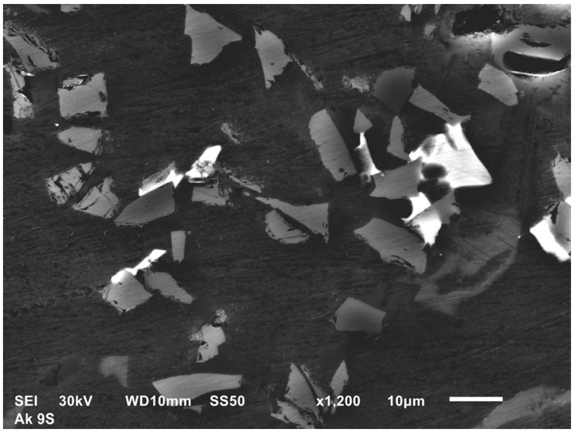


Fig. 3. Macrograph showing weld zones. The welding direction is into the page and the advancing and retreating sides are located on the left and right, respectively

The resulting microstructure of each zone in correlation with the initial material shown in Fig. 4a-d. It was observed that as the size and distribution of reinforcing particles differs considerably not only between the baseline and the weld material, but also in the different zones of the weld.

Microscopic observations revealed that a change in the particle size of the reinforcement phase varies in different areas of the joint. The analysis of changes in the particle size of the reinforcing phase carried out using a Olympus Stream Software, the analytical results are shown in Fig. 5.

a)



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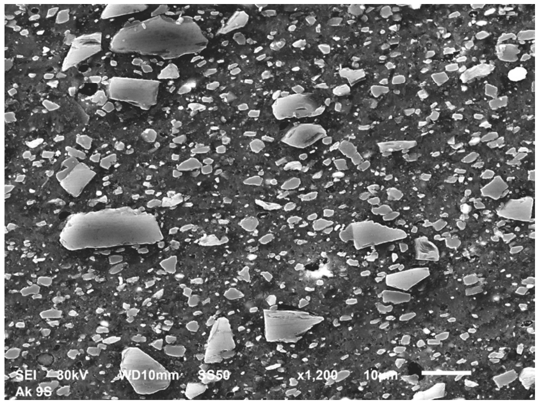

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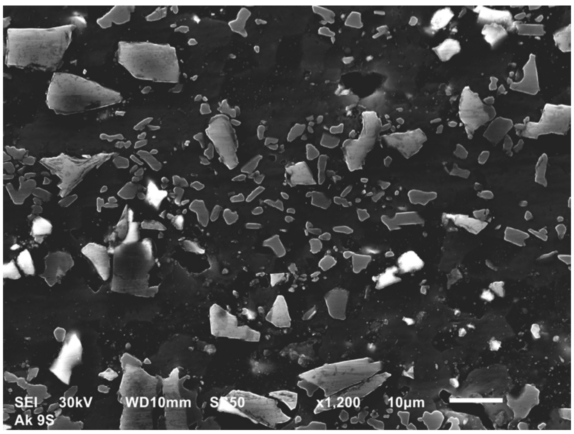

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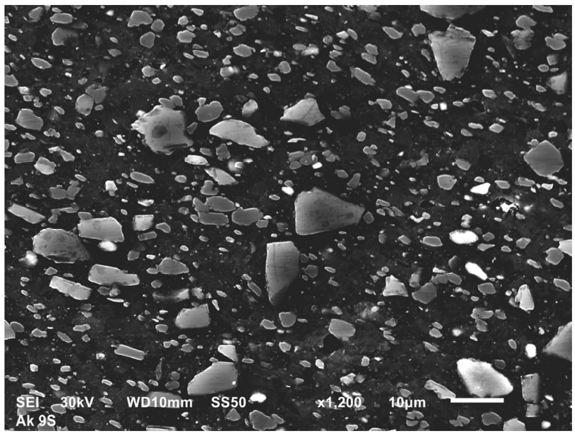

Fig. 4. Microstructure of the F3K.S10 composites: a) initial state, b) advancing side, c) weld nugget, d) retreating side

The size calculation of the reinforcement particles in the superficial layer located in the center of the weld, the weld nugget and the advancing zone compared with similar calculations made for the initial state of the composite. In the case of most of the test weld reinforcement particles fragmentation was observed in the superficial zone (reduction of the average particle size of about 6 times) and the advancing zone (reduction of the average particle size of about 3-fold), while the fragmentation of the particles in the weld nugget is much lower (average size reduction particle size of about 2 times).

Abandoned the analyzes of changes in the particle size in other weld areas because of their lack of plastic deformation caused by welding process, hence the size and distribution were unaffected.

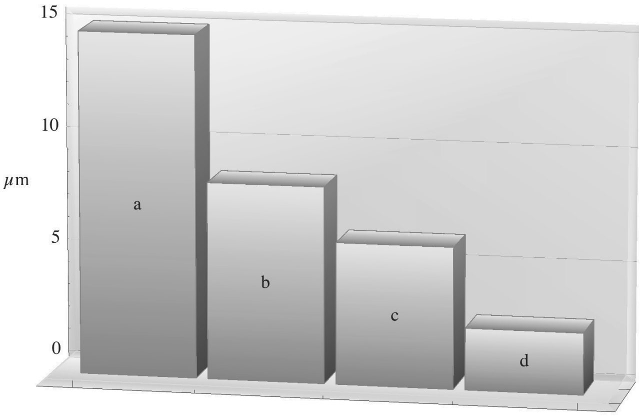

Fig. 5. Mean SiC particle size in the weld zones selected: a) initial state, b) weld nugget, c) advancing side, d) superficial layer located in the center of the weld.

It should be noted that these results are the average SiC particle size and therefore, even in the areas of highest degree of processing, the particles were observed the initial size of about 15 μm. Changing the particle size (fragmentation) is the result of significant plastic deformation which occurs during the welding material. Due to the large deformation of the material flow induced movement of the tool are disrupted particles and then transported along with the matrix material.

Due to the observed change in the joint distribution of reinforcing particles as a result of the movement of material caused by the rotation and the linear tools, the analysis of changes in the SiC particle size distribution using the new theory of representative volume element (RVE) [17-22]. Using the Eisenstein-Rayleigh sums and the new theory of RVE was calculated totals for the starting material and with the highest degree of processing. The image analysis was used a scanning electron microscope, respectively prepared for the selection of computer program that allows the particles of the reinforcing phase [23]. The calculations used fragments of microstructures containing about 20 particles reinforcing phase. It was calculated that the value of the sum of e_2 for the decomposition of the starting material presented in Fig. 6a, $e_2 = -0.002206281$, and the weld material on the distribution of the SiC particles shown in Fig. 6b, $e_2 = 3.19488$. From equation 1 anisotropy coefficient κ was calculated for reinforcing particles. For the composite output was κ=0.500328 and weld material κ=0.016961, where the value of κ = 0 has perfectly isotropic material.

$$\kappa=1/\pi*(e_2-\pi) \qquad (1)$$

where:
κ - coefficient of the anisotropy,
e_2 - Eisenstein-Rayleigh sum.

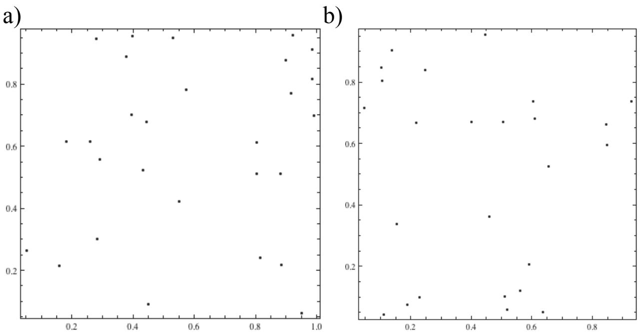

Fig. 6. Analysis of the distribution of the reinforcing phase particles using new RVE theory: a) initial state, b) welded composites.

In order to correlate the changes in the distribution and size of the particles of the reinforcing phase with the mechanical properties of the weld compression tests were performed with samples of the starting material and of the various areas of the weld. First, compression tests were performed on samples of the composite starting at 0 and 90 degrees to the direction of casting. The test results is given on Fig. 7. As the graph shows no significant differences between the results obtained for both tested variants, suggesting that the observed inhomogeneities in the microstructure distribution of reinforcing phase particles have no significant effect on the mechanical properties of the composite.

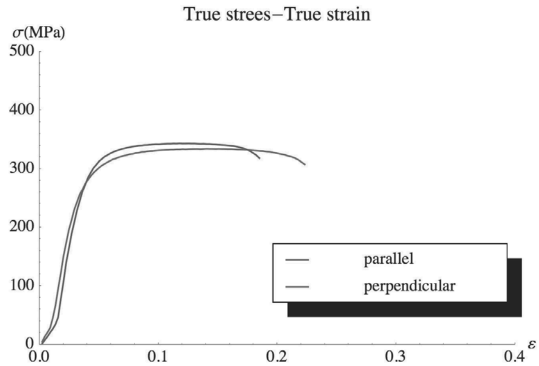

Fig. 7. Stress - strain dependence for the initial state composites tested in two directions 0 and 90 degree, temperature 293 K, strain rate $10^{-4}s^{-1}$

Analogous studies were performed for the weld from which the test specimens were cut into the advancing zone, the weld nugget and the retreating zone at 0 degrees to the direction of movement of the pin. Additional studies were also performed for samples cut out at an angle of 90 degrees in order to assess changes in the mechanical properties perpendicular to the weld. The test results given on Figs. 8-9. As can be seen in the graphs presented, the highest values of plastic flow stress reaches the sample from the advancing zone, while the results obtained for the other two areas are similar. Also, tests conducted at 90 degrees to the direction of movement of the stem, however, confirm previous results due to the overlap of the above. Samples of the range (advancing zone - the weld nugget, weld nugget - retreating zone) results for a variant of the first show marked differences in values.

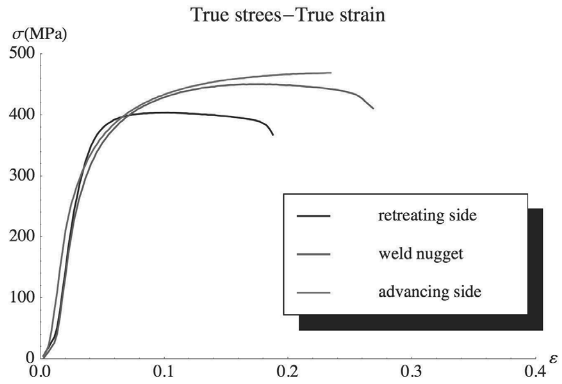

Fig. 8. Stress - strain dependence for the weld zones, temperature 293 K, strain rate $10^{-4}s^{-1}$

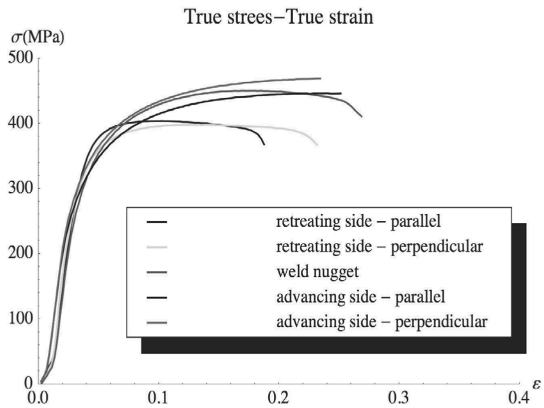

Fig. 9. Stress - strain dependence for the initial state composites and weld zone,s tested in two directions 0 and 90 degree, temperature 293 K, strain rate $10^{-4}s^{-1}$

Comparison of the results obtained from the compression testing of the initial material and the weld revealed significant differences in the plastic flow stress as high as 100 MPa. In order to better illustrate the differences indicated in tabular form contains changes the value of R_c for the tested samples. From Figs. 7-9 and from Table 2 shows that the weld, regardless of the test space, always reaches higher values R_c, of the initial material.

4. Conclusions

Based on the research it was found that during the process of welding of the composite are fragmented and changing the distribution of the reinforcing phase particles. The weld areas are of different sizes of reinforcing particles, their average size, in the zone with the highest degree of fragmentation decreases approximately 6 times of ~ 15 to ~ 2-3 micron. The result is a significant increase in fragmentation of the amount of SiC particles. It was also observed that the change in particle size within the weld is very different, the differences between the mean values of up to several hundred percent. It has been observed that even in the area with the highest degree of fineness of the particles are particles of the "initial", there was no fragmentation during welding process. At the same time demonstrated that the process of welding the composite tested FSW improves the particle distribution in the weld reinforcement phase, in varying degrees, depending on the location of the area. Based on an analysis carried out by use of the new RVE theory with Eisenstein-Rayleigh sums, it was found that the welding process can lead to gain in the joint distribution of the particles close to the isotropic, you can also believe that recycling performance weld by FSW would provide an even better distribution of particle phase reinforcement.

Obtained results indicate an increase in the mechanical properties of the weld with respect to the initial material of about 30%. At the same time it was found that the weld occurring differences in the distribution of the particles have a high to some extent, the mechanical properties of the individual zones in selected areas to give an increase of mechanical properties of the weld to about 50%.

The results suggest the need for further research FSW composites welded method. In particular, should determine the effect of FSW process parameters and tool shape on the fragmentation and distribution of reinforcing phase particles. It also seems advisable to investigate the influence of the particles characteristics such as the size of the output shape selected physicochemical properties (Young's modulus) in the behavior of the reinforcing particles in the welding process.

Table 2.
R_c values for initial state composites and weld zones tested in two directions 0 and 90 degree

Directions	Parallel				Perpendicular		
Zone/Side	Initial	Advancing	Nugget	Retreating	Initial	Advancing	Retreating
R_c [MPa]	399	630	560	465	399	609	481

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