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EFFECT OF FRICTION STIR PROCESSING ON MICROSTRUCTURE AND HARDNESS OF CAST HYPO-EUTECTIC AND HYPER-EUTECTIC Al-Si ALLOYS

The objective of this study was to ascertain the impact of Friction Stir Processing (FSP) on the microstructure and hardness of Al-Si alloys of hypo-eutectic (AlSi8) and hyper-eutectic (AlSi16) composition, with a particular focus on thermomechanical alterations in the microstructure. Microstructural studies were conducted on cross-sections using light microscopy and scanning electron microscopy techniques, in conjunction with an analysis of the chemical composition in the micro-areas. Furthermore, electron backscatter diffraction analyses and analyses of the hardness distributions in the stirred zone after FSP were conducted. The utilisation of FSP to modify both AlSi8 and AlSi16 alloys was demonstrated to facilitate microstructural refinement. Based on the results, the remodelling and dynamic recrystallisation of the microstructure associated with the application of FSP treatment were identified.

Keywords: Al-Si alloys; Friction Stir Processing; microstructure refinement; hardness; dynamic recrystallization

1. Introduction

Aluminium-silicon alloys (Al-Si) represent one of the most frequently utilised aluminium casting alloys. The classification of Al-Si alloys is dependent on the concentration of silicon present, resulting in three distinct groups: (i) hypo-eutectic with a silicon content of less than 11%, (ii) eutectic with 11-13% Si and (iii) hyper-eutectic with a silicon content of more than 13%. In general, hypo-eutectic alloys are composed of α(Al) solid solution dendrites and a hard α(Al)-β(Si) eutectic phase in the form of plates or lamellae [1,2]. Additionally, hypereutectic alloys exhibit brittle, unevenly distributed precipitates of primary silicon crystals, which render the castings challenging to machine and provide an accessible pathway for nucleation and crack propagation. This requires the implementation of specific treatments throughout the production process. These include modifier treatment (primarily involving phosphorus and titanium) [3-5], heat treatment [6-8] and stirring during solidification in the casting process (stirring of solidification), for instance through the use of electromagnetic, ultrasonic, and other techniques [9,10]. However, despite these treatments, cast Al-Si alloys do not exhibit the desired improvements in strength and ductility.

The application of advanced Friction Stir Processing (FSP) has the potential to enhance the performance characteristics of finished components, including increased resistance to frictional wear and fatigue. FSP technology enables the local modification and control of the microstructure in the surface layers of machined metal materials. In the FSP process, the material is heated and plasticised by the friction of a non-wearing tool equipped with a shoulder and a pin embedded in the material, which moves along the surface of the component to be modified. The movement of the tool causes local heating, intense mixing and compaction of the deformed material. The displacement of material around the mandrel is a highly complex process, dependent on a number of factors, including tool geometry, technological parameters and the material to be processed [11]. The process zone can be subdivided into four distinct zones, each exhibiting unique thermomechanical properties. These are the central stir zone (SZ), encircled by the thermomechanically affected zone (TMAZ), the heat affected zone (HAZ), and the base material (BM). The influence of each zone is contingent upon a complex interplay of process parameters, the configuration and morphology of the tool, and the intrinsic characteristics of the material undergoing modification [12].

FSP represents a highly promising surface modification technique that is currently entering the technological application stage. FSP-modified materials exhibiting superplasticity have found applications in the aerospace and automotive indus-

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tries [13,14]. In addition, the FSP process effectively eliminates casting defects, resulting in homogenisation and fragmentation of the microstructure, removal of porosity, improvement of mechanical properties, increase in fatigue strength [15-18] and resistance to abrasive wear [19-21]. A number of authors have investigated the effect of FSW/P parameters, including the speed of tool travel and the speed of tool rotation, on the microstructure and mechanical properties of Al-Si alloys [22-28]. Knowledge of the effect of FSP on the microstructure and properties of these materials is extremely important. For alloys with hypo-eutectic [25,27], eutectic [28] and hyper-eutectic [26] compositions, the degree of microstructure fragmentation varied with changes in FSP process conditions. A high ratio of tool speed to tool travel speed produced a higher volume fraction of finer particles.

It has been demonstrated that FSP is an effective method for eliminating porosity and significantly fragmenting the Si eutectic phase in cast alloys. Moreover, the modification of the microstructure of Al-Si alloys by the FSP process, which entails the fracturing of eutectic phases and aluminium dendrites, the redistribution of fine and equiaxial Si particles in the aluminium matrix and the elimination of porosity, has been shown to result in improved mechanical properties [24-30]. The application of FSP to the cast Al-7Si-Mg alloy resulted in a notable enhancement in plasticity, accompanied by a relatively modest improvement in tensile strength. In contrast, the Al-10Si alloy [25] exhibited a notable enhancement in mechanical properties following the reduction of porosity in the casting and the fragmentation and spheroidisation of the eutectic silicon phase. Studies on the application of FSP to aluminium alloys, such as A380, have shown significant improvements in the microstructure and mechanical properties of these materials [28]. The authors demonstrated that the FSP process effectively breaks up the needle-like silicon (Si) particles and distributes them uniformly in the aluminium matrix, eliminating the porosity present in the microstructure of the casting. The result is a fine-grained microstructure, leading to a significant increase in the hardness of the modified layers and a reduction in wear rates. The Aural-5 alloy, which is widely used in the automotive industry, also shows improved mechanical properties after FSP application. Modification of the microstructure of this alloy increases the yield strength and tensile ductility by approximately 30% and 35% respectively [29]. Similarly, the authors of [30] demonstrated that the mechanical properties of the AA 4032 alloy underwent an improvement following the application of FSP. This study indicated that the utilisation of high rotational speeds during FSP resulted in the appearance of the Mg_2Si phase. Accordingly, the augmentation of the sample's strength subsequent to FSP was ascribed by the investigators to the combined effects of separation strengthening and grain boundary strengthening. The findings of the study on the FSP treatment of hypereutectic Al-Si alloys were presented by the authors of paper [26]. In this study the effects of tool speed, feed rate and number of FSP passes on the change in size of primary Si crystals and Si eutectics, the change in grain size, volume fraction of porosity and microhardness were investigated. It was found that the sample with the highest number of passes exhibited the most homogeneous properties, which can be attributed to the reduced porosity of the casting and the uniform distribution of the fragmented silicon throughout the zone after FSP modification.

The objective of this study was to ascertain the impact of friction stir processing (FSP) on the microstructure of Al-Si alloy castings with varying chemical compositions, specifically those classified as hypo-eutectic and hyper-eutectic. FSP is an advanced processing technique that employs a combination of thermal and mechanical processes to modify the microstructure of materials. This study focuses on the characterisation of the microstructure, with particular emphasis on the thermo-mechanical changes in the microstructure. The IPF and GOS images produced by the EBSD technique provide valuable information on the influence of strain localisation processes together with dynamic structure recovery on the properties of the modified material. Such studies can provide new information on the strengthening mechanisms and microstructural phenomena during FSP, which can lead to the development of new processing techniques to improve the functional properties of Al-Si alloys. We believe that these novel approaches can contribute to the further development of FSP technology and its applications in industry.

2. Test material and methodology

The test material comprised two Al-Si series alloy die castings: AlSi8 (hypo-eutectic) and AlSi16 (hyper-eutectic). The chemical composition of the alloys under examination is presented in TABLE 1.

TABLE 1

Chemical composition of Al-Si alloys subjected to testing

Alloy	% mas.						
	Al	**Si**	**Mg**	**Fe**	**Cu**	**Mn**	**Ti**
AlSi8	balance	7.66	0.34	0.13	0.01	0.01	0.06
AlSi16	balance	15.69	0.63	0.13	0.01	0.02	0.06

The friction stir processing (FSP) modification procedure for the FSP material was conducted on a laboratory bench mounted on an AVIA FNE 40P vertical milling machine. The carbide tool employed comprised a spiral shoulder (Ø13.5) and a truncated conical pin (Ø3.5 → Ø6). The FSP machining process for both AlSi8 and AlSi16 was conducted at a tool speed of 2500 rpm and a linear speed of 10 mm/min. A schematic of the FSP modification process and the configuration of the tool are illustrated in Fig. 1.

Microstructure observations of the samples were conducted using a ZEISS AXIO OBSERVER 7 MAT light microscope, equipped with digital image recording. Microstructure studies were performed on cross-sections of AlSi8 and AlSi16 alloy specimens that had undergone modification by the FSP process in the stir zone (SZ), on the advancing side (AS), and on the retreating side (RS) with respect to the base material (BM). The microstructure was also examined using a scanning electron

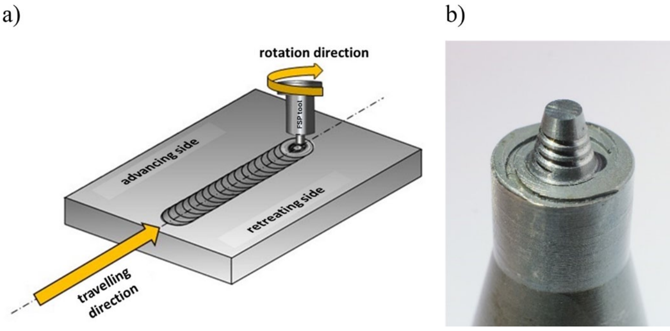

Fig. 1. Schematic illustration of the FSP technique (a) and the tool used for the process (b)

microscope (SEM). Scanning electron microscope (SEM) observations and electron backscatter diffraction (EBSD) studies were conducted using a high-resolution FEI INSPECT F50 scanning electron microscope, equipped with an energy-dispersive spectroscopy (EDS) attachment and an EBSD camera with dedicated APEX™ software from EDAX. EBSD studies are essential for characterising the structure after friction stir processing (FSP), as they facilitate the understanding of microstructural changes, grain orientations and their impact on material properties. The testing was conducted using an accelerating voltage of 20 kV. The sample was inclined at an angle of 70° at a distance of 15 mm from the column. An EBSD analysis was conducted to obtain maps of the distribution of crystalline lattice orientation on the surface of the sample under investigation. The crystallographic orientation maps were analysed to determine the average grain size and the content contribution of both the Al matrix and Si precipitates. Additionally, an analysis of the proportion of recrystallisation progress in the structure was conducted based on the measurement of the orientation spread in the grains (Grain Orientation Spread GOS). The GOS value increases as a result of grain disorientation, caused by the accumulation of dislocations. The GOS value was used as a criterion for identifying recrystallised and/or deformation-free grains (GOS < 1°), partially deformed grains (GOS = 1÷2), and deformed grains (GOS > 2°) [31].

In order to determine the hardness distribution within the SZ mixing zone of the FSP-treated material, microhardness measurements were conducted utilising the Vickers method with a Qness 60 CHD Master+ hardness tester in accordance with the standards set forth in PN-EN ISO 6507-1:2018-05. In order to obtain an accurate hardness distribution, measurement points were selected along the X axis of the cross-section of the FSP zone, starting from the centre and moving outwards (towards AS and RS). The points were evenly spaced every 0.5 mm, with a load of 200 g (HV0.2) and a holding time of 12 s.

3. Results and discussion

3.1. Microstructure and hardness

The results of microstructure investigations of AlSi8 and AlSi16 in the FSP zone, with reference to the BM, are presented in Figs. 2 and 3. The microstructure observations (Fig. 2) revealed the formation of an asymmetric structure within the zone, comprising a central SZ. This asymmetric structure was observed in both alloys. Prior to modification, the microstructure of the AlSi8 alloy comprised α(Al) solid solution dendrites and a lamellar α(Al)-β(Si) eutectic phase, in addition to less abundant Fe-rich and Mg-rich phases (Mg_2Si) with Chinese script morphology (Fig. 2 and Fig. 3 AlSi8-BM). Additionally, the AlSi16 alloy exhibited substantial, irregularly distributed separations of primary silicon crystals beyond the aforementioned phases (Fig. 2 and Fig. 3 AlSi16-BM). As a consequence of the FSP modification, both the eutectics and the primary silicon crystals

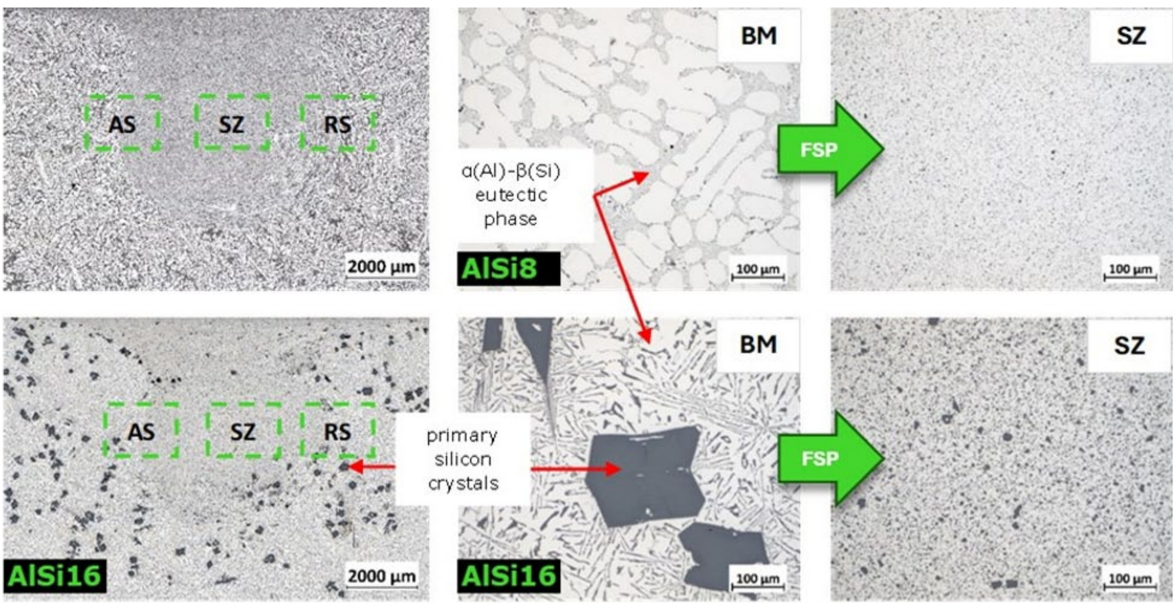

Fig. 2. Microstructure of AlSi8 and AlSi16 specimens following the FSP treatment, with the unmodified area visible in the cross-section through the FSP zone; LM

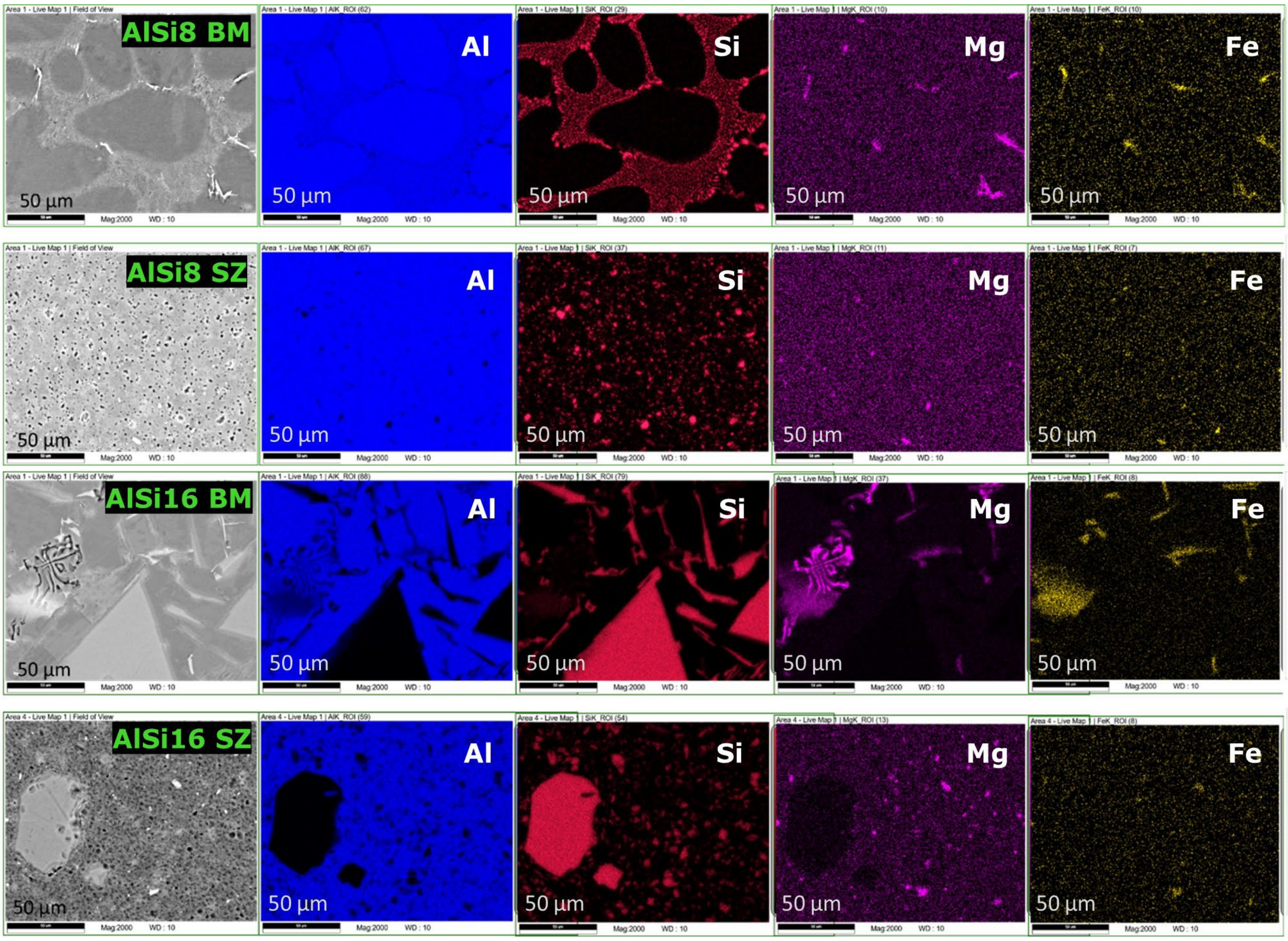

Fig. 3. Microstructure of the AlSi8 and AlSi16 alloys in the FSP modified zone (SZ) and results of the surface distribution of elements in relation to the unmodified area (BM); SEM

underwent significant fragmentation, acquiring a more regular, near-globular shape (Fig. 2 and Fig. 3 AlSi16-SZ). In both the AlSi8 and AlSi16 alloys, the lamellar form of the α(Al)-β(Si) eutectic phase was entirely eliminated, giving way to a globular configuration.

The EBSD results (Figs. 4 and 5) indicate that both the AlSi8 and AlSi16 alloys exhibited remodelling and dynamic recrystallisation of the microstructure in response to the application of FSP treatment. Prior to the application of FSP treatment, no clear dominant orientation was identified in the analysed alloys (Fig. 4 and Fig. 5 IPF – BM). Furthermore, no notable alterations were observed in the crystallographic orientation of the regions subjected to FSP, and the grains exhibited no clear dominance in a particular direction. The application of FSP to the surface treatment of Al-Si alloys, however, resulted in discernible alterations in grain size. The FSP process led to pronounced grain fragmentation in both alloys, giving rise to the formation of fine and equiaxial aluminium-rich matrix grains with diameters of approximately 8 μm for the AlSi8 alloy and 5 μm for the AlSi16 alloy in the SZ (Fig. 6).

Furthermore, alterations in the degree of recrystallisation of Al-Si alloys prior to and following FSP treatment are also discernible (see Figs. 4 and 5 in the GOS). The proportion of grains that have not undergone deformation (with a GOS of 0-1°) is comparable for both alloys when the GOS parameter is measured in the BM material. In contrast, an increase in the proportion of deformed grains (with GOS 1-2° and >2°) is evident for all analysed areas relative to BM in the case of the FSP zone. Moreover, the GOS maps demonstrate that deformed grains (with GOS > 2°) are markedly prevalent in the AS region extending beyond the tool transition boundary, indicative of the presence of the TMAZ zone. In contrast, as one moves towards the tool transition zone, there is an observable increase in the proportion of partially deformed grains (with GOS 1-2°) and recrystallised grains (with GOS 0-1°). A comparable effect, though less pronounced, was observed on the RS side for both alloys.

A quantitative analysis of the contribution of the individual phases illustrated in Figs. 4 and 5 (namely Phase – BM and SZ), revealed a striking similarity in their proportions, particularly in the case of the AlSi16 alloy. This finding suggests that changes in the morphology of the precipitates occur primarily in terms of their degree of fragmentation, while the FSP process itself does not result in the segregation of these precipitates within the deformed material.

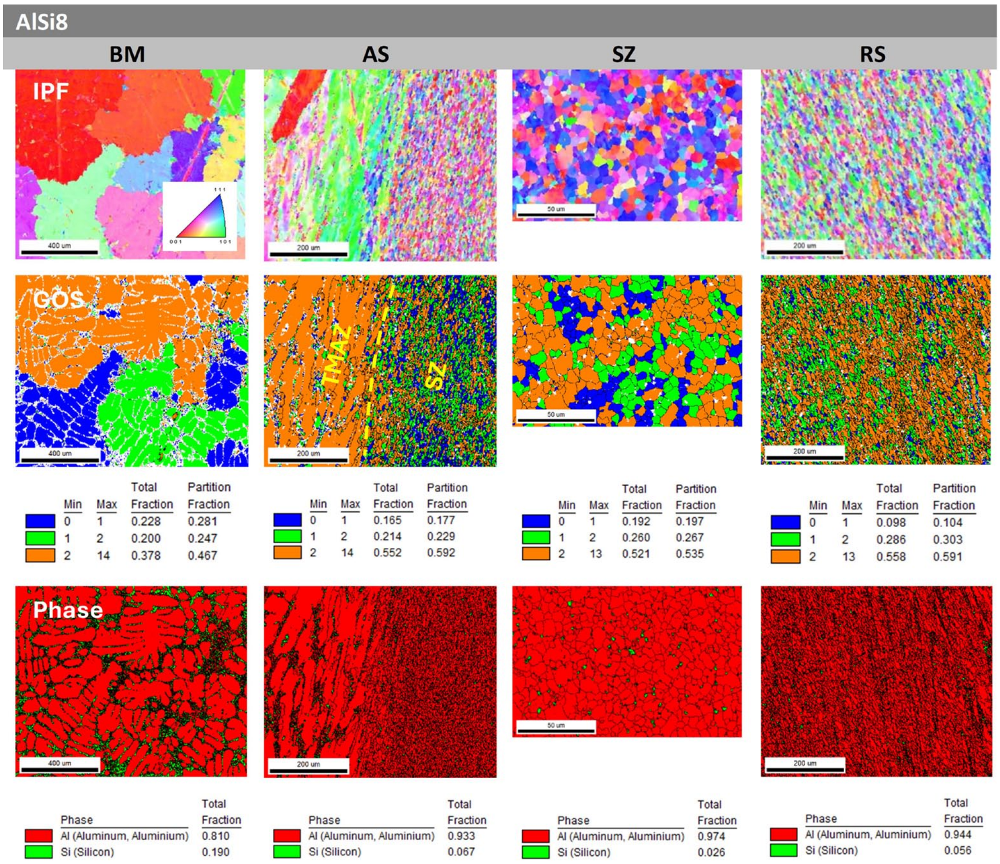

Fig. 4. Results of analysis of crystallographic orientation and recrystallisation degree contribution of AlSi8 alloy for FSP modified zones and unmodified area – EBSD

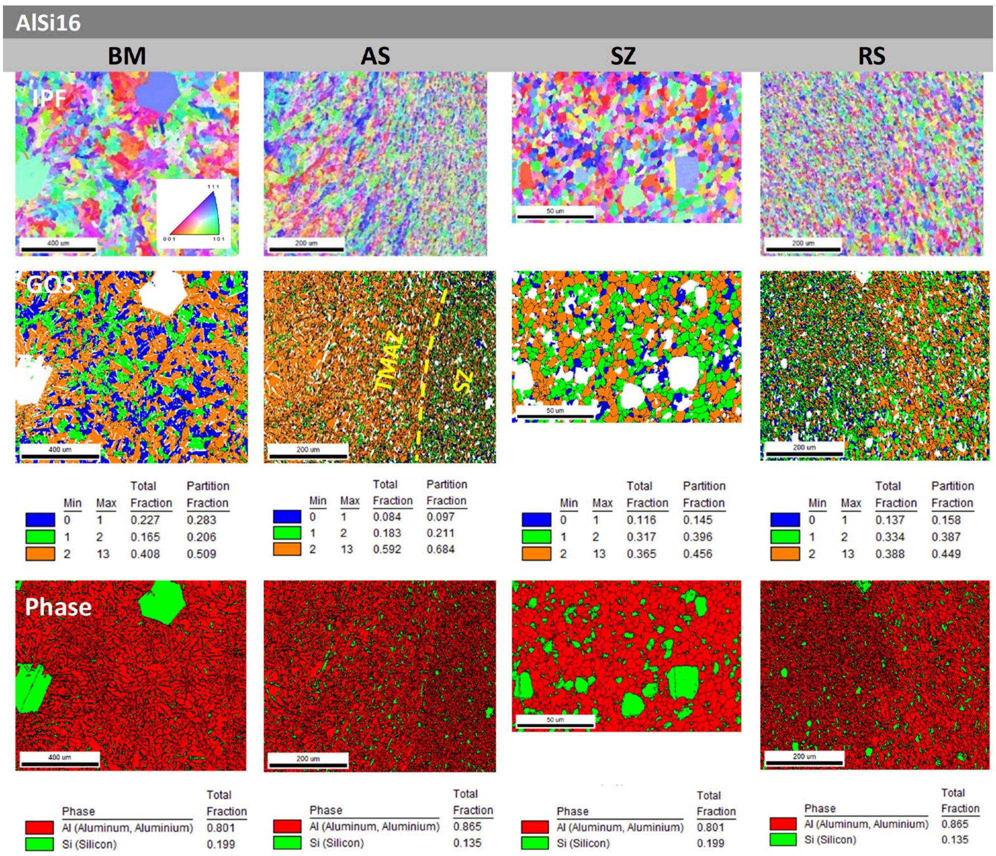

Fig. 5. Results of analysis of crystallographic orientation and recrystallisation degree contribution of AlSi16 alloy for FSP modified zones and unmodified area – EBSD

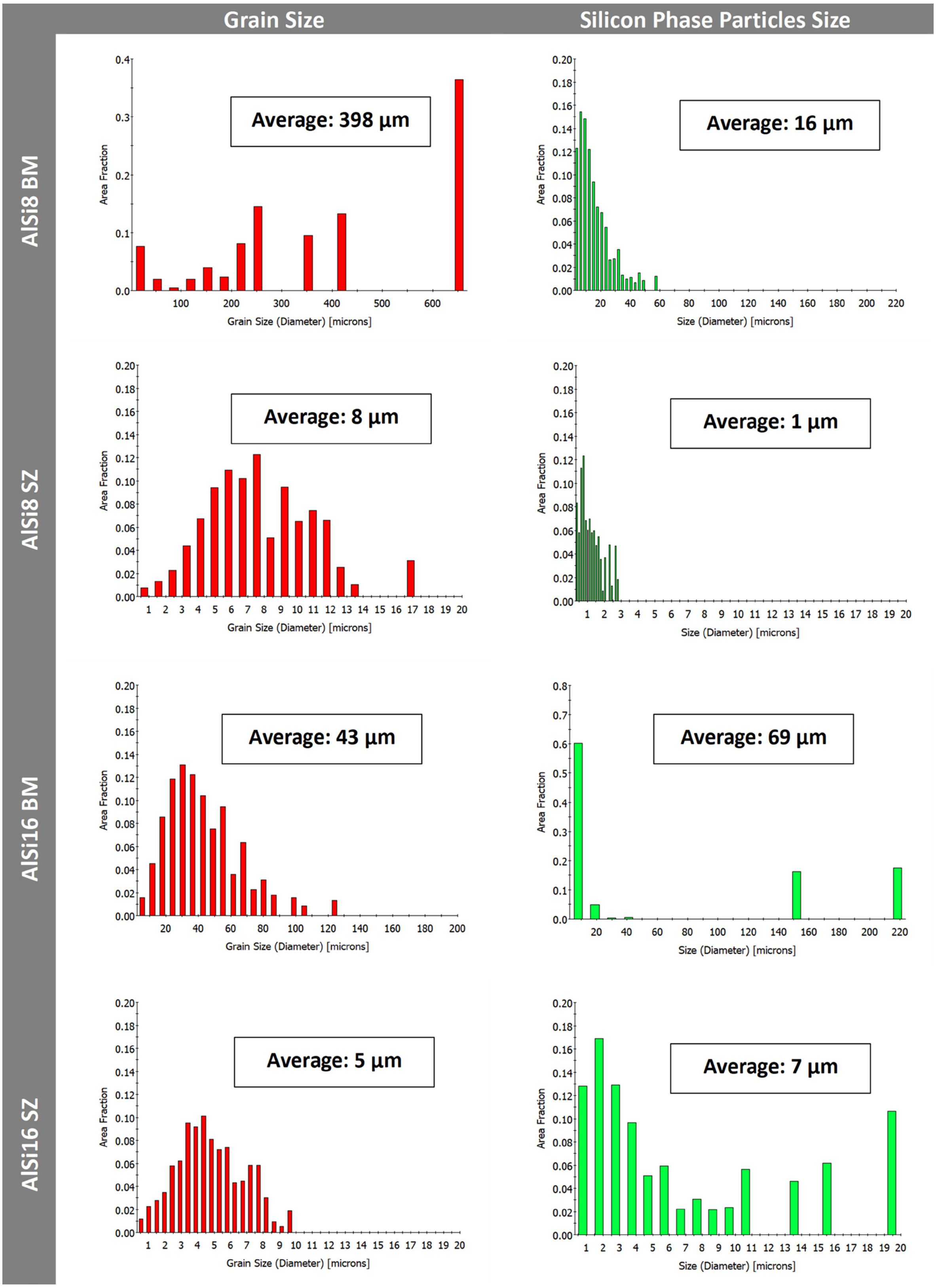

Fig. 6. Grain size and silicon phase particles size distribution diagram obtained from the microstructure of AlSi8 and AlSi16 alloy in BM an SZ area

Figs. 7 and 8 show the hardness results for the alloys tested. In the case of the FSP zone, the silicon particles are much smaller and more uniformly distributed, resulting in consistent hardness results. In contrast, in the base material, and particularly in the AlSi16 alloy, the larger and irregularly distributed primary silicon particles cause significant variation in the hardness results (Fig. 8). A detailed analysis of the hardness distribution (Fig. 7) reveals that the slight variation in hardness observed in the SZ region is a direct consequence of the material's phase composition and the morphology of the castings (for further

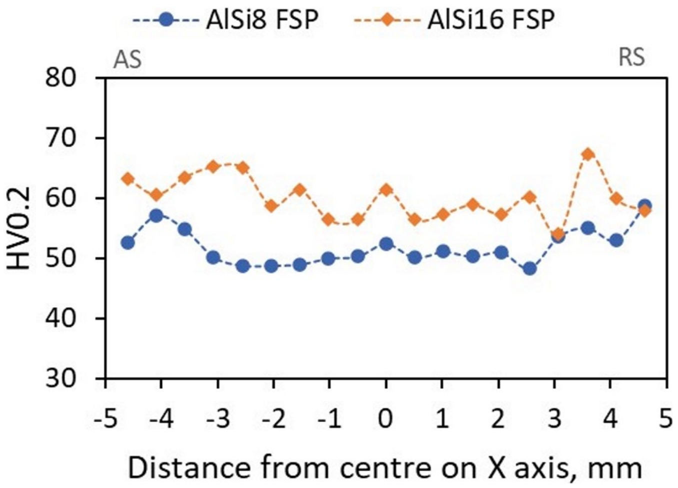

Fig. 7. Vickers hardness distribution in the SZ zone in AlSi8 and AlSi16 alloys after FSP

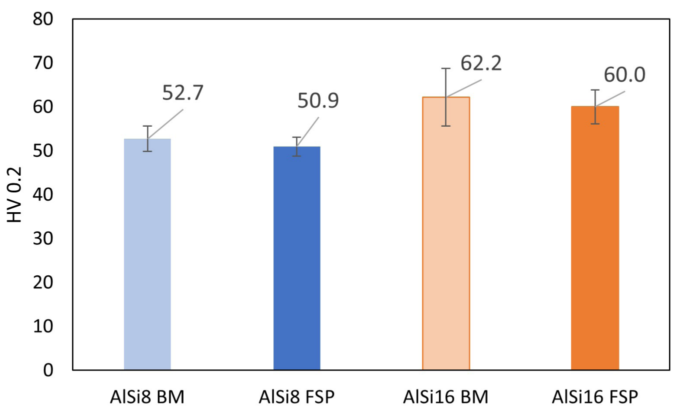

Fig. 8. Average hardness of the AlSi8 and AlSi16 alloys in the BM and FSP zones

details, please refer to the above). The mean hardness of the area subjected to the threaded rod is approximately 60 HV0.2 for the AlSi16 alloy and approximately 51 HV0.2 for the AlSi8 alloy. The higher hardness of the AlSi16 alloy was anticipated based on its higher silicon content in the chemical composition. Both the AlSi8 and AlSi16 alloys exhibited an increase in hardness in the vicinity of the SZ zone axis (x = 0 mm). In this particular area, the degree of plastic deformation may be greater than in other areas of this zone. The turbulent and highly dynamic flow in the SZ is characterised by varying strain and strain rates around the rotating and simultaneously sliding tool, which generates the presence of different stress states. Furthermore, an additional increase in hardness is observed at a distance of approximately 3.5 mm from the SZ axis for AlSi8 and approximately 2.8 mm from the SZ axis for AlSi16, both in the direction of the AS and the RS, which corresponds to the boundaries of the mandrel action area and the occurrence of the TMAZ, in which the deformation state is comparable to that of hot machining of metallic material. The increase in hardness can be explained by an increase in dislocation density as a result of plastic deformation, which is confirmed by the GOS results (Figs. 4 and 5 GOS).

The observed evolution of the microstructure of the material processed in the FSP process can be attributed to the application of elevated temperatures in conjunction with dynamic plastic deformation. Given that the process occurs at a temperature of approximately 0.8 Tt, it is evident that alterations also take place within the heat-affected zones. Dynamic recrystallisation (DRX) represents the prevailing mode of microstructure evolution within the SZ mixing zone and the TMAZ thermomechanical zone [32]. A homogeneous microstructure develops in the SZ mixing zone, while a partially recrystallised structure appears in the TMAZ. Aluminium and its alloys are characterised by high EBU values, which result in dynamic recovery (DRV) processes dominating during FSP. This may then lead to DRX [32]. The elevated temperature and vigorous mixing within the SZ facilitate dynamic recrystallisation, which in turn gives rise to the formation of new, fine grains. In contrast, the material in the TMAZ zone is subjected to a lesser degree of deformation and mixing. Consequently, the grains in this zone are larger and less homogeneous, as the recrystallisation process is less intense than in the SZ. In the TMAZ, the processes of plastic deformation and partial recrystallisation are predominant, resulting in the formation of larger grains, which are particularly evident on the AS side (see Figs. 4 and 5 GOS – AS). The majority of numerical simulations reported in the literature [33, 34] indicate that the predominantly warmer side of the FSP process zone is the AS. This is due to the higher stress level relative to the RS in the material being modified. This phenomenon is attributable to the congruent rotation and feed direction of the tool on the AS, which are in opposition to those on the RS. This results in the tool "rubbing" the material to be machined on the advancing side, along the plane defined by the linear movement of the mandrel. Conversely, it is subjected to much less deformation on the retreating side [34].

4. Summary and conclusions

In light of the findings of the experimental studies and the subsequent analysis of the results, the following conclusions were drawn:

- The application of FSP to the surface treatment of Al-Si alloys has been demonstrated to result in a significant improvement in the microstructure. The process results in a notable enhancement in both uniformity and grain size. The application of FSP results in the fragmentation of grains within the mixing zone (SZ), leading to the formation of fine, equiaxial recrystallised grains with a diameter of approximately 8 μm for the AlSi8 alloy and 5 μm for the AlSi16 alloy. Consequently, the SZ exhibits greater homogeneity in hardness compared to the TMAZ, where the material is subjected to a lesser degree of deformation and mixing. This results in the formation of larger and less homogeneous grains, primarily due to plastic deformation and partial recrystallisation.
- The research findings indicate that FSP has a notable impact on the degree of recrystallisation of Al-Si alloys. This

process alters the ratio between recrystallised and deformed grains, which can influence the mechanical properties of the material.

- The findings suggest that FSP can be an efficacious method for modifying the structure of Al-Si alloys, which can subsequently influence their mechanical and functional properties.

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