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Technological aspects of friction stir processing of AlZn5.5MgCu aluminum alloy

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Abstract. FSP technology was used to modify the surface layer of the AlZn5.5.MgCu aluminum alloy by enriching its SiC particles. For this goal the FSP multi-chamber method was used. The SiC powder was placed in separated chambers hollowed in the modified material perpendicular to the surface of the sample. In order to achieve a more even distribution of the reinforcing phase in the aluminum alloy matrix and to minimize the risk of uncontrolled displacement of the SiC powder at the time of inserting the pin into the material, a two-step treatment was applied. In the first one, the working area of the pin was shifted relative to the axis of the chambers by ΔL. In the second step of the treatment the tool moved centrally along the line of chambers. As a result of friction treatment, intensive sputtering of SiC particles in the surface of the aluminum alloy and strong refinement of the alloy were observed. The consequence of the microstructural changes in the surface layer of the material and the formation of a metal-ceramic composite microstructure was a significant increase in the hardness of the aluminum alloy.

Key words: FSP technology, AlZn5.5MgCu aluminium alloy.

1. Introduction

The microstructure and properties of the surface layer of a product are the result of conscious actions taken by humans in the period preceding exploitation, or they can be formed directly during operation [1–7]. In the case of metals and alloys, one of the newest technologies used to shape the microstructure and properties of these materials is friction stir processing (FSP). In this method, the heat necessary to plasticize the material and induce structural changes results from the friction between the special tool and the surface of the material [8–11]. Approximately 80 to 90% of the heat produced by the friction between the tool and the surface of the modified material results from the friction between the shoulder face and the rest due to the friction between the remaining surface of the tool and the surface of the material [12]. During processing, the melting temperature of the modified material is not exceeded, the temperatures occurring in the FSP process constitute 70–90% of the melting temperature of the material being modified. It is worth emphasizing that FSP technology is an ecological solutions [13] because heat is generated only by friction, therefore high-energy sources, which are accompanied by welding fumes and pose a number of hazards, are not used. In the case where an additional phase, such as ceramic particles or nanofibres, is introduced into the friction zone, a new composite surface layer with a new spectrum of properties is formed [14–19]. Additional material is usually placed in a groove hollowed into the surface of the material to be modified, followed by two-stage processing using two different tools. In the first step, a tool without a pin is used, and the main purpose of this treatment is to seal the groove with the modifying material to reduce the risk of moving the modifying material out of the modified area during proper processing, which in turn is generally performed by a tool equipped with a pin. This treatment aims to uniformly distribute the reinforcing phase throughout the modified area. This solution was used for example in [16] to produce a composite microstructure in the surface layer of the 5052Al alloy, and in [14] the method was used to produce Cu/SiC metal matrix composites. The grooved version does not, however, eliminate the risk of uncontrolled movement of the additive phase along the groove, leading to a reduction in the amount of reinforcing phase in the modified material. This risk exists especially when the modified material is not sufficiently plasticized or when the shape of the pin does not guarantee sufficiently effective mixing. The FSP variant scheme is shown in Fig. 1. The author's multi-chamber method has been developed as an alternative solution to the above-mentioned technological problems. In this solution, the modifying material is placed in separated chambers hollowed in the surface of the material to be modified. These chambers, when filled with the modifying material, act as reservoirs to supply the powder to the plasticized material during friction treatment. During processing, the powder is released from the chamber into the metal die in a cyclic manner i.e. chamber after chamber. The walls of the chambers minimize the risk of uncontrolled movement of the modified material out of the modified area more effectively than using the grooved method, and they significantly reduce the risk of uncontrolled or excessive movement of the modifying material in the direction of tool movement.

This allows the process to be carried out using only one mixing tool and the treatment process can be done in one

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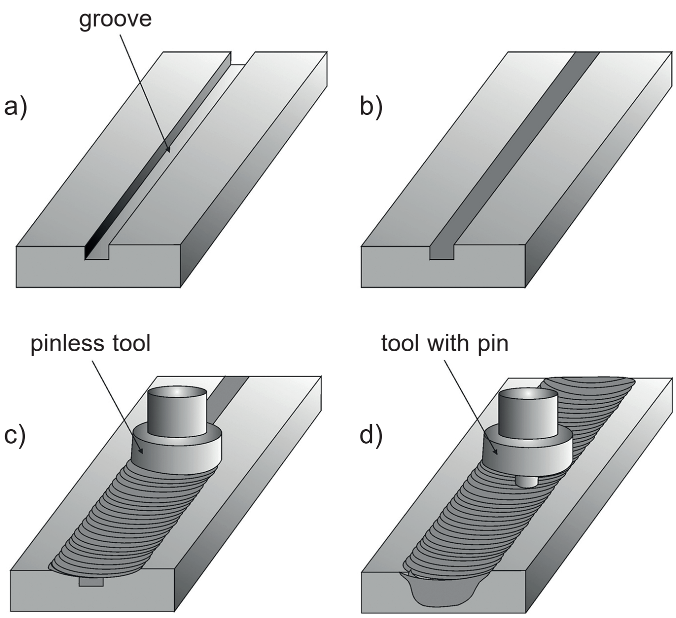


Fig. 1. FSP groove technology: a) groove design, b) groove filled with modifying material, c) pre-friction processing by tool without pin, d) proper friction processing by tool with pin

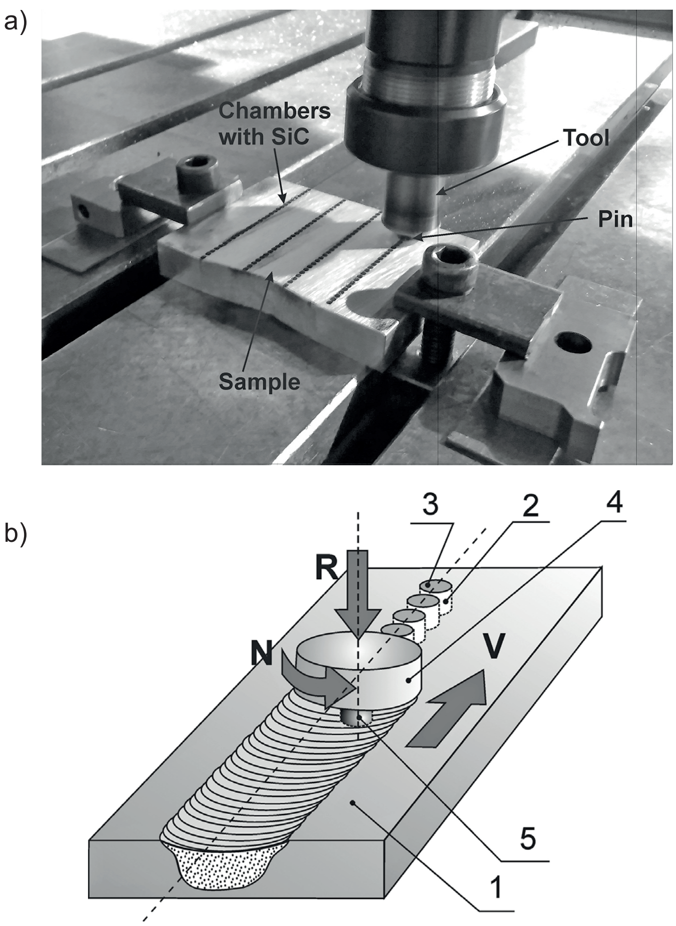


Fig. 2. Friction modification station (a) and friction treatment diagram (b); 1 – modified material, 2 – chambers, 3 – SiC powder, 4 – mixing tool, 5 – pin

Table 1
Comparison of multi-chamber technology with groove technology

No.	Groove technology	Multi-chamber technology
1.	Two different work tools are needed	One work tool
2.	Two-step method	Method may have one or two steps
3.	Risk of moving modifying material along groove and beyond modified zone	Clearly reduced risk of moving modified material beyond modified zone
4.	Groove is usually limited to straight lines	Freedom of form, size and arrangement of chambers to control contribution of reinforcing phase to matrix of modified material

step. A diagram of the method is shown in Fig. 2, and Table 1 summarizes the main features of the different FSP processing variants. The development of multi-chamber technology is a variant with a shift of the tool axis with respect to the axis of the chambers by the value ΔL. By shifting the tool working area, direct contact of the tool pin with the modified material at the stage of its penetration into the material is limited. This minimizes the risk of uncontrolled movement of the modifying material outside the modified area and reduces the wear of the pin by limiting contact with reinforcing phase particles. Moreover, the risk of contaminating the modified sample by the wear material of the pin is also lower. This solution is used in this work to modify the AlZn5.5MgCu aluminum alloy surface layer.

2. Research material and methodology

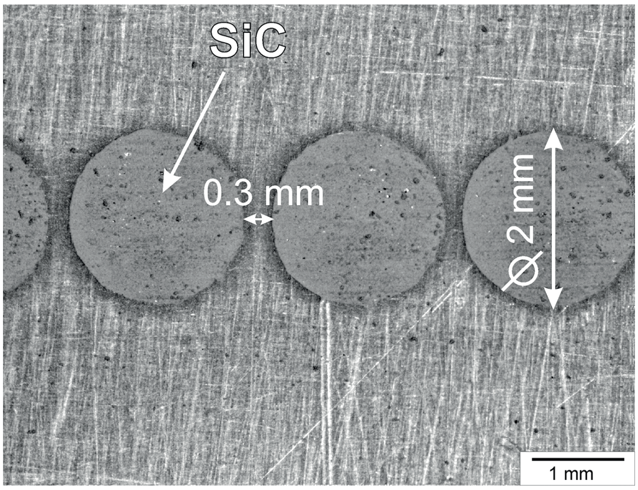
The test material was AlZn5.5MgCu – T6 aluminum alloy and its chemical composition is given in Table 2. The specimens of dimensions 90×70×15 mm were cut from a 15 mm thick sheet and then the chambers of 2 mm in diameter and 4.5 mm deep were hollowed in the samples. The chambers were placed along a straight line along the entire length of the sample. The individual chambers were separated from each other and the wall thickness separating each chamber from the other was at the narrowest point about 0.3 mm. The wall could not be too thick, as the reduced modification fraction could have occurred at its place of occurrence after the friction treatment. On the other hand, the wall thickness between the chambers should be large enough to effectively secure the modifying material contained

Table 2
Chemical composition of AlZn5.5MgCu aluminum alloy

Alloy	Content of elements, % wt.								
	Zn	Fe	Cu	Mn	Mg	Cr	Si	Ti	Al
AlZn5.5MgCu	5.5	0.3	1.6	0.15	2.4	0.2	0.2	0.1	rest

therein before moving out of the modified zone during the dynamic impact of the rotating working tool. Fig. 3a illustrates an exemplary sample after filling the chambers with the SiC powder. Each of the samples consisted of 4 rows of evenly distributed chambers. The chambers were filled with SiC powder. SiC technical powder with an average particle size of about 4 μm and a polyhedral shape was used. Friction processing was performed using a vertical CNC milling machine, which allows the sample to be shifted in the XYZ planes and the working tool tilt. A tool with a pin was used. The pin was cone-shaped and its lateral surface was threaded. The tool was made of X37CrMoV5–1 hot work tool steel. The dimensions of the tool are shown in Fig. 3b. Two-stage friction treatment was applied. In the first processing phase, the tool axis was at a distance ΔL = 2.5 mm relative to the axis of the chambers, while in the second processing phase the tool moved centrally along the line of chambers. This solution was used to achieve a more even distribution of the reinforcing phase in the aluminum alloy matrix and to minimize the risk of uncontrolled displacement of

a)



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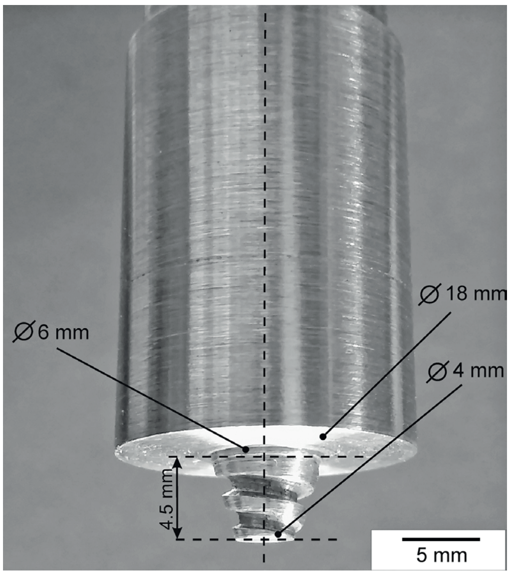
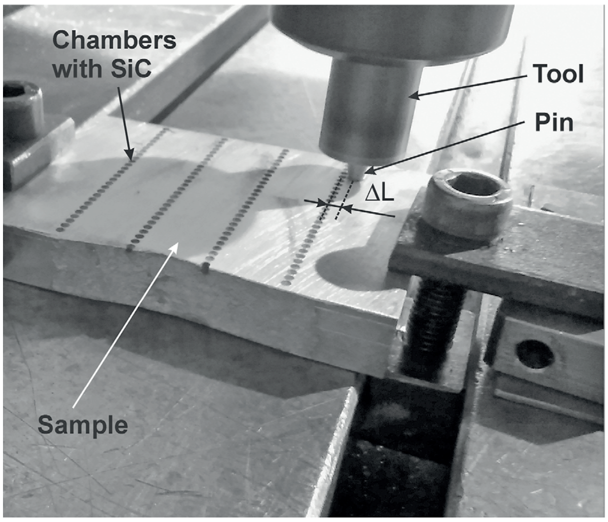


Fig. 3. Samples after filling chambers with SiC powder (a); Tool (b)

a)



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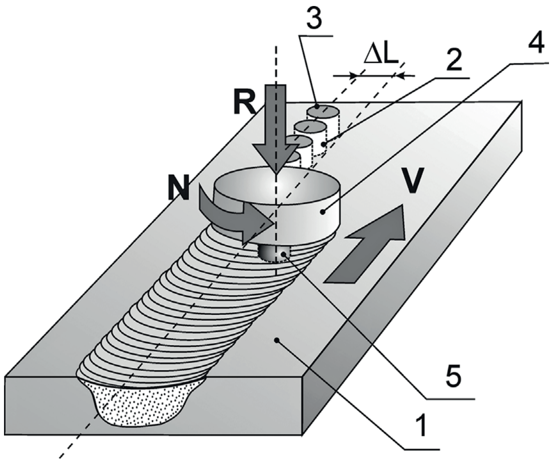

Fig. 4. Friction modification station (a) and friction treatment scheme in variant with shifted tool working area (b); 1 – modified material, 2 – chambers, 3 – SiC powder, 4 – tool, 5 – pin

the SiC powder when the pin enters the modified material. This solution also allowed wear on the pin itself and contamination of the sample with the material from the worn pin to be reduced. Friction treatment was performed using three different rotational speeds, i.e. N = 250 rpm, 400 rpm and 550 rpm and a constant tool travel speed V = 30 mm/min. The angle of deviation of the tool from the vertical axis to the sample surface was in all cases 2°, and the speed of the tool movement along Z axis in the initial phase was R = 6 mm/min and 10 mm/min respectively for the first and second treatment steps. In the first stage of processing, tool movement along the axis of the chambers took place after a time t = 2 s (dwell time), measured from the time the tool was fully immersed in the modified material. This time was necessary to plasticize the alloy that is required to mix the reinforcing phase. In the second stage of processing, tool movement along the axis of the chambers took place immediately after its full recess. The processing scheme and the friction modification station are shown in Fig. 4, and the processing parameters are summarized in Table 3.

Table 3
Friction processing parameters

No.	Parameters	Processing step	
		I phase	***II phase***
Sample 1	N	250 rpm	250 rpm
	V	30 mm/min	30 mm/min
	R	6 mm/min	10 mm/min
	ΔL	2.5 mm	0 mm
	t	2 s	0 s
Sample 2	N	400 rpm	400 rpm
	V	30 mm/min	30 mm/min
	R	6 mm/min	10 mm/min
	ΔL	2.5 mm	0 mm
	t	2 s	0 s
Sample 3	N	550 rpm	550 rpm
	V	30 mm/min	30 mm/min
	R	6 mm/min	10 mm/min
	ΔL	2.5 mm	0 mm
	t	2 s	0 s

The material in initial state and after FSP modification were subjected to comparative microstructural investigations using light microscopy. The observations were performed using an Olympus GX41 optical microscope and an Olympus SZ61 stereoscopic microscope. Hardness measurements were also performed using the Shimadzu HMV-G20 microhardness gauge. The applied load was 980.7 mN and the load time amounted to 10 s.

3. Results

The microstructure of the aluminum alloy in the initial state is shown in Fig. 5. The elongated grain shape and the distinct banding of the intermetallic phases are the most characteristic components of the alloy microstructure and are the consequence of the heat treatment and plastic treatment of the aluminum alloy. Examination of the modified material using optical microscopy revealed that plasticization of the modified material and significant changes in the microstructure of the material in relation to the pre-treatment condition took place within the range of the processing parameters. These changes were due not only to the introduction of SiC particles to the plasticized aluminum alloy and to the formation of a metal-ceramic composite microstructure, but also to the disappearance of the characteristics of the starting materials, including intermetallic precipitates. In addition, the presence of characteristic zones

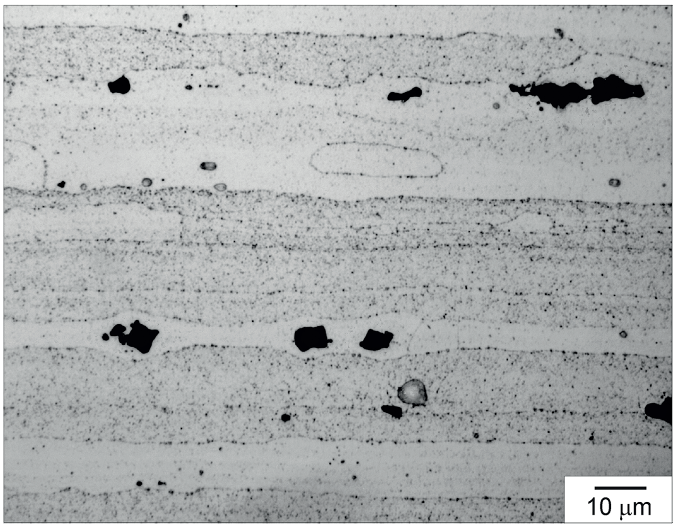

Fig. 5. Microstructure of AlZn5.5MgCu aluminum alloy

typical for friction-modifying materials was found in the modified layer, namely a clearly dominant stirring zone SZ located in the central part of the modified area and a narrow heat-affected zone HAZ separating the core of the material from the thermomechanical affected zone TMAZ. The approximate location of individual zones is shown in Fig. 6.

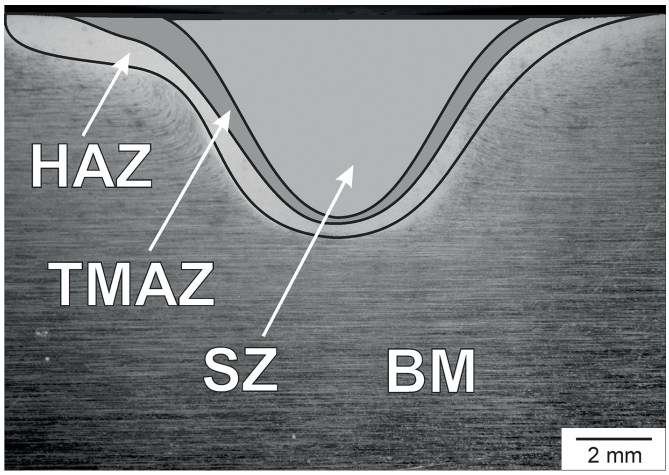

Fig. 6. Friction modified zone, 400 rpm

Microstructural studies revealed the presence of very fine and equiaxed grains in the stirring zone, while in the thermomechanical affected zone the presence of grains with a clearly elongated shape was revealed (Fig. 7a–c). The microstructure of the stirring zone proves that there was dynamic recrystallization of the material there, i.e. a process that is a consequence of strong plastic deformation of the material and the influence of high temperature. The temperature during friction modification is generally 70–90% of the melting temperature of the modified material, hence all the transformations occurring during friction modification are solid state transformations.

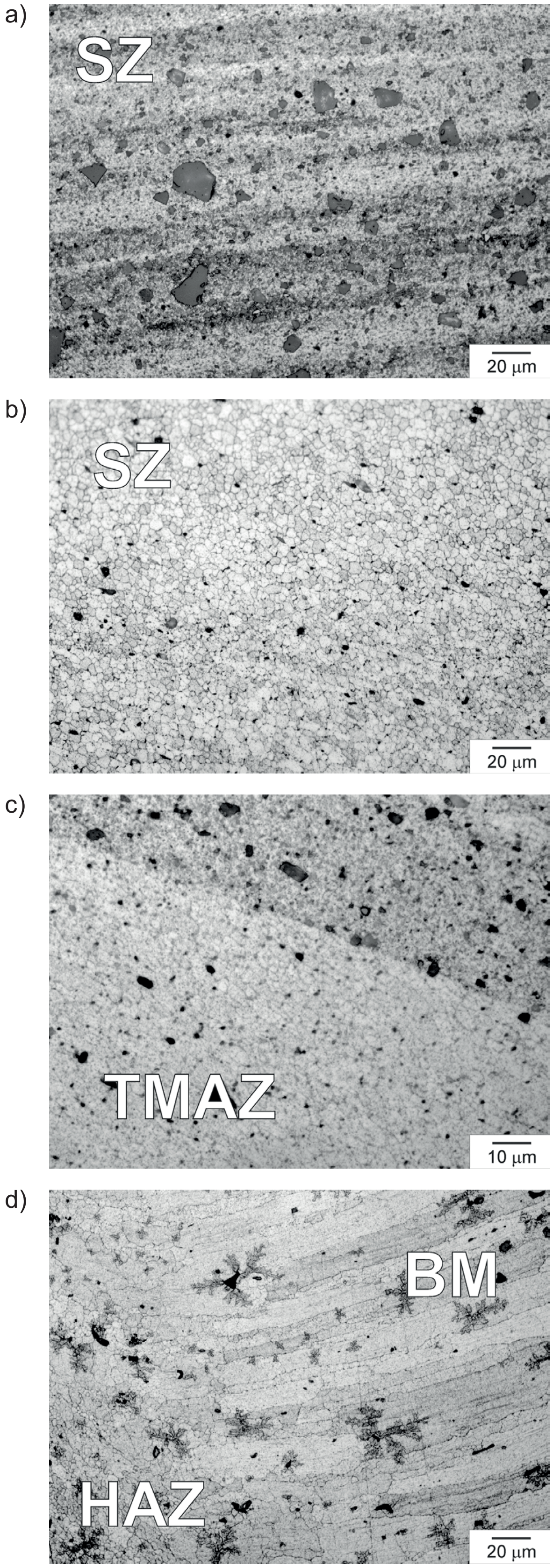

Fig. 7. Microstructures of examined alloy after FSP modification seen in: a/ SZ at the condition of the tool speed 400 rpm (a), at 550 rpm (b), TMAZ at 550 rpm (c), at the border between HAZ and BM at the tool speed 250 rpm (d)

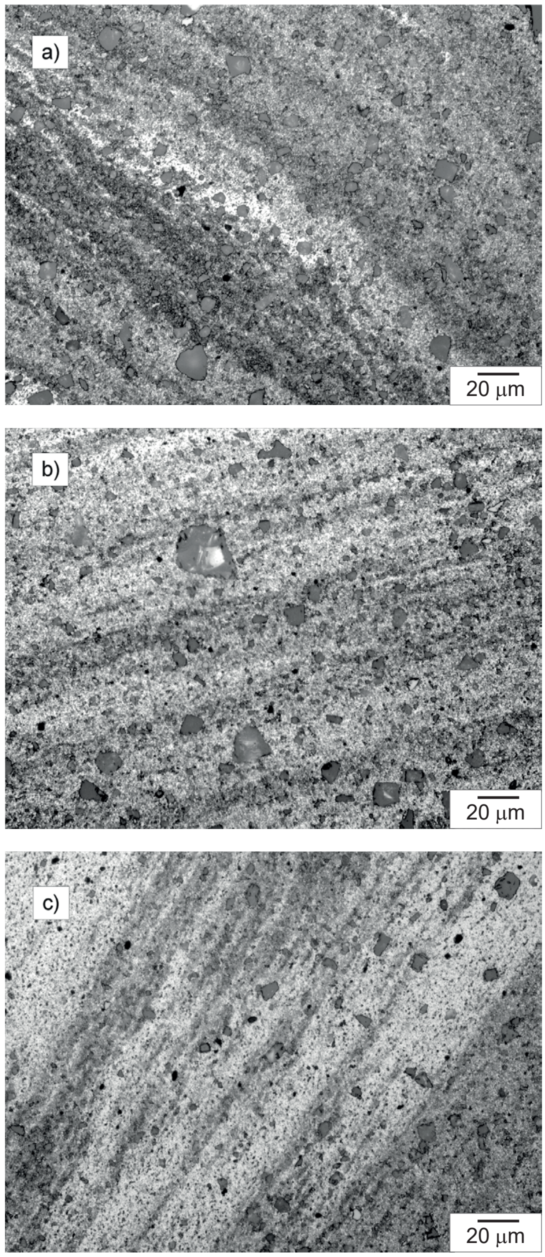

Fig. 8. Metal-ceramic composite microstructures of examined alloy after FSP modification seen in the surface layer at the tool rotational speed: 250 rpm (a), 400 rpm (b), 550 rpm (c); see text for explanation

The most characteristic feature of the stirring zone was the presence of a metal-ceramic composite microstructure (Fig. 8). The SiC particles were intensively dispersed in the metal matrix, with no visible presence of a significantly above-average content of reinforcing phase. The contribution of the reinforcement phase was relatively uniform throughout the volume of the mixing zone, the difference between the highest SiC particle concentration in the mixing zone and the least concentrated site was less than about 10%. On the other hand, there were differences in the shape and size of the composite zone, the largest composite zones were found in the samples treated with tool rotational speeds of N = 400 and 550 rpm. In these samples,

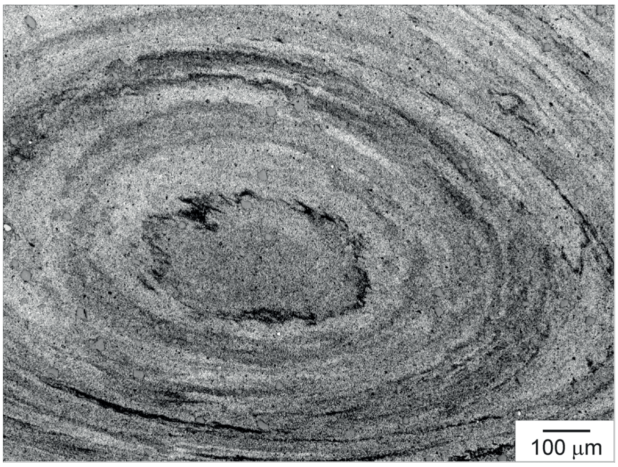

Fig. 9. "Onion rings" seen in the FSP weld formed at the tool rotational speed of 400 rpm; see text for explanation

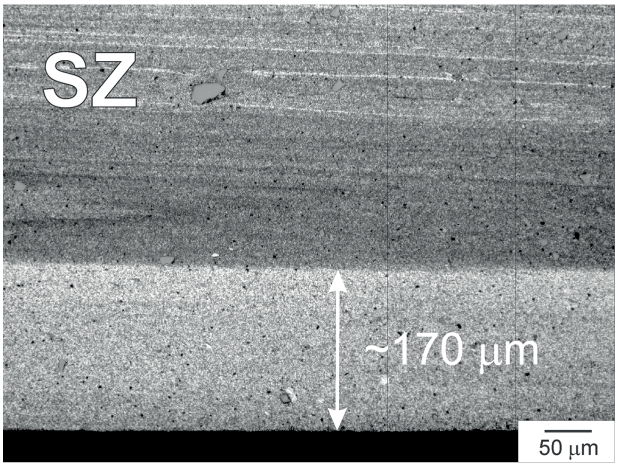

Fig. 10. Microstructures of examined alloy after FSP modification seen in the surface layer at the rotational speed of 250 rpm

a lower mean concentration of the reinforcing phase was noted of approximately 7.8% and nearly 9% for the sample modified at N = 250 rpm. In all the samples, however, the presence of a characteristic „onion rings" microstructure reflecting the movement of the plasticized metal during frictional processing (Fig. 9) and a narrow subsurface zone characterized by a significantly lower contribution of the reinforcing phase (Fig. 10). As long as the average SiC concentration in the SZ was between 7.8% and 9%, and in the TMAZ about 3.5%, it was less than 1% in the subsurface layer. However, given the negligible thickness of the SiC surface layer (up to about 200 μm) compared to the thickness of the entire modified zone, its presence is not a significant technological defect.

Regardless of the processing parameters used, the microstructural effects observed in individual samples were very similar both in the presence of individual zones and in the presence of the composite microstructure. The only noticeable difference was the grain size in the aluminum alloy. It was found that as the tool speed decreases, the grain size is decreased as well. The differences in grain size were not significant, however, the average grain size in the stirred zone was about 4.5 μm and 6.2 μm in the case of the modified samples using N = 250 rpm and 550 rpm respectively. The mere fact of the difference in the microstructure of the material is explained by the difference in the magnitude of the thermal effect associated with the friction treatment. Using a higher tool speed generated more heat, which in turn was conducive to grain growth.

As a result of the friction modification, characteristic circular strips formed on the surface of the specimens, mapping the direction and manner of movement of the plasticized material under the shoulder typical of materials subjected to FSP and FSW. Examples of the macroscopic effects of processing are shown in Fig. 11. The width of the modified area corresponded to the diameter of the tool shoulder and was approximately 18 mm.

The comparative measurements of the hardness of the modified and starting material showed a significant increase in material hardness. The average hardness of the starting material was about 95 HV0.1, while the modified material ranged from 158 HV0.1 to 169 HV0.1 depending on the processing parameters used. The highest hardness was obtained by the sample modified at N = 250 rpm (sample 1), while the lowest by the sample modified at N = 550 rpm (sample 3), however, the differences in hardness between Samples 1 and 2 were lower than the hardness of Samples 2 and 3. These differences should be attributed to the different contribution of SiC reinforcing phase and the different degree of material microstructure, depending on the rotational speed of the tool and the accompanying thermal effect.

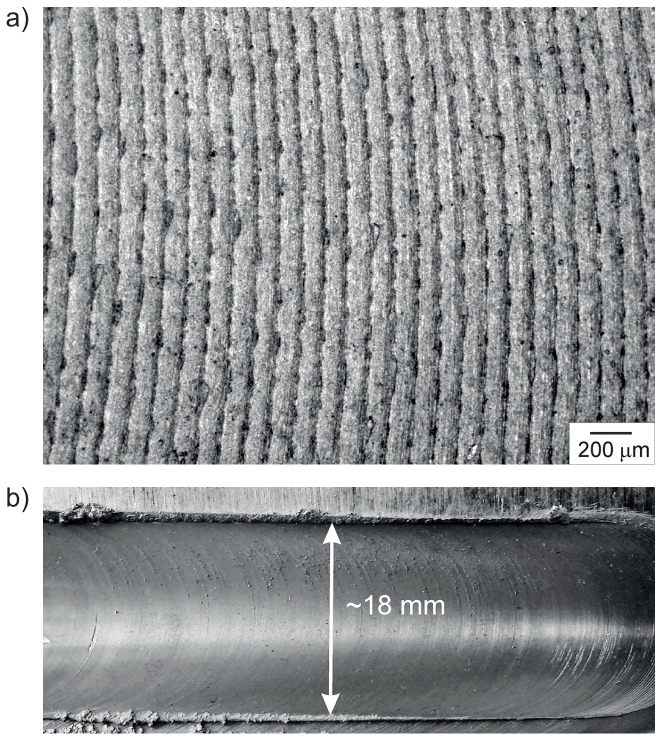

Fig. 11. Characteristic changes in AlZn5.5MgCu alloy surface geometry after FSP modification

4. Summary

The development of one-step FSP multi-chamber technology is a two-stage variant with a shift in the tool working area relative to the axis of the chambers in the first phase of processing and re-processing of the band using the tool moving centrally relative to the original axis of the chambers in the second processing phase. The shift of the tool main axis relative to the axis of the chambers minimizes the risk of the powder moving outside the modified zone during insertion of the pin into the modified material since the rotating pin does not then have direct contact with the modifying material or the contact is greatly reduced. Shifting the tool main axis relative to the axis of the chambers increases the tool life itself and reduces contamination of the specimen with the wear material of the pin since direct contact of the pin with the hard SiC particles is limited. Within the range of adopted frictional processing parameters, plastification of the aluminum alloy and intensive dissolution of the ceramic phase particles in the melt layer resulted in the formation of a metal-ceramic composite microstructure. The consequence of the microstructural changes in the aluminum alloy surface layer was a significant increase in material hardness, depending on the SiC reinforcement phase, tool rotational speed and thermal effect associated with the treatment. FSP technology is an effective solution, relatively cheap and simple to implement, requiring no specialized apparatus to produce a composite microstructure in the AlZn5.5.MgCu aluminum alloy surface layer.

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