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Friction stir processing of the AZ91 magnesium alloy with SiC particles

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ABSTRACT

Purpose: Purpose The main purpose of the research was friction modification by means of material stirring (FSP – Friction Stir Processing) of the surface layer of the AZ91 magnesium alloy with SiC particles.

Design/methodology/approach: For the introduction of SiC particles and the formation of the composite structure in the surface layer of the magnesium alloy, the original multi chamber technology (MChS), developed as part of this study, was used. The scope of research verifying the effectiveness of the friction modification included both macro- and microscopic evaluation of the structural changes triggered by the treatment.

Findings: The research results showed that friction modification of the AZ91 magnesium alloy leads to a strongly refined structure and intensively dispersed SiC ceramic particles in the surface layer of the magnesium alloy, resulting in the formation of the composite structure of the metal-ceramic type. In the stirred zone (SZ), a prevalence of equiaxed grains sized 2–15μm was observed, whereas the degree of refinement of structure depended on the treatment parameters, especially on the rotation speed of the stir tool. In the thermo-mechanically affected zone (TMAZ), deformed grains dominated, the location of which corresponded to the direction of the displacement of the plastified material during the FSP treatment. SiC particles have been found both in the SZ and in the TMAZ.

Practical implications: The obtained results prove that using the FSP technology to modify the surface layer of magnesium alloys with SiC particles is an effective and promising solution with a high application potential, which allows for forming the material structure to a great extent.

Originality/value: The structural research has shown that the Multi Chamber System technology enables a controlled and virtually lossless introduction of an additional phase in the course of the single-stage treatment, and minimizes the dislocation of the powder beyond the working area of the working tool.

Keywords: Friction stir processing; SiC particles; Magnesium alloys

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

One of the latest solutions in the surface treatment of metal materials is friction modification with stirring material (FSP – Friction Stir Processing), which is based on friction stir welding (FSW), a technology developed at the Welding Institute (TWI) in Great Britain in 1991 [1]. In both FSP and FSW, the heat effect accompanying the friction between the working/stir tool and the modified material surface leads to plastifying the material and causes changes in its structure (including the surface geometrical structure) and properties [2-7]. The extent and character of those changes depend both on the treatment parameters, i.e. the rotational speed of the working tool and the speed of the tool travel, and on the dimensions of the stir tool, especially on the shape of its pin and the size of its shoulder diameter [8-12]. More and more often, the FSP technology is also used for the formation of the composite structure in the material surface layer by the introduction of a strange phase into the plasticized material [13-26]. In this case, the material gains new properties resulting from the properties of the individual components and their volume shares. The application of the FSP technology allows for using a very wide range of strengthening materials, from powders such as SiC, WC, Al_2O_3, TiO_2, SiO_2, ZrO_2, Cr_2O_3, etc., to carbon fullerenes and nanotubes [14-16, 27, 28]. Interestingly, in the course of the treatment the fusion temperature of the material being modified is not exceeded. This means that with the FSP technology, also those modifiers can be used, which could be impossible in the case of liquid phase technologies, e.g. because of the adverse interactions between the composite components (the temperatures occurring in the FSP process constitute 70-90% of the melting temperature of the material being modified). The modifying material is normally placed in a groove in the surface of the modified material and subsequently spread in the material matrix following its plastification by means of the working tool [9-12].

However, this solution is troublesome since during the treatment, the powder has a tendency to dislocate, which includes leaving the groove due to the dynamic effect between the working tool and the material surface. To prevent this, a two-stage treatment with two different working tools is normally used. In the first stage, a pinless tool with a flat shoulder surface is used. In this case, the treatment is aimed to seal the channel with the powder and protect the powder against dislocating outside the channel during the treatment proper, which is usually carried out with a tool with a pin. The FSP modification carried out in this way is troublesome for many reasons, hence the need for a method which would minimize the methodology problems referred to above. The conceptual work within this study resulted in developing an alternative solution called the multi-chamber technology (MChS – Multi Chamber System) and using it for modifying the structure of the AZ91 magnesium alloy with FSP while simultaneously introducing SiC particles.

2. Material and research methodology

The research material were samples sized 90 x 70 x 10 mm cut out from a AZ91 magnesium alloy cast made by gravity casting. The chemical composition of the AZ91 magnesium alloy is presented in Table 1. Before the treatment, the surface of the samples was chemically cleaned to remove the contaminations which could affect the process. The FSP treatment was carried out with SiC technical powder with a fragmented-multifaceted shape – the average length of grains amounted to 30 μm (Fig. 1). For the purpose of comparison, friction treatment of the AZ91 alloy without introducing SiC particles was also carried out.

Table 1.
Chemical composition of the AZ91 alloy

Alloy	Content of element, wt. %						
	Al	Zn	Mn	Si	Cu	Fe	Mg
AZ91	8.5	0.7	0.32	0.01	0.001	0.001	rest

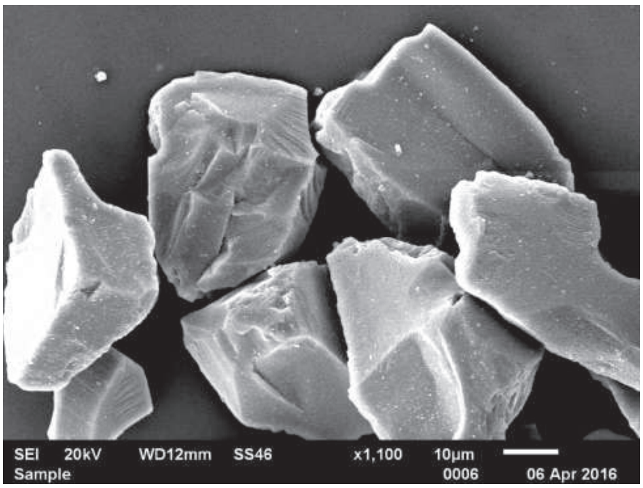


Fig. 1. SiC powder, scanning microscopy

The SiC powder was introduced by means of the MChS technology [29]. The system consisted of open chambers which were filled with the modifying material and located in the places where the friction treatment was carried out. The dimensions of the chambers and the thickness of the walls separating the individual chambers one from another were decisive for the target volume share of the strengthening phase in the surface layer of the material. The use of the chamber system enabled to prevent, or at least minimize, the undesirable displacement of the modifying material out of the modified zone, which is caused by the dynamic effects between the working tool and the modified material. Besides, the developed system enabled forming a layer of a changeable volume share of the modifying material in various places of the alloy surface layer, depending on the needs and operation factors. It is also worth noting that the treatment performed with the MChS technology is a single-stage treatment, and to accomplish it only one working tool is needed. This significantly shortens the time of such treatment.

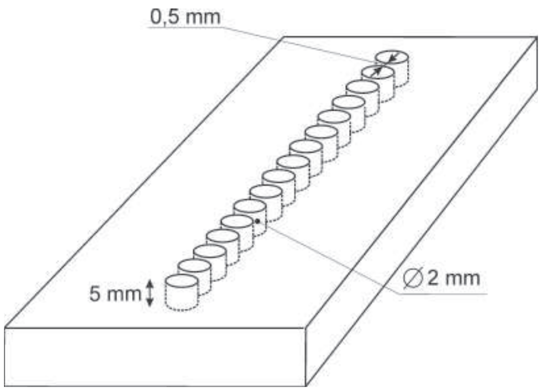


Fig. 2. The sample with cut-out chambers

The friction modification was carried out using a CNC vertical milling machine, which enabled moving the samples in 3 directions: X, Y, Z. In the cuboidal samples of the AZ 91 alloy, the chambers with a diameter of 2 mm and a depth of 5 mm were made, and then SiC powder was placed in them (Fig. 2). The thickness of the walls separating the individual chambers from one another was constant and it amounted to 0.5 mm. The stir tool was made of WCL (X37CrMoV5-1) tool steel for hot work and it consisted of the shoulder of the diameter of 20 mm and the pin of cone shape with the threaded side surface. The length of the stirring pin was 5 mm (Fig. 3). During the treatment, the working tool was deviated from the axis perpendicular to the sample surface by 2 degrees. The FSP treatment was conducted in the course of a single run of the stir tool. The diagram of the treatment and the station for the friction modification are shown in Figs. 4 and 5.

The travel "V" speed of the tool was constant and it amounted to 50 mm/min, whereas the "I" speed of the penetration of the tool into the material being modified was 6 mm/min. The "N" rotational speed of the stir tool was changing in the range of 400 to 750 rpm. The list of the parameters of the friction treatment and the initial macroscopic evaluation are presented in Table 2.

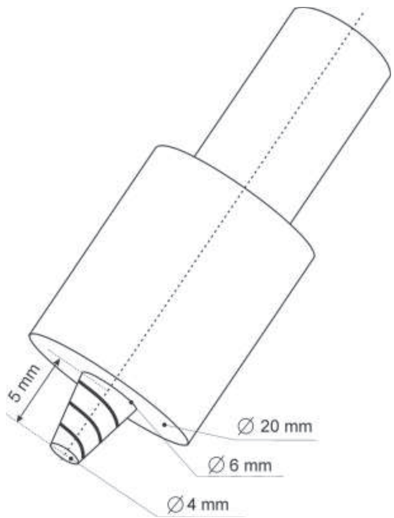


Fig. 3. The diagram of the working tool used for the study

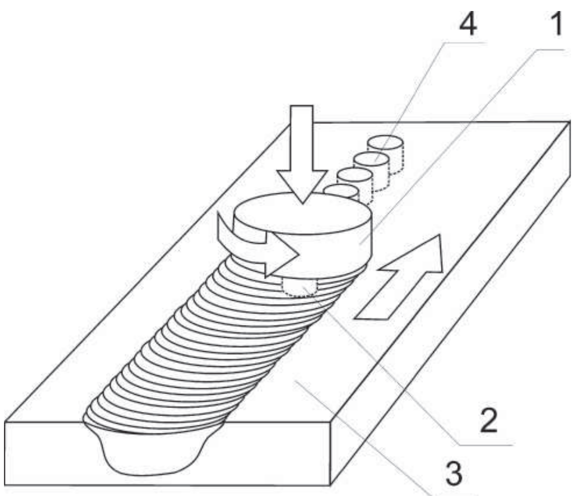


Fig. 4. The friction treatment diagram: 1 – tool, 2 – pin, 3 – the modified material, 4 – the chambers with SiC powder

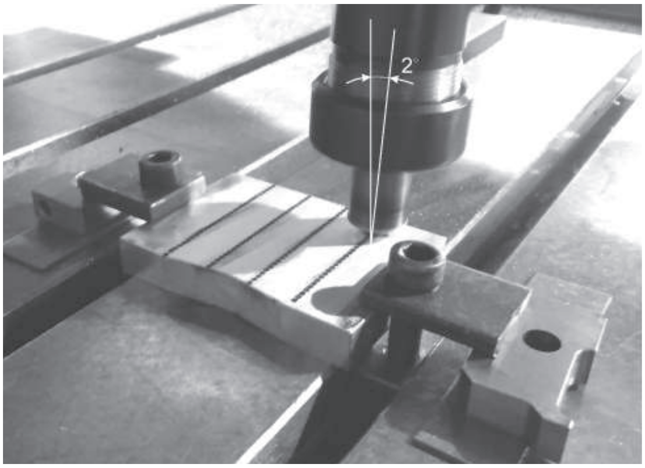


Fig. 5. The station for the friction modification

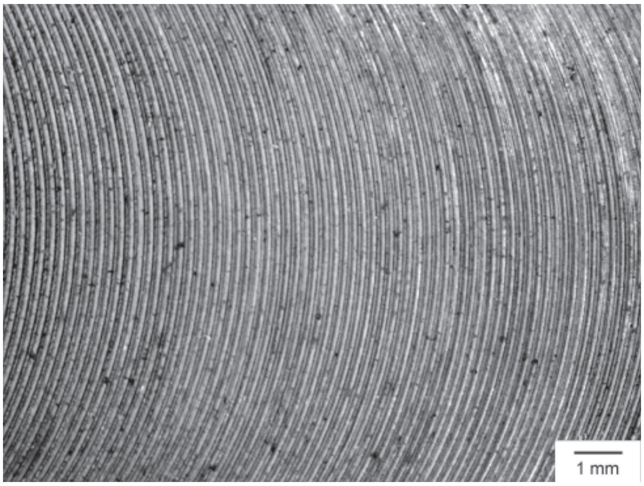


Fig. 6. Examples of the macroscopic effects

Table 2.
Treatment parameters of the AZ91 alloy

No.	Rotational speed N [rpm]	Traveling speed V [mm/min.]	Penetration speed of the tool I [mm/min.]	Preliminary macroscopic evaluation
Treatment with SiC				
1	400	50	6	Without imperfections
2	500	50	6	Without imperfections
3	750	50	6	Without imperfections
Treatment without SiC				
1	400	50	6	Without imperfections
2	500	50	6	Without imperfections
3	750	50	6	Without imperfections

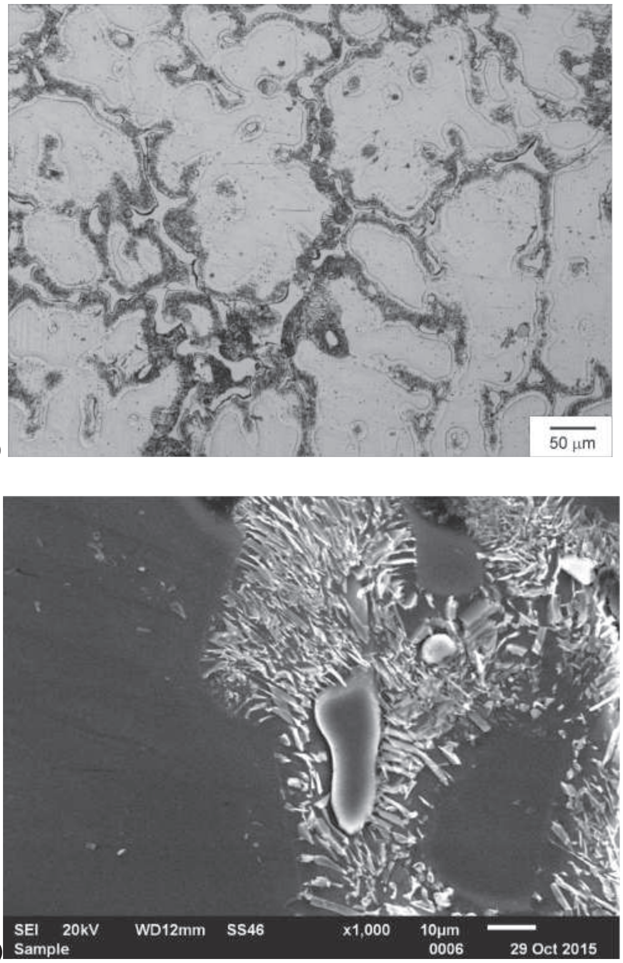
The macroscopic study of the effects of the friction treatment was carried out with the Olympus SZ6 stereoscopic microscope, whereas the material structure was studied with the Olympus GX-41 optical microscope and JEOL JSM-6610LV scanning microscope. Examples of the changes in the surface geometric structure of the magnesium alloy which were caused by the friction treatment obtained at the rotational speed of the stir tool of 500 rpm can be seen in Fig. 6.

3. Description of achieved results of own researches

In the structure of the AZ91 alloy cast, the microstructural studies have revealed the presence of large crystals of the α-Mg solid solution, α+γ eutectics (γ – $Mg_{17}Al_{12}$ intermetallic compound) and the secondary precipitation of the γ phase with characteristic plate morphology. The grain size of the α-Mg grains in as-received AZ91 was in the range of 50–200 µm with the average grain size of about 110 µm. The structure of the AZ91 magnesium alloy in the state of delivery is shown in Fig. 7.

The investigation of the material being modified frictionally showed that in the range of the assumed friction treatment parameters, the plastifying of magnesium alloy occurred, which was a prerequisite condition for the formation of the composite structure in the alloy surface layer. In the structure of the materials being modified frictionally, the presence of the stirred zone (SZ) typical for the materials subjected to the friction modification was found, with very fine α-Mg grain and evenly distributed SiC particles giving it the features of the composite material. The size of α-Mg grain in the stirred zone was evidently smaller than in the starting material and it was merely 2–20 µm.

Such strong refinement of structure is undoubtedly the consequence of the dynamic recrystallisation of the material, since it should be remembered that during the friction treatment no liquid phase is formed, and only the plastification of the material occurs, therefore the processes of the transitions in the material being modified are exclusively the transitions in the solid phase.

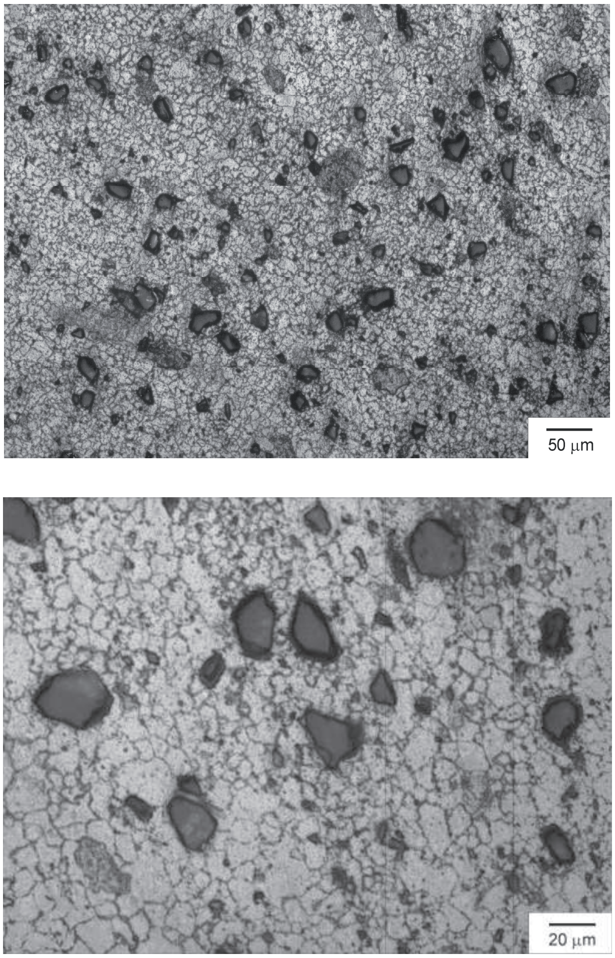


a)

b)

Fig. 7. The AZ91 magnesium alloy structure, (a) optical microscopy, (b) scanning microscopy, (c) etched microsection

The grains found in the stirred zone were mostly equiaxed, in contrast to the grains revealed in the zone of thermo-mechanical deformation (or TMAZ – thermo-mechanically affected zone), the shape of which was evidently elongated, and the grains themselves, as the SiC particles present in that zone were arranged along the lines determining the direction of the displacement of the plastified material, giving that zone banding features. The morphology of the grains in the thermo-mechanical deformation zone proves that the dynamic recrystallisation of the material does not occur in that place. Besides, the characteristic feature of the frictionally modified layer was the dissolution of the γ inter-metal phase in the α-Mg solution. Some examples of the structures of the material subjected to friction modification with SiC particles are shown in Fig. 8. The microstructural research has not shown any occurrences of material discontinuities on the interface of the ceramic-metal phases, the presence of which could be caused by e.g. differences in the thermal expansion coefficients of SiC and the magnesium alloy. Also, in the material being modified frictionally no pores were found, the presence of which could significantly reduce the properties of the layer. The geometric surface structure was typical of the materials modified frictionally, with the characteristic grooves formed as a result of the effect between the tool and the alloy surface.



a)

b)

Fig. 8. The structure of the layer modified by the FSP method with the use of SiC particles

Analogous structural research was carried out for the AZ91 magnesium alloy after performing the friction modification without SiC particles. Analogous treatment parameters were applied, i.e. the "V" constant speed of the tool movement amounting to 45 mm/min, the "I" speed of the tool penetration into the material being modified, which was 6 mm/min, and the following "N" rotational speeds of the stir tool: 400; 500; 750 rpm. The changes found in the structure were of similar character, and the extent of refinement of structure was similar to the refinement of structure observed in the material subjected to the friction treatment with simultaneous introduction of SiC particles. However, the blocking of the growth of grains by the particles located on the grain boundaries, often observed during the friction modification (especially when carried out with the use of the particles of nanometric sizes), did not occur in this case. Some examples of the structures of the magnesium alloy subjected to the friction modification are presented in Fig. 9.

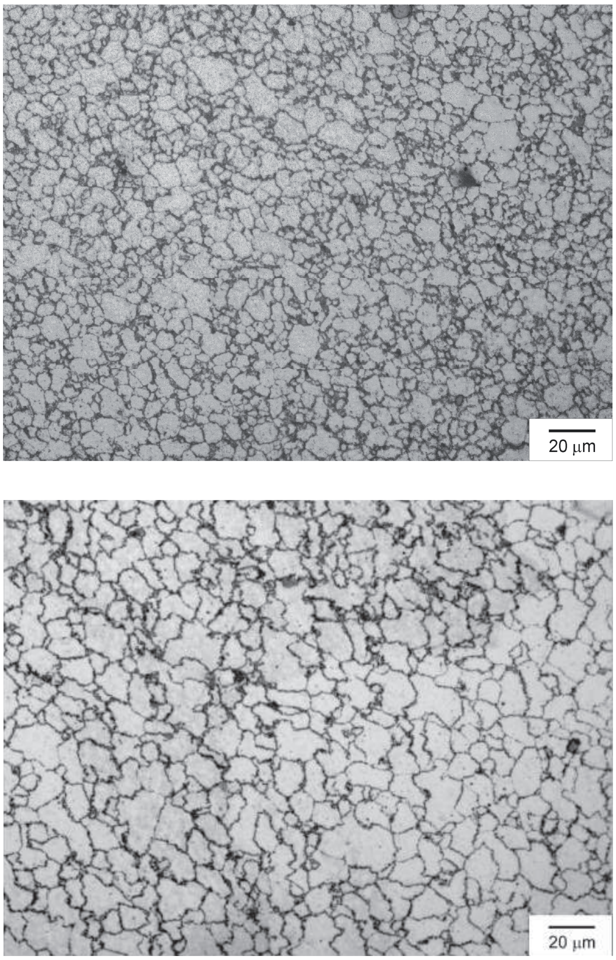


Fig. 9. The structure of the layer modified by the FSP method without the use of SiC particles; a) V=400 rpm, b) V=750 rpm

For both analysed material types, i.e. that modified with the share of SiC particles and that without them, an evident relation between the grain size of the metal matrix and the rotational speed of the stir tool was found. A higher extent of the refinement of structure on the material was observed in the samples subjected to the friction modification with lower rotational speed of the working tool. The found relation should be explained with the fact that with the increase in the rotational speed of the working tool the temperature to which the material being modified heats up also increases, and as a result, the extent of the refinement of structure is diminished. The smallest grain was observed in the samples subjected to the treatment with the use of the "N" speed = 400 rpm, whereas the biggest one in the samples subjected to the modification with the use of the "N" speed = 750 rpm. The average size of the grain in the stirred zone was about 7μm with the use of the "N" rotational speed of the working tool=400 rpm, and 13μm when the "N" rotational speed was 750 rpm.

The conducted studies have shown the effectiveness of the MChS technology. To a great extent, the developed solution allowed for avoiding the adverse displacement of the modifying material and the variability of its share in different places of the layer being modified. It is also worth noting that the treatment was a single-stage treatment, which has limited the cost and the time of its implementation.

4. Conclusions

Based on the conducted research, the following statements and conclusions have been formed:

1. As a result of friction modification of the AZ91 magnesium alloy, the structure is strongly refined, whereupon the extent of refinement depends on the rotational speed of the working tool and the heat effect accompanying the treatment.
2. The presence of very fine equiaxed grains in the stirred zone proves the occurrence of the dynamic recrystallisation of the material during the friction treatment.
3. In case of the FSP treatment with the use of SiC as an additional material, a dispersion of the strengthening phase in the plastified material and the formation of the composite structure in the alloy surface layer have been observed.
4. The use of the MChS technology enables introducing SiC particles effectively into the surface layer of the

AZ91 alloy within the single-stage treatment and minimizes the effect of the displacement of the powder outside the area of the working tool effect due to the dynamic influence of the tool on the material being modified.

5. The MChS multi-chamber technology may constitute an alternative solution with regards to other currently applied technologies of friction modification of metal materials.

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