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MICROSTRUCTURAL MODIFICATION OF CAST ALUMINIUM ALLOY AlSi9Mg VIA FRICTION MODIFIED PROCESSING

MODYFIKACJA MIKROSTRUKTURY ODLEWNICZEGO STOPU ALUMINIUM AlSi9Mg POPRZEZ TARCIOWĄ OBRÓBKĘ Z MIESZANIEM MATERIAŁU

Friction Modified Processing (FMP) is a new solid state processing technique which can be used for microstructural modification in metallic materials. The FMP process has been applied to cast aluminium alloy AlSi9Mg plates to modify the microstructure. The FMP process refinement and dispersed the coarse acicular Si particles creating a uniform distribution of Si particles in the aluminium matrix. Furthermore, the porosity of as cast AlSi9Mg alloy was nearly eliminated by FMP.

The current study also aims to develop a model describing the quantitative relationships between volume and mass of modified material and processing speeds over a wide experimental range. An exponential formula has been found to describe the relationship between penetration depth, volume and mass of modified material and rotational speed. The evaluation on travelling speed affecting penetration depth, volume and mass of modified material can be approximately made through linearly functions.

Keywords: Friction Modified Processing, aluminium alloys, microstructural modification

Technologia tarciowej modyfikacji warstwy wierzchniej z mieszaniem materiału jest nowym procesem prowadzonym w stanie stałym, który może być zastosowany do modyfikacji struktury materiałów metalowych. Proces FMP został zastosowany w celu modyfikacji mikrostruktury stopu odlewniczego aluminium AlSi9Mg. Zastosowanie procesu FMP spowodowało rozdrobnienie i rozproszenie gruboziarnistej struktury krzemu przy jednoczesnym jej równomiernym rozłożeniu w osnowie aluminium. Ponadto proces FMP zlikwidował porowatość w warstwie modyfikowanej.

Prezentowane wyniki badań miały również na celu rozwinięcie modelu, opisującego w sposób ilościowy związek pomiędzy prędkościami prowadzenia procesu modyfikacji, a głębokością oddziaływania wieńca opory, objętością i masą modyfikowanego materiału. Do wyznaczenia zależności pomiędzy prędkością obrotową, a głębokością odziaływania wieńca, objętością i masą modyfikowanego materiału zastosowano funkcję ekspotencjalną, natomiast dla prędkości przesuwu korzystniejszą okazała się funkcja liniowa.

1. Introduction

The selection of a material with unique structural and functional properties is a key factor in numerous industrial applications, especially in the aircraft and automotive industries. In many cases the requirements for surface properties are different than for the bulk material. Furthermore, failure of components by fatigue, wear or corrosion often initiates at the material surface regions. To improve the properties of the material surface various versatile methods are commonly used including welding technology such as cladding, spraying and laser remelting. However, there is a strong necessity to develop a processing technique that would result in microstructural refinement and homogenisation as well as elimination of defects in the surface layer, leading to an enhanced global performance in service and simultaneously would give an advantage in terms of cost and time of production. Friction Modified Processing (FMP) technology can be developed for this purpose.

The basic concept of FMP is remarkably simply. A rotating tool with or without a pin is inserted into single piece of material and transversed along the desired path. The compression force exerted on the material surface results in significant microstructural changes in the processed zone due to intense plastic deformation, mixing, and thermal exposure of material. The characteristics of FMP have led to several applications for microstructural modification in metallic materials,

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including enhanced superplasticity, surface composites, homogenization of nanophase aluminium alloys and metal matrix composites [1].

Friction Modified Processing can dramatically refine grain structures in the surface layer and thus improve its properties [2-6]. Some examples include conditioning microstructures of wrought Al alloys for high strain rate superplastic deformation [4] and refining microstructures to improve ductility of high strength powder metallurgy Al nanocomposite alloys [5]. Other innovative applications include improving the cold workability of wrought Al plate [7] and enhancing the mechanical properties of aluminium castings [2, 8-9] and fusion welds of wrought Al plate [10].

In this study, based on an earlier investigation carried out at the Instytut Spawalnictwa [11], AGH University of Science and Technology [12-15] and Pedagogical University of Cracow [16], FMP is adopted to modify the microstructure of unmodified cast AlSi9Mg alloy to reduce its porosity in the surface layer. Different processing parameters (rotational rate, travelling speed) were used to evaluate the effects of FMP parameters on microstructural changes, penetration depth and mass of modified material.

2. Experimental procedures

Friction Modified Processing experiments were conducted using a vertical milling machine (FYF 32JU2). The material used in this study was a 6 mm thick plate of AlSi9Mg cast aluminium alloy. A non-conventional tool was used in the experiments – a 20 mm diameter shoulder without a pin (Fig. 1). The tool was made of high-speed steel (HS6-5-2).

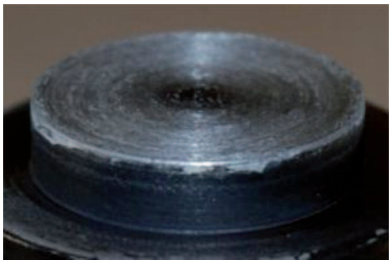

Fig. 1. FMP tool using during experiments

The following Friction Modified Processing parameters were used in experiments: tilt angle 1,5°, travelling speed in the range of 112-1200 mm/min and rotational speed in the range of 112-1800 rpm. The length of modified areas was approximately constant, about 180 mm. The plates were fixed to the machine with suitable grips and then processed. The plate surfaces were not cleaned before processing.

The microstructural investigation was performed on the plane perpendicular to the process direction (cross-section) by light (LM Leica MEF4M) and scanning electron microscopy (SEM FEI Quanta 200 FEG supplemented by energy dispersive spectrometry (EDS) provided by the EDAX company). For light microscopy the samples were mechanically polished and chemically etched in the Keller's reagent. For SEM the samples were electropolished in a solution of perchloric acid and ethanol (1:5) at 10 V and 12°C for one minute and observed in SEM without etching; the Z-contrast formed by backscattered electrons (BSE) was utilized for revealing constituent phases. In the present work, penetration depth was measured using an image analysis software Omnimet Enterprise.

3. Results and discussion

Microstructure

Figure 2 shows SEM micrograph of AlSi9Mg castings in the as received conditions. Coarse acicular Si particles were distributed along the primary aluminium dendrite boundaries. Furthermore, the material exhibited numerous pores with size up to about 300 μm (Fig. 3).

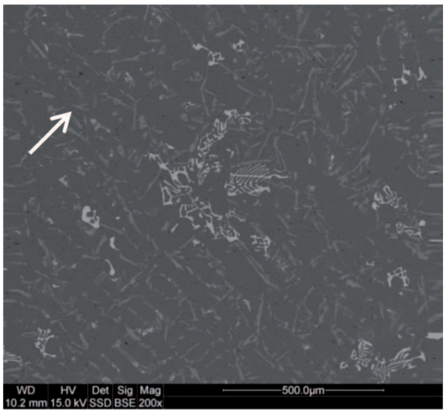

Fig. 2. Microstructure of as-cast AlSi9Mg alloy, Si particle marks by arrow

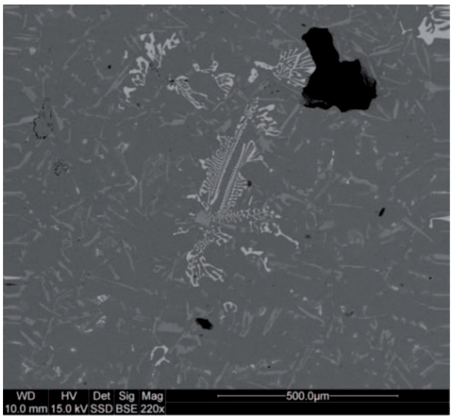

Fig. 3. An example of pores in the microstructure of as cast AlSi9Mg

The constituent phases were characterized by EDS analysis (Fig. 4). The alloy is composed of two predominant phases: the Al solid solution (matrix) – 1 and Si particles – 2. However, the solid solution was not uniform – there were revealed brighter islands enriched with Cu (3). These islands do not well-defined boundaries separating them from the continuous matrix. Also, a complex intermetallic phase rich in Fe and Mn was detected (4). The results of EDS analysis are given in Table 1 (the results cover the amount of elements higher then 0,5 %).

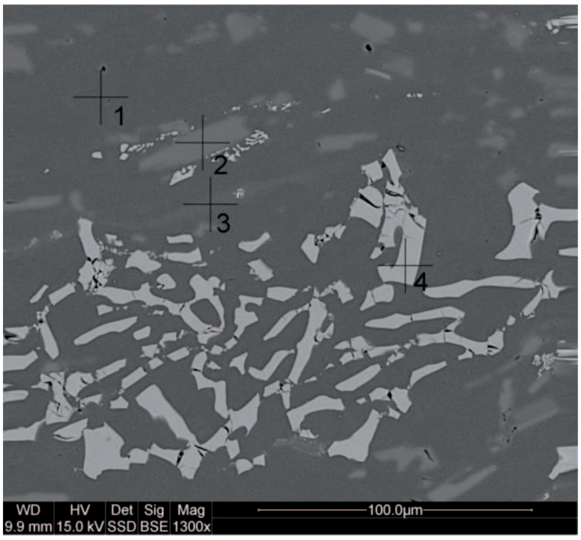

Fig. 4. Microstructure of AlSi9Mg aluminium alloy (SEM) with marks of EDS analysis

TABLE 1

Results of EDS chemical analysis of phases shown in Figure 4

Area	Chemical composition of phases [wt.%]					
	Al	Si	Cu	Fe	Mn	Cr
1	97,5	1,4	–	–	–	–
2	1,2	98,7	–	–	–	–
3	97,2	1,9	0,6	–	–	–
4	62,9	9,6	–	16,4	10,2	0,7

The typical SEM microstructure of the processed material is shown in Figure 5. Two well defined regions (separated by a wide transition zone) could be easily distinguished: the parent material (lower area) and the FMP zone (upper area). The parent material was characterized by the coarse grained structure while the microstructure in the processed zone was modified by the tool action. The modified area resulted in the refinement of the microstructure. The SEM BSE examination revealed characteristic dendrites in the base material (Figures 2 and 3). Figure 5 shows a region closer to the surface where the microstructure changes in a continuous way from that typical for the parent material to the refined one adjacent to the surface.

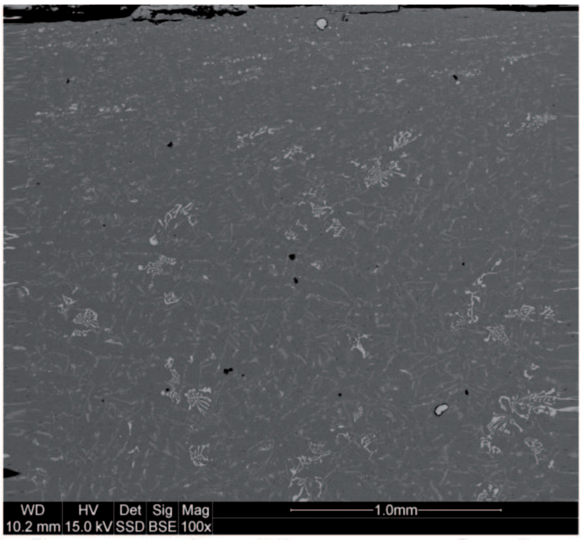

Fig. 5. Typical cross-section of the processed surface layer; SEM

Figure 6 shows SEM microstructure of the FMP AlSi9Mg alloy for sample processing parameters. FMP resulted in a significant refinement of large Si particles and subsequent uniform distribution in the aluminium matrix. Furthermore, porosity in the as cast AlSi9Mg was nearly eliminated by FMP.

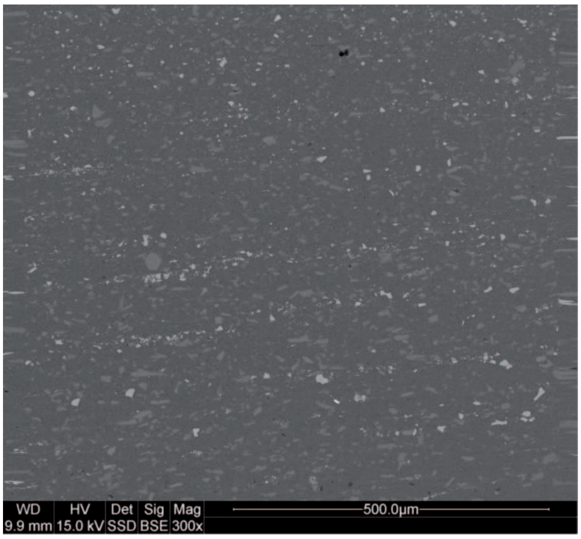

Fig. 6. SEM microstructure of FMP AlSi9Mg alloy at rotational speed of 560 rpm and traverse velocity of 560 mm/min

Severe plastic deformation and material flow caused by the stirring action of the tool together with increased temperatures due to friction force are responsible for the grain refinement and dynamic recrystallization in the processed area [17]. FMP also brings about the closure of casting pores and a general homogenization of the microstructure. As a result of FMP the as-cast material is converted into a near-wrought condition. This homogenized and refined microstructure along with the reduced porosity results in improved mechanical properties [18, 19]. It is also evident from the present study that the dramatic change in microstructure occurs, even when the tool without a pin is used in the FMP.

Measurements

The metallographic examination allowed for evaluating the thickness of the layer under the surface where the microstructure was refined due to the FMP process (penetration depth). The dependence of the penetration depth on the rotational and travelling speeds is illustrated in Figures 7 and 8, respectively. The results indicate that the rotational speed strongly affected the penetration depth of the modified zone. The decrease in penetration depth with an increase in rotation speed is likely due to the rising of temperature within the stir zone. The temperature increase makes the strength decrease and thus the processed aluminium alloy carries lower load. The material undergoes shear faster, and thus the penetration depth of modified zone is narrower.

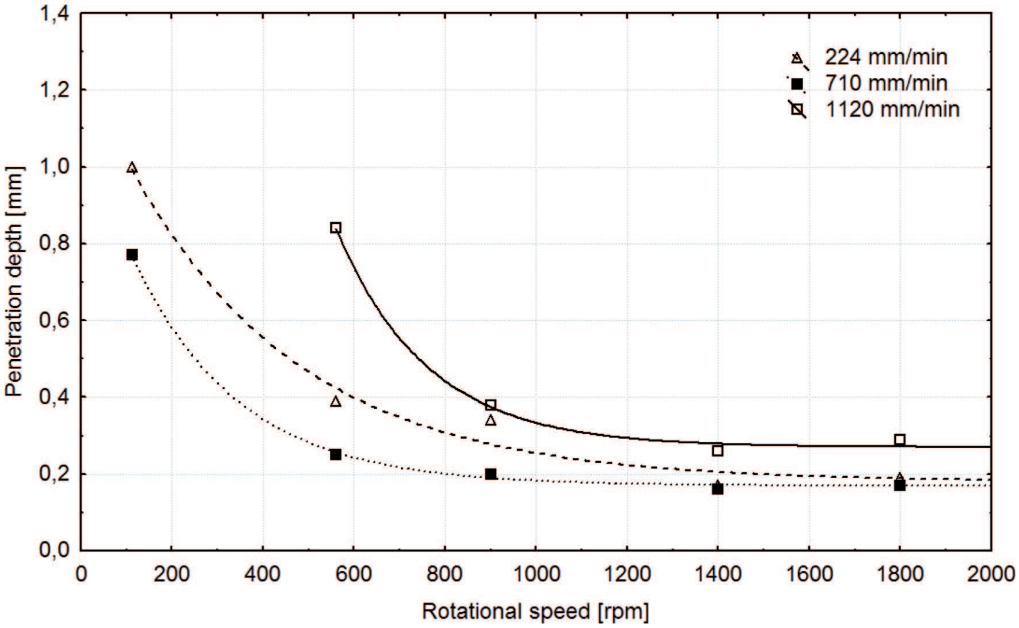

Fig. 7. Influence of rotational speed on the penetration depth for selected parameters

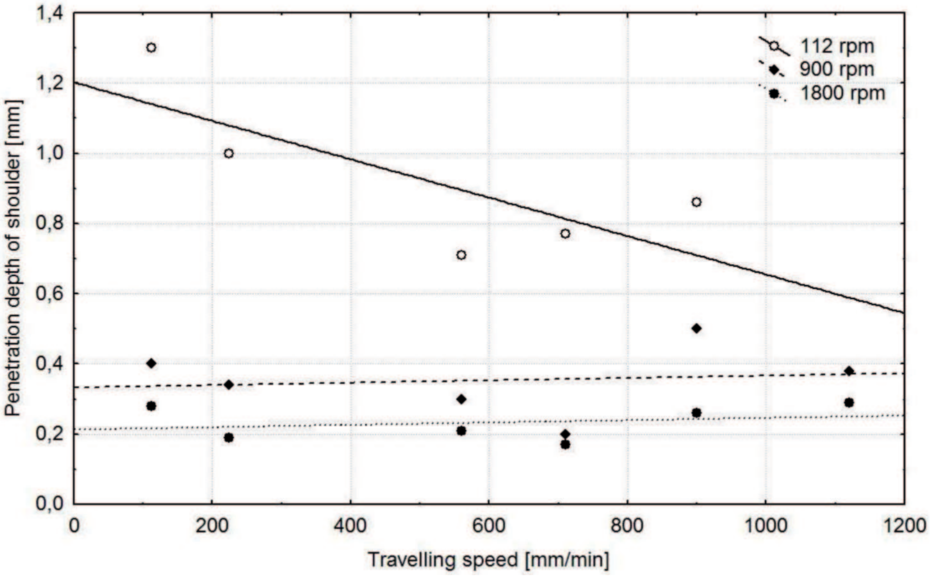

Fig. 8. Influence of travelling speed on the penetration depth of shoulder for selected parameters

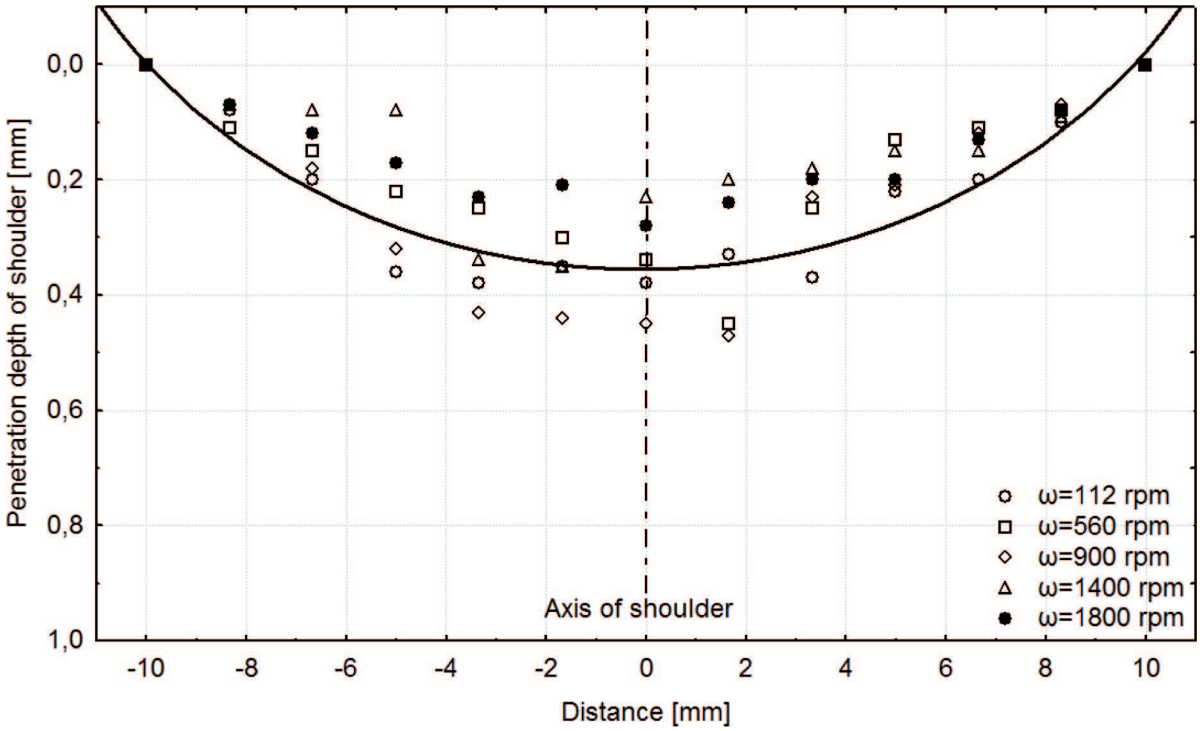

Fig. 9. The penetration depth as a function of distance from centre of tool, with exemplary of fitting of slice of circle, travelling speed v=112 mm/min

To determine the relationship between the FMP parameters and the mass of the modified material, the volume of processed material has to be evaluated. The volume was calculated from the shape of the modified zone (Fig. 9). First, the penetration depth as a function of the distance from the centre of tool was determined (Fig 9). Assuming that the shape of the modified area can be approximated by a slice of circle, the volume of modified material can be calculated as a slice of sphere minus volume of a cone (Fig. 10).

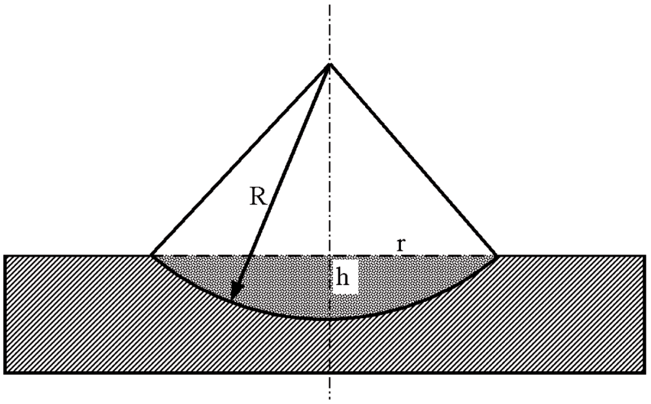

Fig. 10. A sketch of modified area as a slice of sp

The volume of modified material can be expressed as:

$$V = \underbrace{\frac{2}{3}\pi R^2 h}_{\text{Volume of slice of sphere}} - \underbrace{\frac{1}{3}\pi r^2 (R-h)}_{\text{Volume of cone here}} \tag{1}$$

The radius R of sphere (Fig. 10) can be expressed as:

$$R = \frac{r^2 + h^2}{2h} \tag{2}$$

where:

r – radius of base of cone = radius of tool

and after transformation:

$$V = \frac{1}{6}\pi h \left(3r^2 + h^2\right) \tag{3}$$

And the mass of modified material is given by:

$$m = \frac{1}{6}\pi \rho h \left(3r^2 + h^2\right) \tag{4}$$

where: ρ – density of aluminium 2,7 g/cm^3

The effect of rotational and travelling speeds on the volume and mass of the modified material are shown in Figure 11, 12, 13 and 14 respectively. The increase in the rotational speed results in the decrease in the volume and mass of the modified material.

Moreover, as shown in Figures 13 and 14, the increase in travelling speed significantly decreases the volume and mass of the modified material at the rotational speed of 112 rpm. For the higher rotational speed, the travelling speed does not markedly influence the volume and mass.

The physical explanation for this is not yet clear. However, it is likely that the increase in temperature (and thus the decrease in flow stress) as the rotational speed increases is an important factor that would cause easier material transportation at the shoulder region and thus smaller volume of the modified material.

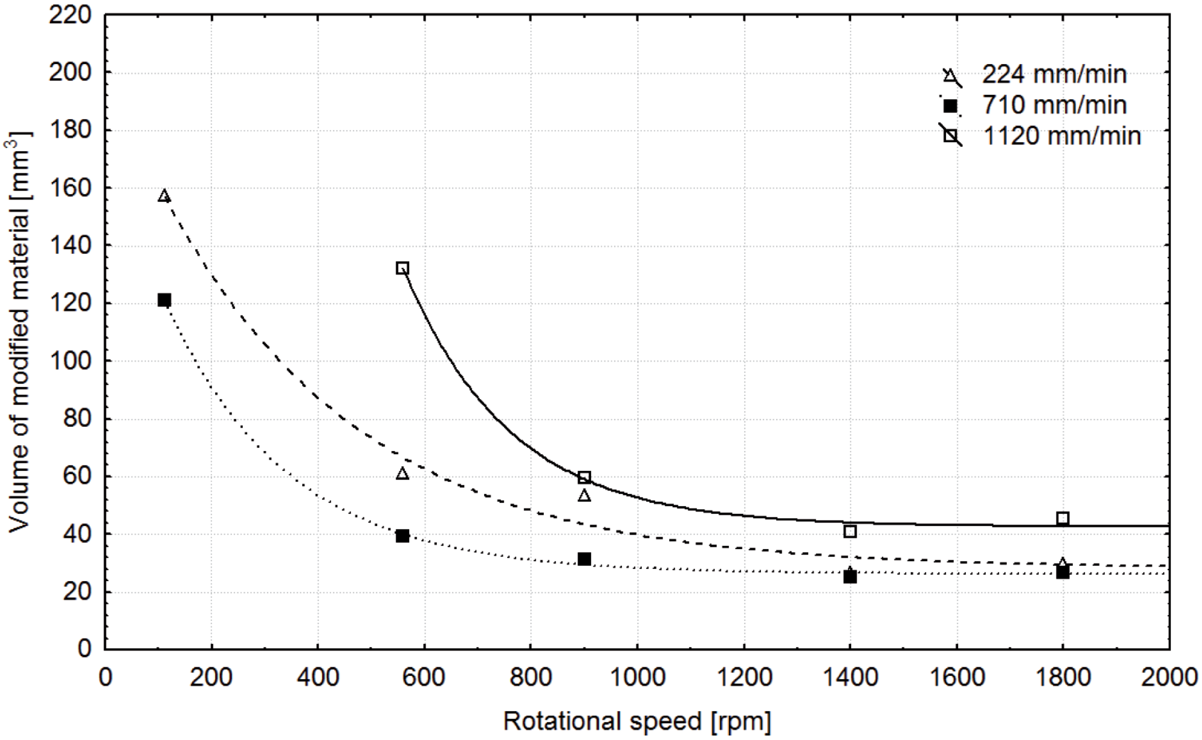

Fig. 11. Influence of rotational speed on volume of modified material

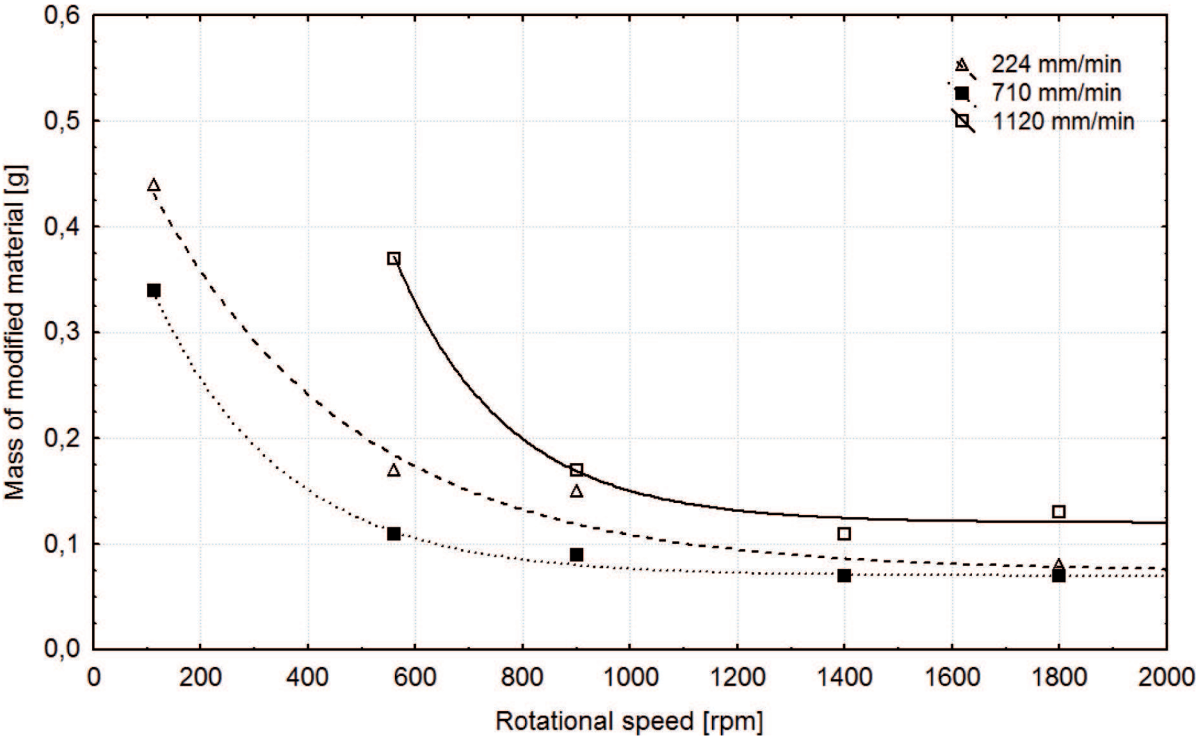

Fig. 12. Influence of rotational speed on mass of modified material

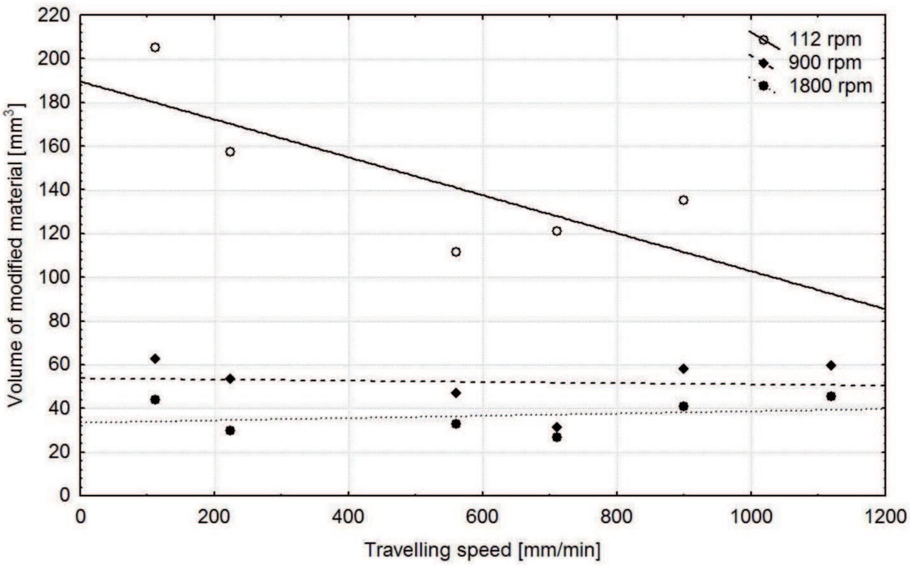

Fig. 13. Influence of travelling speed on volume of modified material

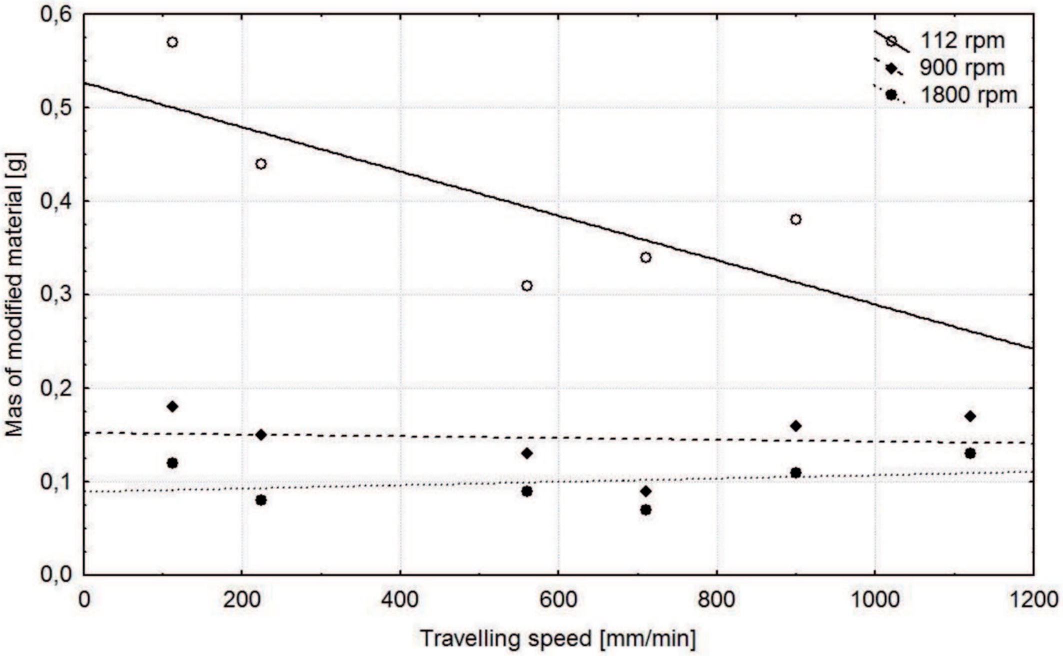

Fig. 14. Influence of travelling speed on mass of material

4. Conclusions

1. Friction modified processing of the AlSi9Mg aluminum alloy resulted in a significant breakup of coarse acicular Si particles and primary aluminum dendrites, created a homogeneous distribution of Si particles in the aluminum matrix, and nearly eliminated all casting porosity.
2. The increase of the rotational speed decreases the penetration depth.
3. The increase of the travelling speed has a negligible effect on the penetration depth compared to the influence of the rotational speed.
4. The increase of the rotational speed decreases the volume and mass of modified material;
5. The increase of the travelling speed has a negligible effect on the volume and mass of modified material.

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REFERENCES

[1] Z.Y. Ma, R.S. Mishra, M.W. Mahoney, Scripta Materialia **50**, 931-935 (2004).

[2] P. Uliasz, M. Blicharski, T. Knych, 8th International Friction Stir Welding Symposium, 18-20 May 2010, Timmendorfer Strand, Germany.

[3] R.S. Mishra, M.W. Mahoney, S.X. McFadden, N.A. Mara, A.K. Mukherjee, Scripta Materialia **42**, 163-168 (2000).

[4] P.B. Berbon, W.H. Bingel, R.S. Mishra, C.C. Bapton, M.W. Mahoney, Scripta Materialia **44**, 61-66 (2001).

[5] N. Saito, I. Shigematsu, T. Komaya, T. Tamaki, G. Yamauchi, M.J. Nakamura, Mater Sci Lett **20**, 1913-1915 (2001).

[6] M.W. Mahoney, W.H. Binget, R.S. Mishra, Mater Sci Forum **426**, 2843-2848 (2003).

[7] M. Miles, C. Smith, M. Mahoney, R. Mishra, Friction Stir Welding and Processing V, Proceedings TMS, 135-140 (2009).

[8] K. Nakata, Y.G. Kim, H. Fujii, T. Tsumura, T. Komazaki, Materials Science and Engineering A **437**, 274-280 (2006).

[9] Z.Y. Ma, A.L. Pilchak, M.C. Juhas, J.C. Williams, Scripta Materialia **58**, 361-366 (2008).

[10] Ch.B. Fuller, B. Christian Mahoney, W. Murray, Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science **37**, 3605-3615 (2006).

[11] M.S. Węglowski, A. Pietras, Archives of Metallurgy and Materials **56** (2011) in print.

[12] C. Hamilton, S. Dymek, M. Blicharski, W. Brzegowy, Science and Technology of Welding & Joining **12**, 702-707 (2007).

[13] C. Hamilton, S. Dymek, A. Sommers, International Journal of Machine Tools & Manufacture **48**, 1120-1130 (2008).

[14] C. Hamilton, S. Dymek, M. Blicharski, Materials Characterization **59**, 1206-1214 (2009).

[15] C. Hamilton, S. Dymek, I. Kalemba, M. Blicharski, Science and Technology of Welding & Joining **13**, 714-720 (2008).

[16] K. Mroczka, J. Dutkiewicz, A. Pietras, Journal of Microscopy-Oxford **237**, 521-525 (2010).

[17] L. Karthikeyan, V.S. Senthilkumar, V. Balasubramanian, S. Natarajan, Mater Des **30**, 2237-2242 (2009).

[18] T.S. Mahmoud, A.M. Gaafer, T.A. Khalifa, Mater Sci Technol **24**, 553-559 (2008).

[19] M. Jayaraman, R. Sivasubramanian, V. Balasubramanian, S. Babu, Met Mater Int **15**, 313-320 (2009).

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