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Influence of Technology Parameters on Properties of AA6061/SiC Composites Produced By Kobo Method

J. Wozniak, M. Kostecki, K. Broniszewski, W. Bochniak, A. Olszyna

Abstract**—**The influence of extrusion parameters on surface quality and properties of AA6061+x% vol. SiC (x = 0; 2,5; 5; 7,5;10) composites was discussed in this paper. The averages size of AA6061 and SiC particles were 10.6 µm and 0.42 µm, respectively. Two series of composites (I - compacts were preheated at extrusion temperature through 0.5 h and cooled by water directly after process; II - compacts were preheated through 3 hours and were not cooled) were consolidated via powder metallurgy processing and extruded by KoBo method. High values of density for both series of composites were achieved. Better surface quality was observed for II series of composites. Moreover, for these composites lower (compared to I series) but more uniform strength properties over the cross-section of the bar were noticed. Microstructure and Young's modulus investigations were made.

Keywords**—**aluminum alloy, extrusion, metal matrix composites, microstructure

I. Introduction

THE 6xxx alloys consists magnesium and silicon as major addition elements. The Al-Mg-Si alloys are heat treatable and have moderately high strength coupled with excellent corrosion resistance. A unique feature is their great extrudability, making it possible to produce relatively complex shapes with good surface quality. These characteristics are particularly essential in construction and automotive industry [1]-[7]. However, if better properties are required, it is necessary to use aluminum alloys matrix composites. Reinforcing of aluminum alloys with ceramic particles improves not only strength properties but also stiffness, fatigue resistance and high temperature properties.

There are several methods viable to fabricate AMCs; they can be classified in: solid state (such as powder metallurgy techniques P/M) [8], liquid-state (infiltration or casting processes) [9], [10] and deposition processes (spray forming) [11]. One of the most commonly used method of AMCs production is P/M. In this technique metal and ceramic powders are blended, hot/cold consolidated and then plastic deformation treated e.g. forged, extruded.

J. Wozniak is with the Faculty of Material Science and Engineering, Warsaw University of Technology, Warsaw, Woloska Str 141, 02-507 Poland, (phone/ fax: 22-234-57-19; e-mail: (j.wozniak@inmat.pw.edu.pl).

M. Kostecki is with the Faculty of Material Science and Engineering, Warsaw University of Technology, Warsaw, Woloska Str 141, 02-507 Poland.

K. Broniszewski is with the Faculty of Material Science and Engineering, Warsaw University of Technology, Warsaw, Woloska Str 141, 02-507 Poland.

W. Bochniak is with the Faculty of Non-Ferrous Metals, AGH University of Science and Technology, Cracow, A. Mickiewicza Av. 30, 30-059 Poland.

A. Olszyna is with the Faculty of Material Science and Engineering, Warsaw University of Technology, Warsaw, Woloska Str 141, 02-507 Poland.

The properties of composites depend mainly on the process parameters of plastic deformation. In the case of extrusion, applied parameters affect not only on the mechanical properties but also the surface condition of final products. Hong et al. [12] described impact of temperature and extrusion ratio on strength properties and surface quality of composites bars. Shiomi et al. [13] researched influence of temperature, extrusion ratio and speed on surface quality of aluminum alloy rods. Reiso [14] examined affect of billet preheating and extrusion cooling conditions on microstructure and surface quality of 6xxx alloy products. Obtained by the authors results demonstrate that, in order to achieve products with good properties, strict control of plastic deformation parameters is necessary.

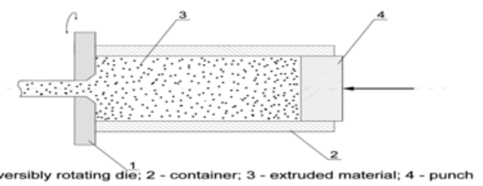

Fig. 1 Schematic representation of the extrusion process realized by the KoBo method

One of the techniques, allowing to control the process parameters in a wide range, is extrusion realized by the KoBo method. Its underlying idea is based on forcing plastic flow within shear bands. It is realized by superimposing an additional cyclically reversed action of the shaping tools upon the unidirectional operational forces of punch. The die movement is transmitted onto the treated material, by the rows made on its front face [15], [16]. Schematic representation of the extrusion process realized by the KoBo method is shown in Fig. 1. Apart from the parameters typical for conventional extrusion methods i.e. temperature, extrusion ratio and load of punch additional parameters, such as angle and frequency of reversibly rotating die, are applied. The objective of this process is a significant reduction in the deformation work, less wear of the tools, as well as the possibility of controlling the final structure of the product [17]-[20].

In the present study the influence of extrusion parameters on surface quality and properties of composites were investigated. Authors focused mainly on two factors: preheating compacts before extrusion and cooling bars immediately after extrusion. AA6061/SiC composites were prepared by P/M technology. In the last stage of the manufacturing process, powder mixtures were consolidated using direct extrusion with reversibly rotating die (KoBo method).

TABLE I
CHEMICAL COMPOSITION OF AA6061 (WT. %)

AA6061	0,272	0,011	1,04	0,111	0,634	0,001	0,179	0,006	0,006	Balance
Alloy	Cu	Mn	Mg	Fe	Si	Zn	Cr	Ni	Ti	Al

II. EXPERIMENT

In this work, the used alloy was commercial AA6061 powder with a chemical purity of 99.7 % and an average particle size of 10.6 μm delivered by Aluminium Powder Company Ltd, Alpoco. The alloy composition is given in Table I. The reinforcing phase was SiC powder with a chemical purity of 99.8 % and an average particle size of 0.42 μm supplied by Alfa Aesar Co. Powders of AA6061 and SiC were blended in isopropyl alcohol suspension for 7 h and cold pressed (CIP) to achieve consolidation of the Al matrix. The prepared compacts with a diameter of Ø = 40 mm and a length of ~ 80 mm were extruded by KoBo method. The process was conducted at 623 K. Other parameters of the extrusion process were as follows: ram speed 0.25 mm/s, frequency of the die oscillation were changed in the range of 5-8 Hz, oscillation angle of 4 deg, extrusion ratio 25 which correspond to true strain of 3.2. To reduce friction on die/compact interface, compacts were wrapped with aluminum foil. Before, extrusion compacts were preheated at extrusion temperature. Two series of composites were produced. In the first one, compacts were preheated at extrusion temperature through 0.5 h and rods were cooled by water directly behind the die after extrusion (series I). In the latter, billets were preheated at extrusion temperature for 3 hours and rods were not cooled (series II).

The AA6061/SiC composites rods with diameter of 8 mm and a length of 1 m were cut perpendicular and parallel to the extrusion axis. The specimens were mechanically polished down to a grit size of 0.2 μm. Microstructures on both cross-sections were investigated using an optical microscope Nikon Eclipse MA200. Homogeneity of the composites was also analyzed by the use of quantitative characterization.To determine the uniformity of the composites properties, microhardness route contour (distance between each indentation 1 mm) on the perpendicular cross-section, were performed applying Matsuzawa Microhardness Tester MMT-X7B. Fundamental properties of the materials such as density, hardness and Young's modulus were studied as well. The density of the composites using an Ultrapycnometer 1000 helium pycnometer (Quantachrome Instruments) was determined, their hardness applying a Vickers Hardness Tester FV-700e (Future-Tech) was measured, and the Young's Modulus utilizing an Optel ultrasonic refractometer was determined.

III. RESULTS

A. Surface condition

The surface of I and II series composites are shown in Fig. 2. For the composites preheated before extrusion through 0.5 h, cracks on rods surface, were observed, whereas for the composites preheated through 3 h surface cracks were not noticed. The reason for the cracks are local melting reactions in the matrix material during extrusion [21].

In the case of the produced composites, where 25 extrusion ratios were applied, the inner part of the rod is extruded in a conventional manner. This is due to the fact that the die orifice is centrally located in the axis of the die. The result is that the middle part of the rod is not twisted. For conventional extruding a large part of supplied mechanical energy is converted into heat. In this situation in short period of time melting temperature can be reached. As Reiso [14] reported, when the 6061 alloy is heated at a high rate from low temperature β-Mg_2Si, phase particles do not have enough time to dissolve. In this instance, melting of the material starts at lower temperature than during low rate heating.

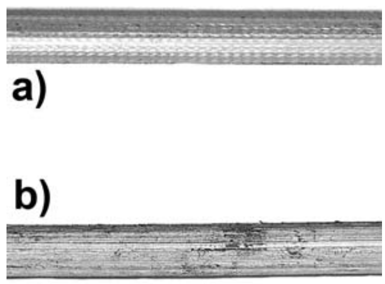

Fig. 2 Surface of 6061+10% vol. SiC composites rods, a) after 3 h preheating; b) after 0.5 h preheating

For the I series composites, preheating for half an hour is too short to achieve softening of hardened (after CIP) matrix material. Hardened alloys require much larger load of punch to initiate plastic flow of extruded material. It results in generation of high temperature. After 3 h preheating, recovered material requires lower load level to initiate plastic flow. Raise of temperature is also lower and cracking might not occurred. A different situation could occur during extrusion with greater extrusion ratio. In this situation bigger part of the rod would be subjected to torsion. According to Bochniak et al. [20], [22], the use of torsion causing of dislocation structure destabilization, in consequence, lower extrusion force are required and the lower amount of heat is generated.

B. Microstructure

Microstructures of the 6061/SiC composites in cross-section perpendicular and parallel to the axis of the rod are shown in Fig. 3. For the both series of composites, there was no difference in the distribution of silicon carbide particles. It indicates that the applied extrusion parameter changes mainly affect the properties of the matrix material. Analysis of the composites microstructure showed the presence of agglomerates of silicon carbide particles. In addition, on parallel cross section, bands of SiC particles were observed. The bands are arranged in the extrusion direction, and their amount rises with increasing of reinforcement particles volume fraction (Fig. 3b and 3d).

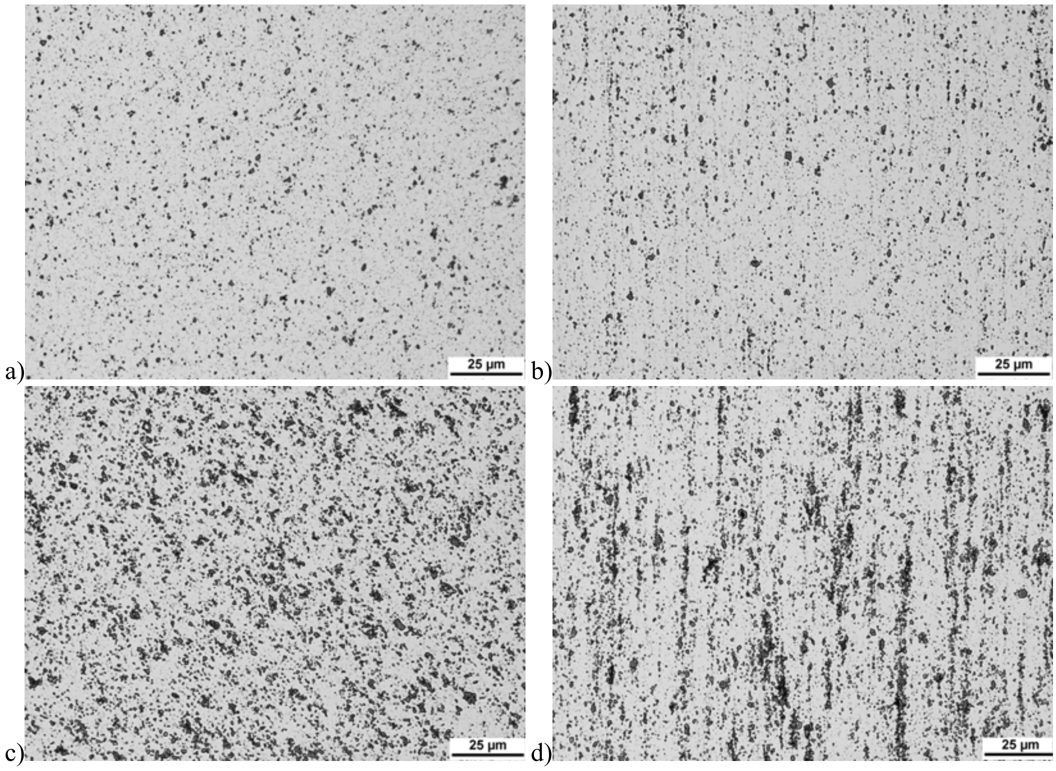

Fig. 3 Examples of composites microstructures, a) 6061+2,5% vol. SiC - perpendicular section to extrusion direction; b) 6061+2,5% vol. SiC - parallel section to extrusion direction; c) 6061+7,5% vol. SiC - perpendicular section to extrusion direction; d) 6061+7,5% vol. SiC - parallel section to extrusion direction

Quantitative analysis by the use of network of tessellated Voronoi cells was applied to determine homogeneity of SiC particles distribution. The analysis was performed in perpendicular to the rod axis cross section. Coefficient of variation (CV[A] where A was Voronoi cell surface) was used to estimate SiC homogeneity. The results of analysis are shown in Fig. 4. Coefficient of variation rises with the increase of the SiC particles volume fraction. This means that the higher amount of SiC particles causes higher tendency to agglomeration. These results confirm the observation of the composites microstructures (Fig. 3a and 3b).

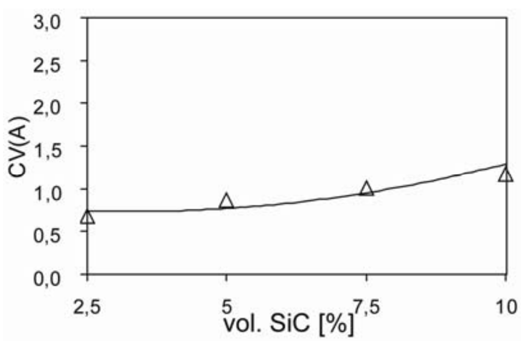

Fig. 4 Variation of CV(A) as a function of the SiC volume fraction

C. Mechanical properties

The variation of the relative density of the AA6061/SiC composites is shown in Fig. 5. For the both series of composites almost the same value of densities was observed.

Preheating of compacts and cooling of rods after the die have negligible effect on composites density. Moreover, the relative density decrease with increasing volumetric share of the SiC, was noticed. This can be explained by increasing the amount of SiC agglomerates. SiC particles within the agglomerates are surrounded by voids which increase the porosity of the composites. However, for all the composites high relative density value, greater than 97%, were observed.

Different situation is observed in the case of the composites hardness. The variation of the composites hardness of the I and II series composites is presented in Fig. 6. The hardness in both cases grows linearly with increasing volume fraction of SiC particles. However, for the first series of composites, cooled after die, the increase in hardness is much greater. The biggest difference in hardness, observed for composites containing 10% vol. SiC, is about 19%. Such a large discrepancy in the hardness values, for both composites series, is associated with application of cooling of products after the die.

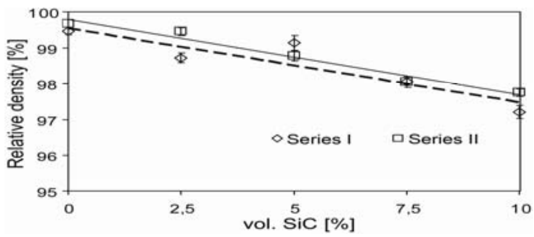

Fig. 5 Variation of the relative density as a function of the volume fraction of SiC – cooled and not cooled directly behind the die after extrusion

During a plastic deformation a large number of defects are cumulated in the material. This increases the energy stored in the material. The energy may be released in the processes responsible for the transformation of the microstructure, i.e.: recovery, recrystallization and growth of grains. Recovery processes are related to the annihilation of point defects and dislocations as well as their migration and the formation of low-energy configurations (low-angle boundaries subgrains). This reduces the amount of defects in the crystal structure and decreases strength properties of the material. In addition, processes may also occur in a dynamic manner during plastic deformation of the material. The recovery process can be stopped by application of cooling of a material directly after die. The cooling decreases the mobility of defects by which the recovery process is interrupted. Moreover, due to the difference of thermal expansion coefficient (ΔCTE) between ceramic particles and matrix during cooling around reinforcement high dislocation density is created [23]-[25]. This increases the strength of the composites.

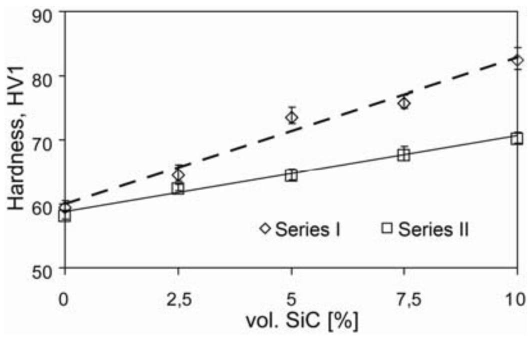

Fig. 6 Variation of the hardness as a function of the volume fraction of SiC – cooled and not cooled directly behind the die after extrusion

Additionally, to determine the uniformity of the composites properties a microhardness route contour on the perpendicular cross-section, was made. Examples of results of measurements are presented in Fig. 7. As in the case of hardness, lower microhardness values were noticed for the uncooled composites. Moreover, the values of microhardness across the cross-section were the same. This indicates that the recovery processes proceeded uniformly over the cross-section of the bar. For the composites cooled after die higher microhardness values were observed on the edge of rod than in their central part. It is associated with different cooling rate between the edge and center. Cooling speed at the edge of the rod is high so recovery processes are quickly inhibited. In the central part of bar, speed of heat dissipation depends on the thermal conductivity of the material. As a result, the recover processes taking place longer and more energy stored in the material is release.

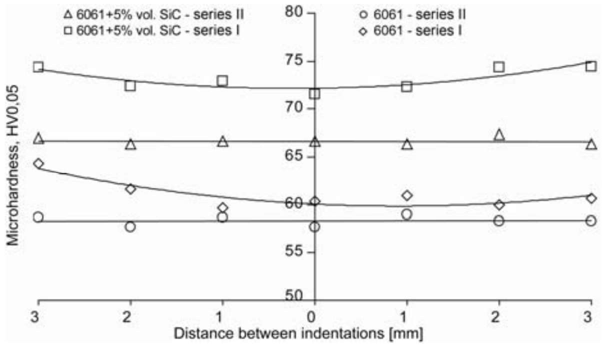

Fig. 7 Examples of microhardness route contour on perpendicular section to extrusion direction

Fig. 8 shows a variation of Young's modulus as a function of the volume fraction of SiC. For both series of composites values of Young's modulus were similar and were increasing with the volume share of SiC. Slightly higher values of Young's modulus were observed for the I series composites (cooled).

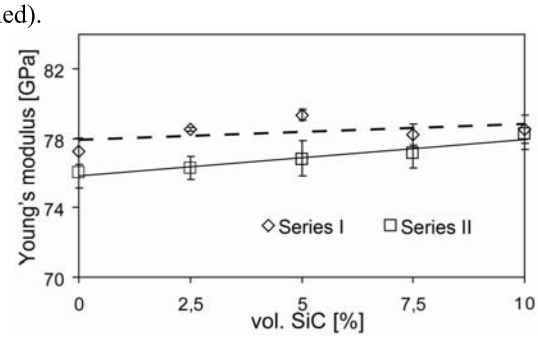

Fig. 8 Variation of the Young's modulus as a function of the volume fraction of SiC – cooled and not cooled directly behind the die after extrusion

However, for this series of composites smaller slope of a Young's modulus curve, in comparison to the series II, was observed. This proves that for the I series of composites, greater impact on the Young's modulus value has the microstructure of the matrix material than the amount of SiC. This may be due to the fact that the applied cooling after extrusion inhibits the recovery process. In addition, as mentioned earlier in the case of short preheating time the Mg_2Si particles, formed during aluminum powders atomization, might have not dissolved. Due to the specificity of atomization process (heating above the melting temperature, atomization and rapid cooling) Mg_2Si particles can be uniformly distributed in material, this positively influences the properties of the material. Larger slope of a Young's modulus curve for the I series of composite indicate the greater influence of SiC volume fraction on Young's modulus values. The produced rods were not cooled, which might have result in recovery of the matrix material. In addition, longer preheating before extrusion could lead to the dissolution of Mg_2Si particles. As a result of slow cooling after extrusion, larger and more heterogeneous distributed (both within the Al grains, and at their borders) Mg_2Si particles were formed, this had less effect to matrix strengthening.

IV. Conclusion

Two series of composites were successfully produced using KoBo method. Change of manufacturing parameters allowed controlling the surface quality and mechanical properties. Better surface quality, free from cracks and discontinuities and more uniform mechanical properties on cross section were obtained for composites of series II (3 h preheated and uncooled). Whereas the higher mechanical properties were noticed for series I composites. This is caused by cooling the rods directly after die. This resulted in stopping the dynamic recovery processes in the composites microstructure. Regardless of the applied production parameters high density composites were obtained. The relative density decreased slightly with increasing volumetric share of the SiC. The microstructure of the composites is characterized by uniform distribution of SiC particles with visible agglomerates for higher volume fraction of SiC. Moreover, bands of SiC in the parallel cross section to the extrusion direction were visible.

Despite the fact that worse properties for the II series of composites were obtained, this material seems to be more attractive because of the surface quality and more uniform properties. The applied material of matrix allows improving mechanical properties through the use of the aging process. It allows for production of composites characterized by high and homogeneous properties with simultaneous good surface quality of the manufactured rods.

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