

**INFLUENCE OF EXTRUSION PARAMETERS ON SiC DISTRIBUTION
AND PROPERTIES OF AA6061/SiC COMPOSITES PRODUCED BY KOBO METHOD**

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Abstract

The influence of extrusion parameters on reinforcements distribution and properties of AA6061+x% vol. SiC_p (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. The composites were consolidated via powder metallurgy processing (without the sintering) and extruded by KoBo method. The microstructure was examined on each steps of production. High values of density for all produced composites were achieved. Additionally, hardness and Young's modulus were investigated. The best reinforcement distribution and mechanical properties were obtained for composites extruded with the highest extrusion ratio.

Key words: aluminum alloy, extrusion, aged hardening, metal matrix composites, microstructure

1. INTRODUCTION

Despite many years of experiences the aluminum matrix composites (AMCs) still make a lot of difficulties at the manufacturing stage. High physical properties are obtained by strict control of the technological parameters. It is essential to provide not only the appropriate matrix alloy microstructure, but also a homogeneous distribution of the reinforcements and the proper matrix /reinforcement interface.

One of the main difficulties in the preparation of AMCs is to achieve good interfacial bond between the matrix and the reinforcement [1-4]. At a typical sintering temperature range, wettability of reinforcement with molten aluminum matrix is generally poor. Another problem is possibility of occurrence chemical interactions (formation of deleterious products such as: aluminum carbide) on matrix/reinforcement interface. In order to improve the wettability and reduce the interface degradation several methods including the modification of the matrix composition, coating of the reinforcement and control of process parameters have been widely used [5-9].

Many technological difficulties provide also achieve homogeneous distribution of reinforcement in the matrix alloy. In the case of casting methods particle segregation can occur on three stages of the manufacturing process: during the mixing of particles in the melt alloy, after mixing but before solidification, and during the solidification of the matrix. In case of composites made by powder metallurgy (PM) route, clustering can occur either because of static charge present on reinforcement particle surfaces [10] or due to particle size mismatch [11]. In the first case, reinforcements segregation can be reduced by the use of polar solvents, which neutralize the charges at the particles

surface [12]. In the second case the agglomeration can be controlled by modifying the relative particles size ratio (RPS), which can be define as the ratio between average size of matrix and reinforcement particles. Based on the matrix and reinforcement particles size the model, which allows selecting appropriate components particles size, was developed [13]. The model describes the relationship (1):

$$d_p \geq \frac{d_m}{\left[\left(\frac{\pi}{6f} \right)^{\frac{1}{8}} - 1 \right]} \quad (1)$$

where: d_p – reinforcement particles size,

d_m – matrix powder size required to attain homogeneous reinforcement distribution ,

f – reinforcements volume fraction.

The equation shows that to obtain a uniform distribution of reinforcement particles the matrix and reinforcement particles size should be similar. As follows from literature [14, 15] higher strength properties of composites reinforced with fine particles are received. Consequently to obtain a homogeneous reinforcements distribution the use of fine matrix particles are required. However, it is very difficult to fabricate such small metal powder particles (especially from aluminum) due to the formation of oxide layer, agglomeration, etc. [16]. Smaller size of d_p can be applied by the use of secondary deformation methods such as extrusion or rolling. The formula for required matrix and reinforcement particle size, depending on the extrusion or rolling ratio is described by the equation (2) [17]:

$$d_p \geq \frac{d_m}{\left[\left(\frac{\pi}{6f} \right)^{\frac{1}{8}} \right] \frac{\sqrt{R}}{1-R'}} \quad (2)$$

where: R – extrusion ratio,

R' – rolling ratio.

However, even in this case, when fine reinforcing particles were applied, extremely high values of extrusion or rolling ratio are required.

Method which allow for application high value of extrusion ratio is direct extrusion with cyclic changes of deformation path (KoBo method). The idea is based on forcing plastic flow within shear bands. It is realized by superimposing an additional cyclically reversed action of the die on the unidirectional operational forces of punch. The die movement is transmitted into the treated material, by the rows made on front face of die [18, 19]. 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 [20]. Furthermore application of movable die can improve the homogeneity of the composites by crushing the agglomerates [21-23]

In this study, the influence of extrusion parameters on reinforcements distribution and properties of AA6061/SiC_p composites was investigated.

2. EXPERIMENTAL PROCEDURE

Composite powders of AA6061 matrix (alloy composition shown in Tab. 1).) reinforced with 2,5; 5; 7,5; 10 vol. % of SiC_p were fabricated via powder metallurgy technique. Additionally reference (unreinforced) sample was produced. The AA6061 powders (average grain size 10.6 μm) and β-SiC_p (average grain size 0.42 μm) were mechanically blended and then cold isostatic pressed (CIP) to achieve compacts with a diameter of 40 mm and a length of 50 mm. Prepared “green compacts” were consolidated by direct extrusion with reversibly rotating die (KoBo method). The parameters of the extrusion process are shown in Tab. 2. More detailed information on the KoBo method are given elsewhere [24, 25].

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

Table 1. Chemical composition of AA6061 alloy (wt. %)

Two sets of extrusion parameters (named as preliminary and optimized) were applied to investigate they influence on materials properties. Moreover, for optimized parameters, two series of composites (with different extrusion ratio, λ) were produced to examine the influence of λ value on SiC_p distribution. Additionally for composites extruded with $\lambda=100$ the die hole was moved from axis to edge of die. The idea of different die hole position was applied to eliminate possible non-uniformity of the SiC_p distribution in the perpendicular cross section of the rods. When the die hole is placed in the die axis, the central part of extruded material could not be twisted, so the material microstructure can change on the rod diameter. This problem can be eliminated by application the die hole located on the die edge.

The AA6061/SiC composites rods with diameter of 8 and 4 mm and a length of 1 m were cut perpendicular/parallel to the extrusion axis. The composites microstructure was analyzed after the compaction of powder mixtures, and the extrusion by KoBo method.

	Rod diameter [mm]	Temp. [°C]	Oscillation angle [deg]	Frequency of the die oscillation [Hz]	Ram speed [mm/s]	Extrusion ratio
Preliminary	8	350	8	5	0,5	25
Optimized	8	350	4	max. 8	0,5	25
	4	350	4	max. 8	0,5	100

Table 2. The parameters of the extrusion process

Microstructure observations using an optical microscope (Nikon Eclipse MA200) were executed. The size of SiC agglomerates, before and after the extrusion process, was analysed applying image analyzer equipped with NIS-Elements software. Furthermore, the reinforcement distributions on perpendicular and parallel cross section were measured. Fundamental properties of the materials such as hardness and Young's modulus were studied as well. The hardness applying a Vickers Hardness

Tester FV-700e (Future-Tech) was measured, and the Young's Modulus utilizing an Optel ultrasonic refractometer was determined.

3. RESULTS AND DISCUSSION

Figure 1 shows the surface condition of AA6061-10 vol. % SiC_p composites rods extruded at preliminary and optimized conditions. It was clearly seen that for composites extruded at preliminary parameters the surface condition was poor (Figure 1a). The fir-tree cracks were observed on the rods surfaces. Moreover, the cracking was more intensive for composites reinforced with higher volume fraction of SiC_p. The effect is widespread disadvantage of extruded materials and occurs both in the unreinforced and composites materials [26, 27]. Cracks formation is associated with high extrusion temperature, high friction, or high extrusion speed [28] and causes a reduction of mechanical properties and waste of material. The cracking can be eliminating by decrease of temperature and/or extrusion speed [29]. In case of the KoBo method determination of the speed of materials plastic flow is complicated because its value affects not only on ram speed but also on the oscillation angle and frequency of the die rotation. Increase of those parameters increase of plastic flow. In order to reduce the flow speed the decrease of rotation angel was applied. Moreover, the frequency of die rotation was not constant but was being changed during extrusion in range 8-5 Hz (optimized parameters). As a result rods with good surface quality were achieved (Figure 1b).

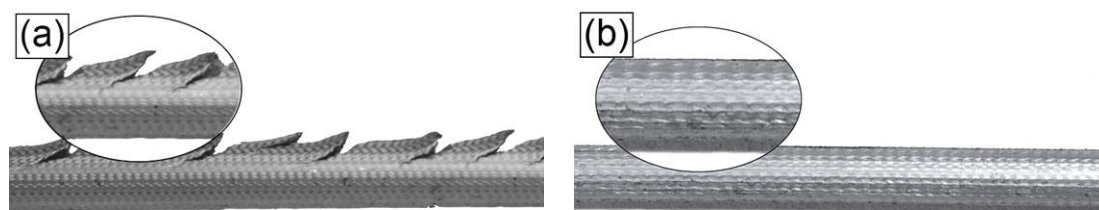


Figure 1. Surface of the AA6061 -10 vol. % SiC composite rods ($\lambda=25$), a) preliminary parameters, b) optimized parameters

For composites extruded in optimized parameters microstructural analyses were determined. Figure 2 presents the microstructure of green compact and composites extruded with different extrusion rates. Compact microstructure (Figure 2a) shows individual matrix alloy particles and SiC_p agglomerates. Application of plastic deformation significantly decreases the agglomerate size (Figure 2b). Moreover, comparing microstructures of composites extruded with $\lambda=25$ and 100 more homogenous distribution of SiC_p was noticed for composites obtained with higher extrusion ratio. The microstructural observations confirmed the quantitative analysis of the agglomerates size (Figure 3).

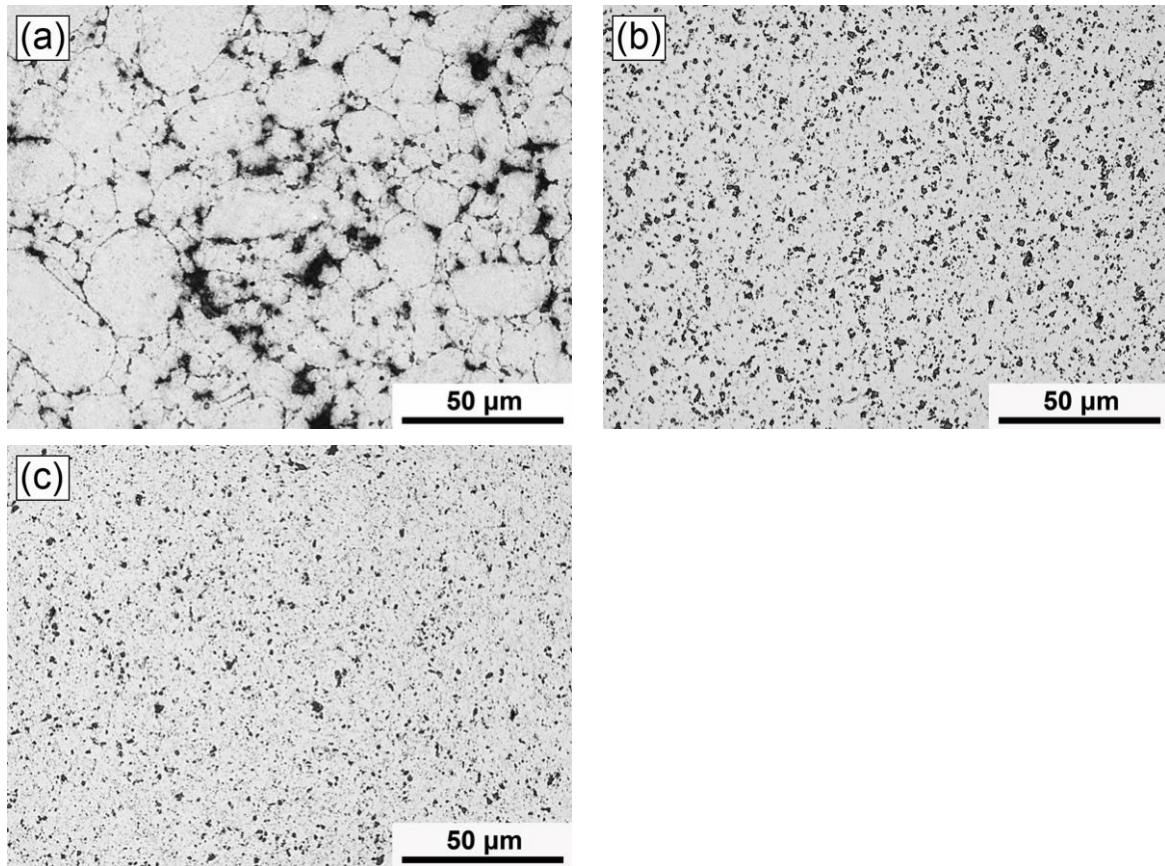


Figure 2. Microstructure of AA6061-5 vol. % SiC_p composites a) green compacts, b) composites extruded with $\lambda=25$ - perpendicular cross section to the axis of extrusion, c) composites extruded with $\lambda=100$ - perpendicular cross section to the axis of extrusion

The average equivalent diameter of reinforcements agglomerates was three times lower for composites extruded with $\lambda=25$, than for the compact. Application of higher extrusion ratio additionally decreases the agglomerates size by 20 %. Moreover, for all series, the agglomerates size increased with increasing of SiC_p volume fraction.

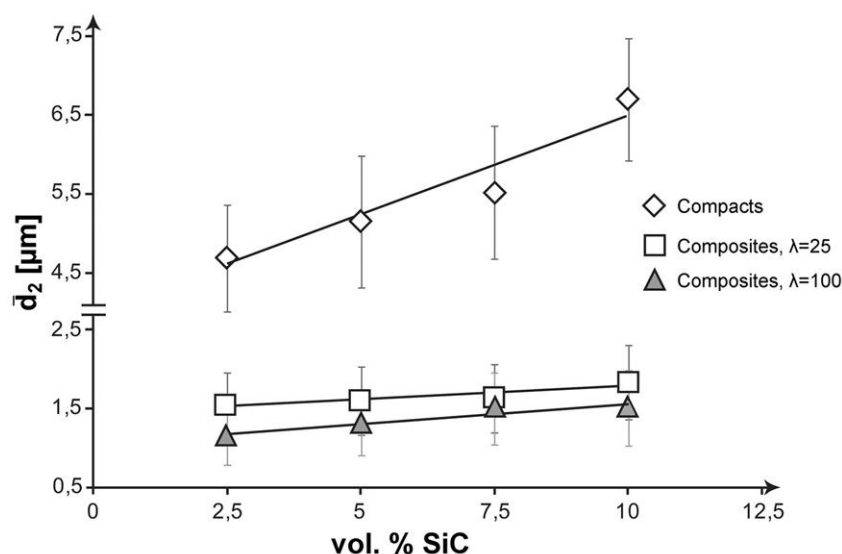


Figure 3. Influence of reinforcements volume fraction on average equivalent diameter of SiC_p agglomerates

Besides size also shape of agglomerates changed after extrusion. The stereological parameters are summarized in Table 3. The circularity η and elongation μ values are lower for composites, compared to compacts. This may indicate that the agglomerates have a more irregular shape. There are no significant differences in the shape parameters between composites extruded with $\lambda=25$ and 100.

λ	vol. % SiC	η	CV(η)	μ	CV(μ)
Green compacts					
-	2,5	0,7	0,3	1,84	0,31
	5	0,68	0,31	1,94	0,31
	7,5	0,67	0,27	2,04	0,35
	10	0,57	0,39	1,97	0,31
Composites - perpendicular cross section					
25	2,5	0,55	0,33	0,55	0,29
	5	0,49	0,32	1,83	0,26
	7,5	0,47	0,41	1,77	0,26
	10	0,48	0,4	1,77	0,46
Composites - parallel cross section					
25	2,5	0,5	0,35	2,02	0,36
	5	0,39	0,37	2,05	0,34
	7,5	0,39	0,52	1,89	0,34
	10	0,4	0,5	1,96	0,34

Composites - perpendicular cross section					
100	2,5	0,54	0,37	1,8	0,3
	5	0,52	0,34	1,79	0,36
	7,5	0,5	0,33	1,78	0,26
	10	0,55	0,34	1,75	0,26
Composites - parallel cross section					
100	2,5	0,59	0,33	1,90	0,33
	5	0,49	0,32	1,95	0,32
	7,5	0,47	0,37	1,86	0,34
	10	0,47	0,33	1,88	0,27

Table 3. Stereological parameters of SiC_p agglomerates

Due to the fact that materials after extrusion indicate directional microstructure (parallel to the extrusion direction) the microstructures was also examined in parallel to the rods axis direction (Figure 4). In both series of the composites, SiC_p and their agglomerates are distributed in bands parallel to the extrusion direction. The average equivalent diameter of SiC_p agglomerates were approximately 7 % higher compared to perpendicular cross section (Figure 5).

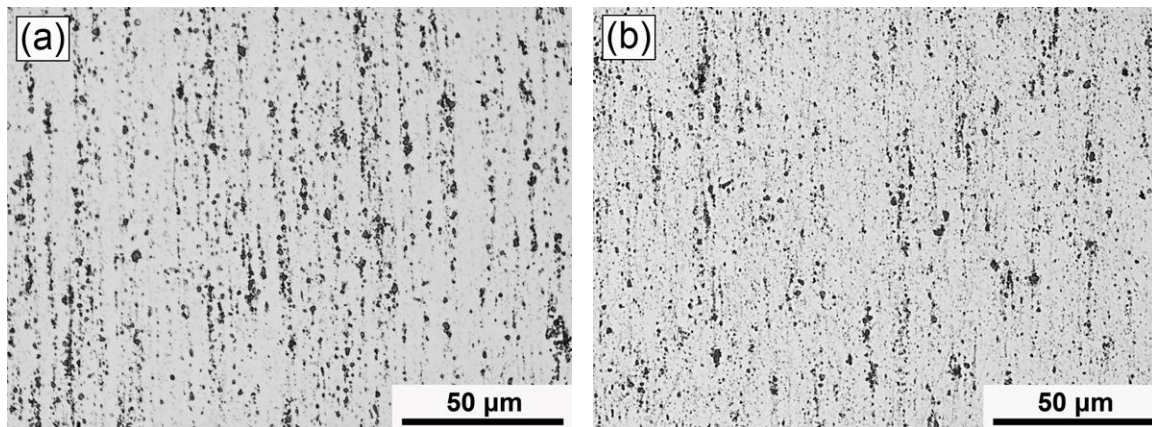


Figure 4. Microstructure of the AA6061 - 5 vol. % SiC_p composites - parallel cross section a) $\lambda=25$ b) $\lambda=100$

Similarly, as in perpendicular cross section, the agglomerates size decrease with increasing extrusion ratio. The μ coefficient values (Table 3) are higher compared to the perpendicular cross section, which mean that the agglomerates are elongated.

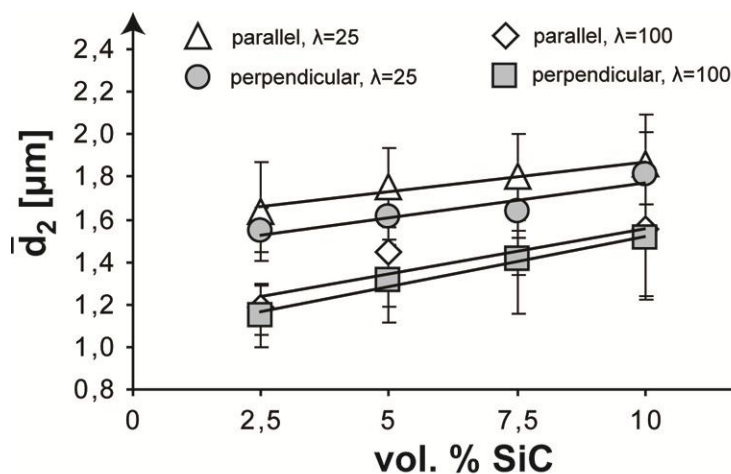


Figure 5. Comparison of the average equivalent diameter of the SiC_p agglomerates in the perpendicular and parallel cross section

Another factor, next to SiC_p agglomerates size, which has significant impact on strength properties is homogenous distribution of reinforcement in the matrix. The SiC_p distribution was analyzed by using skeleton by influence zone (SKIZ). In this method, the influence zones of microstructure elements are determined. Base on coefficient of variation of zones area (CV(A)) it is possible to compare of homogeneous distribution of tested materials. Additionally, to determine the SiC_p distribution along the rods diameter, analysis was performed near axis and edge of the rods. The analysis results are shown in Figure 6. For composites extruded with $\lambda=25$ the difference between edge and axis were seen. Higher values of CV(A) were observed in axis of the rods which mean that SiC_p distribution was worse in axis area. Application of higher extrusion ratio and changing the die hole position causing not only decreasing of CV(A) but also more uniform distribution of reinforcements along the rods diameter. Moreover, for both series of composites, increase of CV(A) with increasing of SiC_p volume fraction was noticed. The results indicated that higher extrusion ratio improve the reinforcement distribution. The obtained results confirm literature data concerning the nature of the material flow during extrusion by the KoBo method [30]. When the die hole is arranged in the axis of forming tool, the central part of the material is not subjected to torsion. This may causes by poor reinforcement distribution along the rod diameter. Changing the hole position from axis to edge of the die makes that entire material volume is subjected to torsion and better reinforcement distribution is obtained.

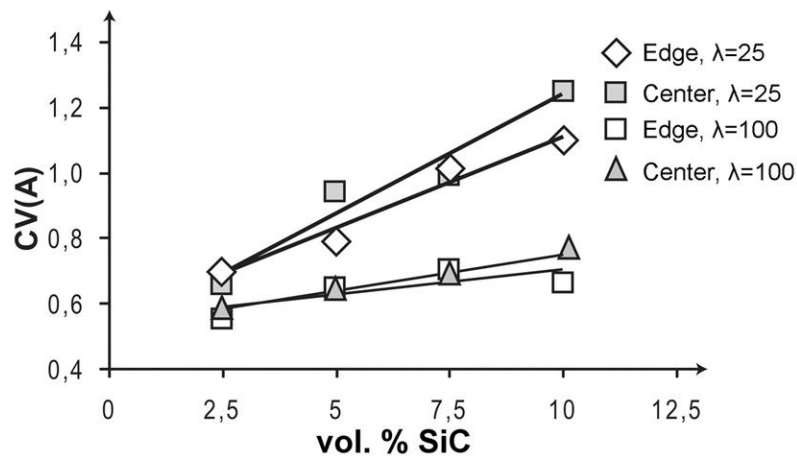


Figure 6. Comparison of the CV(A) values for different extrusion ratio vs. SiC_p volume fraction

Besides the microstructure also hardness of composites were analyzed. The measurement results are summarized in Figure 7. For both series of composites, the hardness increase with increasing of SiC_p volume fraction. Comparing the results obtained for composites extruded with $\lambda=25$ and $\lambda=100$, no significant differences were observed. Slightly lower hardness values for unreinforced, 2.5 and 5 vol. % SiC_p composites (extruded with $\lambda=100$) were noticed compared to composites extruded with $\lambda=25$. However, almost the same level of hardness is reached for composites reinforced with 7.5 and 10 vol. % SiC_p.

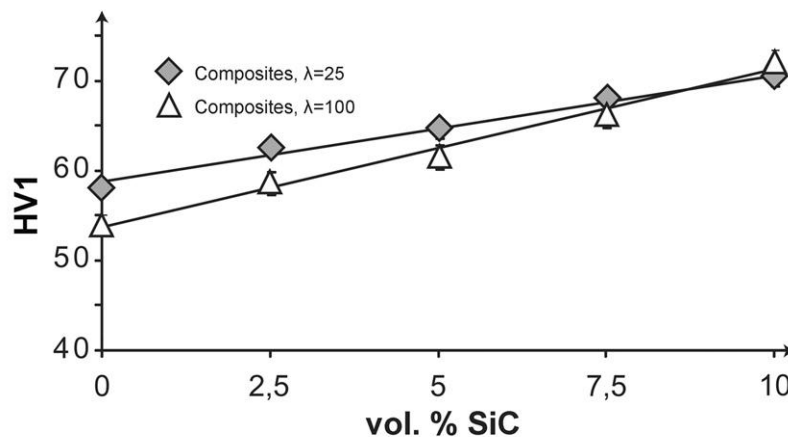


Figure 7. Influence of SiC_p volume fraction on Vickers hardness

The highest hardness values were obtained for AA6061-10 vol. % SiC_p composites (70 and 72 HV respectively for $\lambda=25$ and $\lambda=100$ composites). A similar relation was observed in the case of Young's modulus (Figure 8).

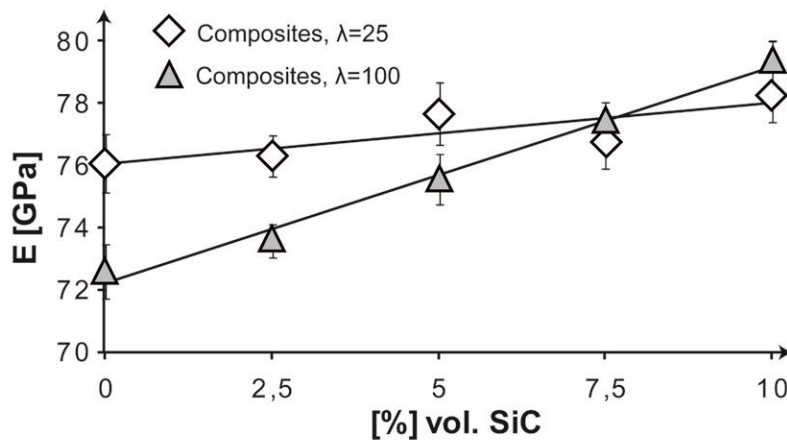


Figure 8. Influence of SiC_p volume fraction on Young's modulus

Similarly as hardness, also Young's modulus values increase with increasing of SiC_p volume fraction. However, big differences (almost 6 % for unreinforced alloy) were observed between the composites extruded with $\lambda=25$ and $\lambda=100$. The reasons for this effect can be found in the texture of materials. As follows from literature, E value can change from 77 GPa $\langle 111 \rangle$ to 64 GPa $\langle 100 \rangle$ [31]. Due to the fact that, in the case of extrusion with $\lambda=100$ the die hole was placed on the edge of forming tool, the entire volume of the material was subjected to torsion. This could lead to changes in the crystallographic texture of materials (lower volume of $\langle 111 \rangle$ direction) and consequently decrease the Young's modulus for composites extruded with $\lambda=100$.

CONCLUSIONS

The conclusions drawn on the basis of this study can be summarized as follows:

- The higher extrusion ratio and placement the die hole on die edge improves homogeneous SiC_p distribution in edge and centre of the rods. Moreover, differences in reinforcements distribution, between edge and center, were lower for composites extruded with $\lambda=100$. Additionally, the reinforcements agglomerates size, in perpendicular and parallel cross section decrease with increase extrusion ratio value.
- The SiC_p distributions along the rods diameter were better for composites extruded with $\lambda=100$. It is extremely important because homogeneous reinforcements distribution along rod diameter could provide stable mechanical properties of composites on cross section
- The hardness and the Young's modulus increases with increasing SiC_p volume fraction. However, those parameters were slightly higher for composites extruded with $\lambda=25$

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