Polskie Towarzystwo Materiałów Kompozytowych
Polish Society of Composite Materials
Kompozyty 11: 4 (2011) 331-335
KOMPOZYTY
COMPOSITES

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Otrzymano (Received) 20.10.2011

INFLUENCE OF SIZE OF SiC PARTICLES ON SELECTED PROPERTIES OF ALUMINIUM-BASED COMPOSITES OBTAINED BY EXTRUSION OF P/M COMPACTS

The results of investigations are presented, which are aimed at determining the effect of the size of SiC particles on selected properties of aluminium-based composites. As initial materials, atomized aluminium powder and silicon carbide powders of different particle size were applied. The scope of the research included the preparation of a matrix and composite material samples, as well as the determination of their selected properties. Powder metallurgy and plastic working technologies were applied to obtain the composite materials. The volume fraction of the reinforcing phase particles in the matrix was set constant at the level of 10%. All the samples were formed using the same parameters. The manufacturing process included the mixing of the components, cold compaction of the aluminium powder and mixtures as well as hot forward extrusion of the P/M compacts. Based on extrusion force measurements, it was shown that introducing smaller silicon carbide particles into the matrix resulted in the necessity to apply a higher load. For extruded materials, their relative density, hardness and abrasion resistance were determined. The results obtained from compression tests performed at room temperature and at 200°C allowed us to construct flow curves for the investigated materials. Microstructure examination was also performed. It was shown that application of the proposed forming technology results in obtaining products showing a relative density close to that of a solid material. The introduction of silicon carbide particles into the matrix caused an increase of true stresses at which deformation proceeded, regardless of the test temperature. In the case of compression of the samples performed at 200°C, the increase of stresses was observed as a result of a reduction of the reinforcing phase particles size in the matrix. In case of compression tests performed at room temperature, no unequivocal influence of particle size on the character of the obtained curves was observed. The realized microstructure examination revealed uniform distribution of SiC particles in the aluminium matrix. The particles were closely adherent to the matrix, and the metallographic specimens did not reveal any voids caused by particles falling out during specimen preparation. The comparative abrasion test showed that the introduction of 10% SiC particles into the matrix and increasing their size, with their volume fraction held constant, leads to lower abrasive wear of the investigated materials. Based on the obtained results, it was concluded that in the case of the given components and their forming technology, the introduction of particles into the matrix has a favourable effect, while their size influences individual properties differently. Therefore, the final selection of the proper size of silicon carbide particles applied as reinforcement in the aluminium matrix, should be based on the knowledge of the characteristic and working conditions of the composite product, as well as the expectations to be met.

Keywords: **powder metallurgy, forming, aluminium powder, SiC particles, cold compaction, hot extrusion, physical and mechanical properties, microstructure**

WPŁYW WIELKOŚCI CZĄSTEK SiC NA WYBRANE WŁAŚCIWOŚCI KOMPOZYTÓW NA OSNOWIE ALUMINIUM FORMOWANYCH PRZEZ WYCISKANIE WYPRASEK

W pracy przedstawiono wyniki badań, których celem było określenie wpływu wielkości cząstek węglika krzemu na wybrane właściwości kompozytów na osnowie aluminium. W roli materiałów wyjściowych zastosowano rozpylany proszek aluminium oraz proszki węglika krzemu o różnej wielkości cząstek, odpowiednio SiC_{220}, SiC_{400}, SiC_{800}. Zakres pracy objął wykonanie próbek tworzyw kompozytowych oraz określenie ich wybranych właściwości. Do formowania kompozytów wykorzystano technologie metalurgii proszków i przeróbki plastycznej. Przyjęto stały udział cząstek fazy umacniającej w osnowie, który wynosił 10% objętościowych, wszystkie próbki wykonano, stosując te same parametry ich formowania. Proces wytwarzania kompozytów objął mieszanie składników, prasowanie na zimno proszku aluminium i mieszanin oraz wyciskanie współbieżne na gorąco wyprasek. Na podstawie pomiarów siły koniecznej do wyciskania wykazano, że wprowadzenie do osnowy mniejszych cząstek węglika krzemu skutkowało koniecznością zastosowania większych sił. Dla wyciskanych tworzyw wyznaczono ich gęstość względną, twardość oraz odporność na zużycie ścierne. Na podstawie wyników z prób ściskania w temperaturze pokojowej oraz przy temperaturze 200°C opracowano krzywe umocnienia tworzyw, przeprowadzono również obserwacje ich mikrostruktury. Wyniki badań pozwalają na stwierdzenie, iż zastosowanie proponowanej technologii formowania kompozytów prowadzi do uzyskania wyrobów o gęstościach względnych zbliżonych do litego materiału. Wprowadzenie do osnowy cząstek węglika krzemu powodowało zwiększenie naprężeń rzeczywistych, przy którym przebiegało odkształcenie, niezależnie od temperatury badań. W wyniku ściskania próbek w temperaturze 200°C przyrost wartości naprężeń obserwowano w wyniku zmniejszenia wielkości cząstek fazy umacniającej w osnowie kompozytu, w przypadku prób prowadzonych w temperaturze pokojowej nie stwierdzono jednoznacznego wpływu wielkości cząstek na przebieg otrzymanych krzywych. Przeprowadzone obserwacje mikrostruktury ujawniły równomierne rozmieszczenie cząstek węglika krzemu

w aluminiowej osnowie. Cząstki ściśle przylegały do osnowy, na zgładach nie zaobserwowano pustek powstałych w wyniku ich wypadania podczas przygotowywania zgładów metalograficznych. Porównawczy test odporności na zużycie ścierne wykazał, iż wprowadzenie do osnowy 10% cząstek węglika krzemu oraz zwiększenie ich wielkości przy niezmiennym udziale objętościowym prowadzi do obniżenia zużycia ściernego badanych tworzyw. W świetle przeprowadzonych badań można stwierdzić, że dla przyjętych do badań komponentów i zastosowanej technologii ich formowania wprowadzenie cząstek do osnowy powoduje korzystne rezultaty, natomiast ich wielkość ma różny wpływ na poszczególne właściwości. Dlatego ostateczny dobór korzystnej wielkości stosowanych do umocnienia aluminiowej osnowy cząstek węglika krzemu powinien być oparty na znajomości charakterystyki i warunków pracy wyrobu kompozytowego oraz stawianych przed nim oczekiwań.

Słowa kluczowe: **metalurgia proszków, przeróbka plastyczna, proszek aluminium, cząstki węglika krzemu, prasowanie, wyciskanie na gorąco, fizyczne i mechaniczne właściwości, mikrostruktura**

INTRODUCTION

Metallic matrix composites reinforced with particles are a group of construction materials showing such advantages as superior strength to weight ratio, abrasion resistance, corrosion resistance, stability of properties at elevated temperatures as well as good thermal and electrical conductivity [1]. The presence of particles in the matrix also causes the recrystallization temperature and grain growth to be shifted to a higher range. The size of the reinforcing phase particles influences the above mentioned composite properties significantly. In the case of composites with reinforcing particles size exceeding 1.0 μm, their presence in the matrix results in mechanical blocking of free slipping between the grains [2]. The strengthening mechanism depends on the characteristics of the components being combined. Two basic configurations are possible [3]: a ductile matrix with hard-deformable particles and brittle matrix with ductile particles. In the first case, typical matrix materials are light metals such as aluminium, titanium, magnesium and their alloys. As a reinforcing phase, the following materials can be used: aluminium oxide (Al_2O_3), zirconium oxide (ZrO_2), titanium oxide (TiO_2), carbides (SiC, TiC, B_4C) as well as graphite and mica [4, 5]. At present, numerous R&D works and industrial applications are focusing their attention on composites based on aluminium or its alloys. Special attention should be paid to composites reinforced with silicon carbide (Al/SiC). The relatively low density of aluminium and its low price as compared to other light metals (Ti, Mg) are the preference factors choosing it to be applied as a matrix material. The introduction of reinforcement in the form of SiC into the matrix of aluminium or its alloys, mainly aims at increasing the strength properties and abrasion resistance of the matrix [6]. An additional advantage of Al/SiC composites is the possibility of controlling the properties, e.g. thermal conductivity, through the selection of volume fraction and distribution of the reinforcing phase [7]. In the case of the discussed combination of components, the size and shape of the particles as well as the composite forming technology also significantly influence the composite properties [8]. The materials under consideration are produced mostly with the application of casting and powder metallurgy techniques. In the case of forming composites from powders, it is advantageous that the introduction of a reinforcing phase into the matrix can be easily realized by mixing components, and the forming temperatures are low. Al/SiC type composites find their applications mainly in the transport industry, e.g. for brake drums or brake disks used in cars and railway carriages [6, 7].

EXPERIMENT

Objective and methodology of research

The objective of the investigations was to determine the influence of the size of reinforcing phase particles on selected properties of aluminium-based composites. Powder metallurgy and plastic working methods were applied to composite formation. The initial materials were aluminium powder and silicon carbide particles of different size. The volume fraction of the reinforcing phase particles in the matrix was set constant, and all the samples were formed using the same parameters. The manufacturing process included the mixing of the components, cold compaction of the aluminium powder and mixtures as well as hot forward extrusion of the P/M compacts.

Material under investigation and sample preparation

As initial materials, atomized aluminium powder and silicon carbide powders of different particle size were applied. SiC_{220}, SiC_{400} and SiC_{800} sizes were used and the corresponding parameters, according to FEPA (Federation of European Producers of Abrasives) standards [1], are given in Table 1 [9, 10]. The volume fraction of the silicon carbide particles in the composite matrix was set constant at the level of 10%.

TABLE 1. **Powder particle size specifications according to FEPA standards [1, 2]**

TABELA 1. **Specyfikacja wielkości cząstek proszku w standardzie FEPA [1, 2]**

Powder	Grid size (FEPA)	3% max. larger than μm	50% min. in size range μm	95% min. larger than μm
SiC_{220}	F220	75	50.0÷56.0	45
SiC_{400}	F400	32	16.3÷18.3	8
SiC_{800}	F800	14	5.5÷7.5	2

The aluminium powder and silicon carbide powders were dry-mixed using a two-cone mixer, at room temperature, with a 0.9 s^{-1} speed of rotation, during 60 minutes. The mixtures and matrix powder were subjected to compaction at room temperature. A unit pressure of 85 MPa was applied to all the samples. P/M compacts of a cylindrical shape were obtained and their relative densities were determined (Table 2). A slight decrease of relative density was observed as a result of increasing the size of the silicon carbide particles. The aluminium P/M compacts and compacted mixtures were then subjected to hot forward extrusion to obtain bars. The extrusion process was realized at 500°C by applying an extrusion ratio of 4.1 and tool speed of 0.15 s^{-1}. The extrusion forces were registered as a function of punch displacement. The example results are presented in Fig. 1. In the first extrusion stage, when upsetting and consolidation of a material takes place (Fig. 1 - punch displacement up to approx. 12 mm), the presence of silicon carbide particles in the matrix did not cause an increase of the extrusion force in relation to non-reinforced aluminium, regardless of the particle size. In subsequent extrusion stages, when the material fills up the die (Fig. 1 - punch displacement approx. 12÷20 mm) and during laminar material flow through the die under stable conditions, an increase of force was observed as a result of the introduction of a reinforcing phase into the matrix and resulting from a decreasing size of silicon carbide particles.

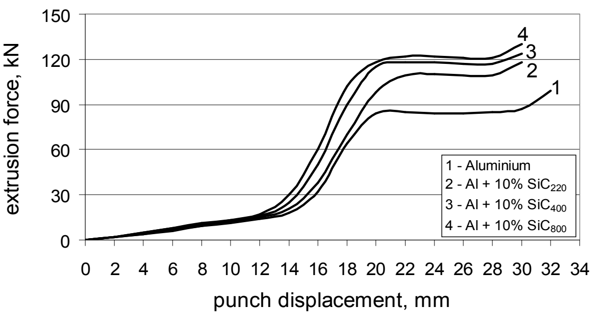


Fig. 1. Extrusion forces during hot extrusion as function of punch displacement

Rys. 1. Wartości sił występujących podczas wyciskania na gorąco w zależności od drogi stempla

For the aluminium and composite samples after extrusion, their relative densities and hardness were determined and their abrasion resistance levels were compared. Based on the results of compression tests, flow curves were constructed for the investigated materials. Microstructure examination was also performed.

Results of investigations

Relative density. The density testing of the non-reinforced matrix and composites was realized using the Archimedes method. The results are presented in Table 2. Forming the composites under the assumed conditions allowed us to obtain materials showing a relative density close to that of solid materials. The highest consolidation was achieved for the aluminium samples, while the presence of SiC particles resulted in a slight decrease of relative density. A decrease of composite density was observed with a decreasing size of silicon carbide particles. The lowest density (97%) was observed in the case of the composite reinforced with 10% SiC_{800}.

TABLE 2. **Influence of chemical composition and size of reinforcing phase particles on relative density of P/M compacts and hot-extruded materials produced from aluminium and Al-based composites reinforced with 10% silicon carbide particles**

TABELA 2. **Wpływ składu chemicznego i wielkości cząstek fazy umacniającej na gęstość względną wyprasek i wyciskanych na gorąco tworzyw z aluminium i kompozytów na jego osnowie umocnionych przez 10% cząstek węglika krzemu**

	Al	Al+SiC_{220}	Al+SiC_{400}	Al+SiC_{800}
Compacts	74.45±0.86	74.22±0.40	75.09±0.23	76.19±0.0
Extruded	99.35±0.17	99.03±0.86	98.27±0.71	97.12±0.76

Hardness measurements. Hardness measurements were performed using the Brinell method. The results are presented in Table 3. The introduction of silicon carbide particles into the aluminium matrix resulted in only a slight increase of hardness of the investigated materials. No significant effect of the size of the reinforcing phase particles on the obtained results was observed. The highest average hardness (38.1 ± 0.48 HB) was obtained for the composite reinforced with 10% SiC_{800}.

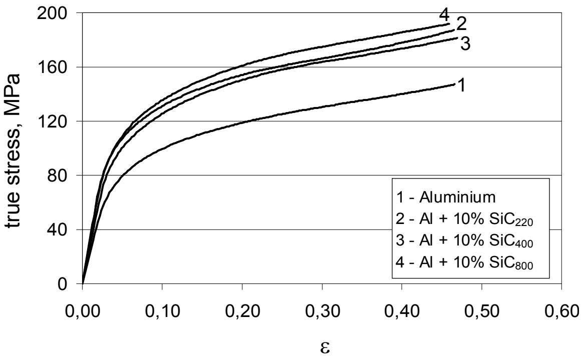
TABLE 3. **Influence of chemical composition and size of reinforcing phase particles on HB hardness of hot-extruded materials produced from aluminium and Al-based composites reinforced with 10% silicon carbide particles**

TABELA 3. **Wpływ składu chemicznego i wielkości cząstek fazy umacniającej na twardość HB wyciskanych na gorąco tworzyw z aluminium i kompozytów na jego osnowie umocnionych przez 10% cząstek węglika krzemu**

	Al	Al+SiC_{220}	Al+SiC_{400}	Al+SiC_{800}
HB	30.7±0.34	37.8±0,85	37.5±0.86	38.1±0.48

Stress-strain curves. The behaviour of the aluminium matrix and composites reinforced with silicon carbide particles in the state after extrusion was analysed in a uniaxial compression test. The test was realized at room temperature and at 200°C, at the speed of 0.01 s^{-1}. True stress-strain curves constructed for the matrix material and for the composites are shown in Fig. 2. It was found that the presence of SiC particles causes an increase of stress at which deformation proceeds, at room temperature as well as at 200°C. In the case of samples compressed at room temperature, no unequivocal influence of the SiC particle size on the character of the obtained curves was observed. The highest stresses were observed for the composite reinforced with 10% SiC_{800}. In the case of compression tests performed at 200°C, the effect of the SiC particle size is visible: a decreasing particle size leads to an increase of true stresses necessary for the realization of a given strain.

a)



b)

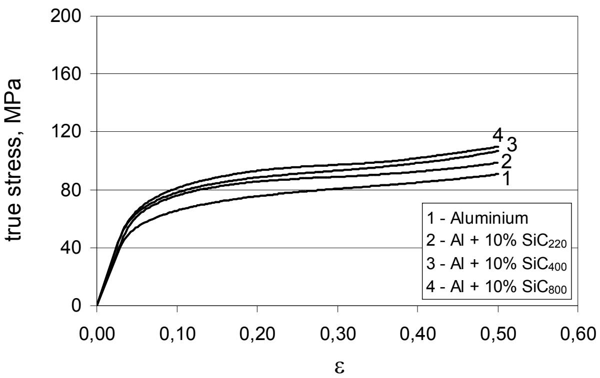


Fig. 2. Influence of chemical composition and size of reinforcing phase particles on character of true stress-strain curves obtained in compression test at room temperature (a) and at 200°C (b), for hot-extruded samples of aluminium and Al-based composites reinforced with 10 % silicon carbide particles

Rys. 2. Wpływ składu chemicznego i wielkości cząstek fazy umacniającej na przebieg krzywych naprężenie rzeczywiste - odkształcenie otrzymanych w próbie ściskania w temperaturze pokojowej (a) i 200°C (b) wyciskanych na gorąco próbek z aluminium i kompozytów na jego osnowie umocnionych przez 10% cząstek węglika krzemu

Abrasive wear testing. Comparative abrasive wear tests were performed, using a high-speed steel disk of 64 HRC hardness, 125 mm diameter and 3 mm thickness, as a counter-specimen. The measurement was realized along a distance of 2400 m, applying a 0.25 rps disk speed of rotation, while the applied load was 7 N. Based on weight loss measurement, the loss of volume of the samples was calculated, which was the measure of abrasive wear. The results of the tests are presented in Figure 3. In each case, the presence of SiC particles resulted in increased abrasion resistance. The size of silicon carbide particles was also found to influence the obtained results. Increasing the size of the reinforcing phase particles, with their volume fraction held constant, resulted in a lower abrasive wear of the composite. For the investigated materials, under the assumed testing conditions, the highest abrasion resistance was observed for a composite reinforced with 10% of SiC_{220}. In the case of the discussed test, large particles act as more effective support for a counter-specimen, thus being better protection for a soft matrix against abrasion.

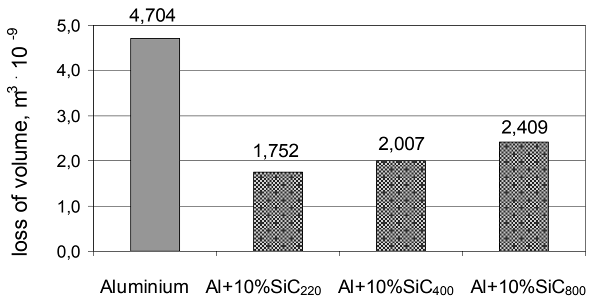


Fig. 3. Influence of chemical composition and particle size on abrasive wear of samples extruded at 500°C, produced from aluminium and composites reinforced with 10% silicon carbide particles

Rys. 4. Wpływ składu chemicznego i wielkości cząstek na zużycie ścierne wyciskanych przy temperaturze 500°C aluminium i kompozytów umocnionych przez 10% cząstek węglika krzemu

Microstructure examination. The observation of the microstructure of the composites was realized with the application of optical microscopy on longitudinal polished sections. The micrographs of the composites are shown in Figure 4.

a) b) c)

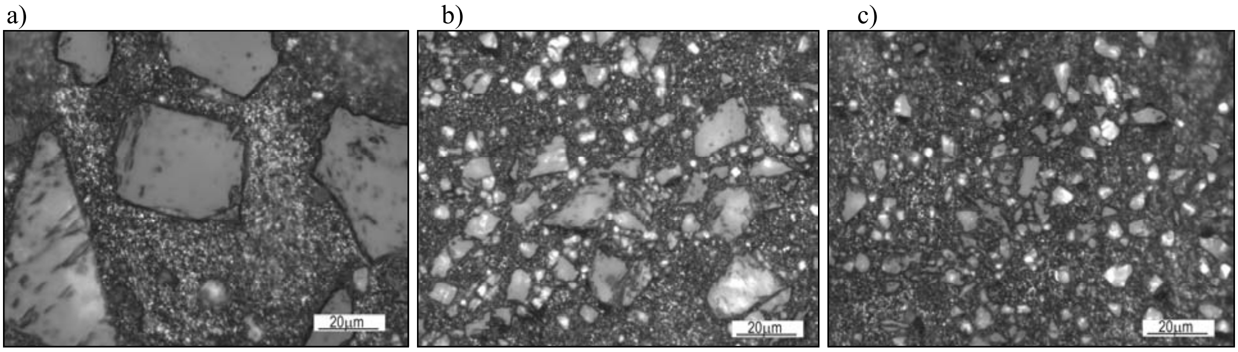


Fig. 4. Microstructures of hot-extruded aluminium-based composites reinforced with 10% particles: a) SiC_{220}, b) - SiC_{400}, c) SiC_{800}. Longitudinal polished sections

Rys. 4. Mikrostruktury wyciskanych na gorąco kompozytów na osnowie aluminium umocnionych przez 10% cząstek; a) SiC_{220}; b) SiC_{400}; c) SiC_{800}. Zgłady wzdłużne, polerowane

Based on the performed observations, it was found that the distribution of SiC particles in the aluminium matrix is quite uniform, regardless of their size (Fig. 4). Silicon carbide particles were closely adherent to the surrounding matrix and no discontinuities were observed at the component boundaries. The metallographic specimens did not reveal any voids caused by particles falling out during specimen preparation. This allows us to conclude that the extrusion process resulted in the formation of a good-quality mechanical bonding of the particles in the matrix.

CONCLUSIONS

Based on the results of the investigations of the materials obtained by the hot extrusion of aluminium powder compacts and compacted mixtures of Al powder with 10% SiC particles of different size, it was found that:

1. By the hot extrusion of semi-finished products of aluminium powder and composite mixtures, under the assumed parameters, it is possible to obtain products showing a relative density close to that of a solid material. The introduction of SiC particles of decreasing size into the aluminium matrix caused a slight decrease of density.
2. The level of extrusion force depends on the chemical composition of the composite and the size of the reinforcing phase particles. The application of smaller particles resulted in a necessity to apply a higher load.
3. The presence of SiC particles in the aluminium matrix caused a slight increase of HB hardness. No effect of the particle size on the obtained results was observed.
4. The introduction of SiC particles into the matrix caused an increase of true stress at which deformation proceeds, at room temperature as well as at 200°C. In the case of samples compressed at room temperature, no unequivocal influence of the SiC particle size on the character of the obtained curves was observed. In the case of compression tests performed at 200°C, a decreasing particle size leads to an increase of true stresses.
5. The microstructure of the obtained products is characterized by uniform distribution of SiC particles in the matrix. The particles were closely adherent to the matrix and metallographic specimens did not reveal any voids caused by particles falling out.
6. The introduction of SiC particles into the matrix resulted in higher abrasion resistance of the investigated materials. The presence of larger particles of reinforcing phase caused a lower abrasive wear of the analysed materials.

The obtained results allow us to conclude that in the case of the given components and their forming technology, the introduction of particles into the matrix has a favourable effect, while their size influences the individual properties of the composites differently. Therefore, the final selection of the proper size of silicon carbide particles applied as reinforcement in the aluminium matrix should be based on the knowledge of the working conditions of the composite product, as well as the requirements to be met.

Acknowledgements

I wish to thank Mr. Dariusz Kukla, M.Sc., for his assistance during the realization of this research work.

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