MICROSTRUCTURAL FEATURES OF DC CAST AL/SIC MMCS

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MIKROŠTRUKTURÁLNE CHARAKTERISTIKY PRIAMO ODLIEVANÝCH AL/SIC KOMPOZITOV S KOVOVOU MATRICOU

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Abstrakt

Kontinuálne a diskontinuálne spevnené Al/SiC kompozity s kovovou matricou (MMCs) sú sľubné moderné a ľahké materiály s excelentnými vlastnosťami ako sú: vysoká tvrdosť a pevnosť pri teplote okolia i pri zvýšených teplotách, dobrá odolnosť voči opotrebeniu a vysoký modul elasticity. V súčastnosti sa MMCs prevažne uplatňujú len vo vojenskom a vesmírnom priemysle. Avšak tieto materiály sa začínajú uplatňovať i v civilných aplikáciach.

Medzi niekoľkými výrobnými procedúrami diskontinuálne spevnených Al/SiC MMCs, priame začlenenie spevňovacej komponenty (SiC častice, doštičky alebo whiskre) do roztaveného hliníka počas priameho vertikálneho kontinuálneho liatia čapov je najsľubnejšia a pravdepodobne aj najlacnejšia priemyselná technológia výroby Al/SiC kompozitov. Táto procedúra je už rozvinutá do priemyselnej škály, avšak tak použitie ako aj vlastnosti liatych kompozitov ktoré sú dôležité pre ich ďalšie formovanie až do tvaru blízkemu konečnému tvaru stále vyžadujú ďalší výskum. Preto bol zakúpený a analyzovaný priamo kontinuálne liaty kompozit Duralcan F3S.20S (Al-9%Si zliatina s 20 obj.% SiC častíc). V tomto článku sú prezentované a diskutované mikroštrukturálne a mechanické charakteristiky tohto kompozitu.

Abstract

Continuously and discontinuously reinforced Al/SiC metal matrix composites (MMCs) are promising modern, light weight materials with excellent properties, such as: high hardness and strength at ambient and elevated temperatures, good wear resistance, and high modulus of elasticity. Currently, the use of MMCs is limited predominantly to the military and the aerospace industry. However, the penetration of these materials has already begun also in civilian applications.

Among several manufacturing procedures of discontinuously reinforced (DR) Al/SiC MMCs, a direct incorporation of the reinforcement (SiC particles, platelets or whiskers) into the molten Al alloy during direct vertical continuous (DC) casting of billets is the most promising and probably the cheapest industrial manufacture technology of Al/SiC composites. The procedure is already developed on the industrial scale; however, the use, as well as properties of cast composites important for further forming to near net shape products are still need to be investigated. Therefore, Duralcan's DC cast composite F3S.20S (Al-9%Si alloy with 20 vol.% of SiC particles) was purchased and analyzed. In this article, microstructural and mechanical characteristics of the cast composite are presented and discussed.

Introduction

Compared to conventional Al alloys, the Al alloy matrix based composites, reinforced with ceramic particles have the best density-properties-price combination. Therefore, it is legitimate to expect that these materials will substitute for part of conventional materials in mass production, for example in automotive, as well as in other industries of transport vehicles. Today, these materials have already begun to replace the conventional materials in computers, audio and video equipment, as well as in equipment for sports and leisure [1-4].

There are several ways of DR Al/SiC manufacture: direct incorporation of relatively rough SiC particles into the molten Al alloy, infiltration of porous SiC preforms with the molten Al alloy or via powder metallurgy (PM) procedures [1,2,5]. Generally, Al/SiC composites manufactured by PM have the best mechanical properties because they contain in the Al alloy matrix finer and more uniformly distributed reinforcement (SiC particles or whiskers) [6,7]. These composites also have better chemical and microstructural homogeneity, but are very expensive because of the complexity of the manufacturing.

The basic purpose of adding reinforcement into the metal matrix is to increase the yield strength. Tensile strength and hardness at ambient, as well as at elevated temperatures are also increased. The result is improved wear resistance of the material. With increased SiC addition, the module of elasticity increases linearly and thermal expansion decreases. Unfortunately, with increased content of reinforcement the ductility of the composite is drastically decreased. Tensile and compression ductility of Al/SiC MMCs are very different. These composites resist compression loading very well, but they are very sensitive to tensile load. Therefore, these materials are appropriate for hot forming in closed dies (die forging, hot pressing, extrusion etc.). Experimental investigations [8] show also that these materials can be successfully cold formed into near net shaped products if proper heat treatment of the metal matrix is performed. Specific studies [9,10] show that increased hot/cold working of the composite increases tensile ductility and fracture toughness for a given state of the metal matrix. These improvements are attributed to the more uniform distribution of local stresses and larger distances between crack initiation sites. Numerous investigations [10-12] show that increased hot/cold deformation increases damages of reinforcement and decreases the mean SiC particle size or the length/diameter ratio of SiC whiskers, respectively. Considerable efforts have also been made to accommodate chemical composition of the metal matrix in order to increase/optimize deformability of these materials.

The production of DR Al/SiC composites by incorporation of up to 25 vol.% of SiC particles into a molten Al alloy during direct vertical continuous (DC) casting of billets is already developed on the industrial scale [13-15]. In this way (see Figure 1), produced blocks or billets of composites are cheaper than the composites manufactured by the PM route. First of all, these cast composites are appropriate for further forming of near net shaped products with pressure die or sand casting [13-17] because the key problem of these materials is its poor machinability [18-21]. Successful machining is only possible with PCD (Poly-Crystalline Diamond) tools and recently also with CVD DCC (Chemical Vapour Deposited Diamond Coated Carbide) inserts, and at appropriate machining rates.

Fig.1 Schematic presentation of Al/SiC MMCs manufacture by incorporation of SiC particles during direct vertical continuous casting [15]

Considering that it is not realistic to expect essential improvement of composite machinability, the only reasonable way of composite product manufacture is developing technologies that make it possible to manufacture products requiring minimal mechanical treatment. The prevailing technology is casting (the above mentioned DC casting followed by pressure die casting or infiltration of porous ceramic preforms). However, the procedures of hot/cold forming would also be worth considering, but having regards that composites with the metal matrix (besides Al- also Mg- or Ti-alloys) can contain 10-50 vol.% of very hard (3000 HV) and abrasive particles or whiskers (not only SiC or Al_2O_3, but also AlN, TiB_2 etc.).

The most frequently selected matrix materials, reinforced with alumina (Al_2O_3) or SiC are wrought alloys type 2014 or 6061 and casting Al-Si alloys (silumins with approximately 7-12 % of Si) [22]. For our investigations and experiments, Duralcan´s composite F3S.20S (359/SiC/20p according to Aluminium Association MMCs) was selected. According to the manufacturer, this material is appropriate for sand and pressure die casting. Furthermore, some hot working experiments (die forging) and investigations have already been made [23] with this material for the production of brake discs.

In Table 1 nominal and actual (determined at IMT, Ljubljana) chemical compositions of the metal matrix are given. The selected composite in this metal matrix contains (according to the manufacturer`s specification) approximately 20 vol.% of SiC particles with the mean diameter (d_{50}) of ≈13 μm. For comparison, in Table 1 the chemical composition of the F3K matrix is given. This material is recommended for high-temperature applications and therefore contains a higher content of alloying elements (Cu, Ni and Mg).

Table 1 Metal matrix chemical compositions of Duralcan´s Al/SiC MMCs, types F3S and F3K

* Al in matrix and 20-23 vol.% of SiC particles as reinforcement

A Slovenian manufacturer of wrought and cast Al products expressed interest in the possibility of developing an extrusion technology of MMCs. Therefore, in the first stage of our project (supported also by the Slovenian Ministry of Science and Technology), mechanical and microstructural characterization of the selected composite was made. The results of our investigations are given below.

Experimental work

Proper microstructural and mechanical characterization of the selected material is necessary for successful laboratory and industrial hot extrusion experiments. Therefore, from DC cast billets of composite (Φ178 × 1000 mm) we cut off samples, parallel and perpendicular to the cast direction of billets. Slow and relatively expensive, high water pressure (3000 bars) jet equipment was used for cutting off samples from relatively large DC cast billets. Afterwards, standard test specimens for metallographic and mechanical investigations were machined from samples. Some problems occurred during the machining of specimens, because only standard tungsten carbide tools were used. The preparation of test specimens is complex because of the nature of this type of composite materials (very hard particles in soft matrix). For the preparation of metallographic samples, it was necessary to select proper cutting, grinding and polishing materials, as well as to develop proper procedures.

In order to estimate the pressure necessary for the hot extrusion of billets, the true stress (k_f in MPa) of composite under compression in the expected extrusion temperature region (420-470°C) and at different deformation rates ($d\varepsilon/dt$=0.1-3 s^{-1}) was determined. The true stress of the composite under compression loading of cylindrical specimens (Figure 2) was determined with Gleeble 1500 (Duffers Scientific Inc.) apparatus.

Results and discussion

Brinell hardness and tensile properties of DC cast billets were determined on standard test specimens (DIN 50351, 50125 and 50145). Room temperature hardness $HB_{2,5/187,5}$=105-110 is expected. Average tensile strength in perpendicular direction (Rm ≈260 MPa) does not differ considerably from the average tensile strength in longitudinal direction of billets casting (Rm $\approx$275 MPa). Tensile elongation and contraction are minimal.

Therefore, one can conclude that the investigated composite (in cast condition) is very brittle. Scanning electron microscope (SEM) micrograph (Figure 3) of fractured surfaces shows quasi ductile fracture with some individual ductile crests. Among them, small transcrystalline regions (SiC particles) are noticed where fracture is initiated and passed.

Microstructural investigations show that on the surface of billets there is a thin shell (thickness of approximately 1,25 mm) of unreinforced material (Figure 4). This can be attributed to the nature of vertical continuous casting where, because of rapid cooling of the melt at the wall mould, the solidification front drives the SiC particles towards the center of the mould/billet. This thin surface layer consists of about 60 % of α_{Al} solid solution (white) and 40 % of the eutectic (α_{Al}+Si, light grey heterogeneous package). Between this outer thin layer and the core of the billet, a transitional, only partially reinforced region is noticed. The thickness of this region is approximately 0.5 mm. This heterogeneous region is followed by the core of the billet (Figure 5), where a relatively homogeneous microstructure can be observed. The SiC particles (dark grey) are uniformly distributed in the metal matrix. The metal matrix consists of about 70 % of α_{Al} solid solution and 30 % of eutectic (α_{Al}+Si). The content of the SiC particles was estimated on 20-25 vol.%, which is in accordance with the manufacturer`s specification. This SiC content was also confirmed by automatic image analysis (Kontron Elektronik KS 200; University of Maribor) during observation of samples with optical microscope. The SiC particles are sharp edged with flat surfaces, uniform in size and surprisingly uniformly distributed in the metal matrix. The largest SiC particles have a diameter of approximately 25μm, but the majority of particles are smaller than 15 μm.

Detailed quantitative image analysis showed that the average equivalent spherical diameter of SiC particles is 7,6 μm, its form factor/index (roundness) is 0,75 and its content in the metal matrix is 23 %. Figures 6 and 7 show a sample of particle size and roundness distribution results determined by the quantitative image analysis.

SiC particles are located in eutectic fields (Figure 5), pushed away from the α_{Al} grains of solid solution due to the fact that eutectic solidifies last (at ≈577°C). In accordance with the small difference in mechanical properties between parallel and perpendicular direction of casting, larger microstructural differences are not observed. The observation of polished samples with optical microscope showed that porosity of billets is negligible. On the basis of microstructural investigations and comparing the outer layer and the core of the billet it can be concluded that during solidification of billets, growth of α_{Al} grains was hindered. This results from the facts that in the core (reinforced with SiC) of the billet, primary dendrites of α_{Al} are smaller and more globular than in the outer (with SiC poorer or unreinforced) region. In contrast with the billet core, the outer layer has well defined dendrite morphology of solidification.

In literature [24-28], there is little data about deformability of Al/SiC MMCs at elevated temperatures. It can be concluded that Al/SiC MMCs can be extruded at similar conditions as wrought Al alloys without reinforcement. Extrusion velocities are practically the same, working pressures are 10-20% higher and extrusion can be performed successfully at extrusion ratios from 16:1 up to 45:1. For the investigated material, the extrudability was unknown to us. Therefore, the above mentioned true stresses were determined. Figures 8 a and b show true stresses of the investigated material in the temperature range commonly applied for the extrusion of Al alloys, as well as at expected deformation rates.

On the basis of theoretical and semi-empirical equations [29], the determined true stresses of the investigated material made it possible to estimate the working pressure of the extrusion and the capacity of the extrusion press for the selected billet dimensions, respectively. It was established that the 20 MN industrial press (Schlömann, Germany), located at the Slovenian factory Impol would be appropriate for our experimental work. The biggest problem of the extrusion of Al/SiC MMCs is their already mentioned poor machinability. This leads to difficulties during billets/extruded profiles cutting and causes excessive wear of extrusion die. Therefore, conventional cutting and tool steel are unsuitable. As a die material, it is recommended [24] to use tungsten carbide or PM tool steel, PVD or CVD coated with a tin layer of TiN/TiC and in addition, special die lubricants have to be used. In comparison with conventional unreinforced materials, thermal conductivity of Al/SiC MMCs is lower and heat capacity is higher. Therefore, one can expect longer duration of billet heating on the extrusion temperature and more intensive heating of extrusions during the deformation.

Conclusions

The results of our microstructural and mechanical investigations show that it is already possible to manufacture, on the industrial scale, DC cast Al/SiC MMCs of good quality. Therefore, in the near future, these materials may become a serious rival to conventional Al alloys. These investigations also allow us to carry out extrusion experiments and further improvement of mechanical properties by additional hot deformation of DC cast Al/SiC MMCs and its proper further heat treatment.

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