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INVESTIGATION OF THE MECHANICAL PROPERTIES OF A SQUEEZE-CAST LM6 ALUMINIUM ALLOY REINFORCED WITH A ZINC-COATED STEEL-WIRE MESH

DOLOČEVANJE MEHANSKIH LASTNOSTI LIVARSKIH Al-ZLITIN LM6, OJAČANIH S POCINKANO JEKLENO MREŽO

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Composites of an LM6 aluminium alloy reinforced with a zinc-coated steel-wire mesh were prepared with squeeze casting. Three different orientations of 0°, 45° and 90° of the zinc-coated steel-wire mesh were used with the aluminium alloy. The microstructures of the castings were analysed and the hardness, tensile strength and ductility were investigated. The fracture surfaces of the matrix and the composites were examined using a field-emission scanning electron microscope (FESEM). The results revealed that the hardness of the composites increased compared to the matrix. Also, the tensile strength of the composites increased with the increasing angle of orientation. The tensile strength increased by up to 11 % for the composite with a steel-wire mesh at the 90° orientation. However, the ductility of the composites decreased due to the presence of micropores at the interface of aluminium and the steel-wire mesh. Micrographs of fracture surfaces showed a dimple formation in the matrix and a wire pull-out; a broken wire was observed in the composites.

Keywords: aluminium alloy, steel-wire mesh, squeeze casting, mechanical properties

V članku avtorji opisujejo izdelavo kompozitov s kovinsko osnovo iz LM6 Al zlitine, ki so ojačani z mrežo iz pocinkane jeklene žice. Kompozite so pripravljali s postopkom tlačnega litja v testastem stanju (angl.: squeeze casting). Uporabili so tri različne orientacije pocinkane jeklene mreže (0°, 45° in 90°) za ojačitev matrice iz Al zlitine LM6. Analizirali so mikrostrukture ulitkov in določili njihove mehanske lastnosti, to so: trdota, natezna trdnost in duktilnost. Prelomne površine matrice in kompozitov so pregledali pod vrstičnim elektronskim mikroskopom na poljsko emisijo (FESEM). Rezultati raziskav so pokazali, da se je trdota kompozitov povečala v primerjavi s trdoto kovinske matrice. Prav tako se je natezna trdnost kompozitov povečevala z naraščajočim kotom orientacije ojačitve. Pri 90° orientaciji je bila natezna trdnost večja do 11 %. Vendar pa se je duktilnost zmanjšala zaradi prisotnosti mikropor na mejah med Al matrico in jekleno mrežo. Mikroskopski posnetki kažejo jamičasto prelomno površino kovinske matrice in izvlek pretrgane žice v kompozitih.

Ključne besede: zlitina na osnovi Al, mreža iz pocinkane jeklene žice, ulivanje s stiskanjem, mehanske lastnosti

1 INTRODUCTION

Aluminium-based metal-matrix composites have been used as lightweight structures in the aerospace, transportation, communication and manufacturing industries because of their excellent strength-to-density and stiffness-to-density ratios.[1–9] The most commonly used reinforcement in the form of particles, whiskers and fibres increases the mechanical properties and wear resistance of these composites. However, it also decreases the ductility of the composites.[10–17] Fiber-reinforced composites have distinct advantages over particulate reinforcement. In structural applications, the matrix transmits the load to the fibers and in this way the composite offers a high tensile strength.[18]

Aluminium-matrix composite materials have been prepared by various processes such as powder metallurgy, diffusion bonding, spray co-deposition, in-situ solidification and casting. Out of these, casting is the most economical, viable and simple method to produce components.[17] Squeeze casting is the preferred casting technique as it produces quality castings with a good surface finish and a near-net-shaped component with minimal post-processing operations, porosity and shrinkage. In this technique a metered quantity of molten metal is poured into a preheated die cavity, then the squeeze pressure is applied to the liquid metal until solidification.[20–26]

In the present work, a steel wire mesh has been selected because of its high strength and elastic modulus. Several authors [27,28] have investigated the stainless-steel-wire/steel preforms reinforced in an aluminium matrix using the squeeze-casting process. R. B. Bhagat[28] experimented with the reinforcement of stainless-steel wires in aluminium-fabricated components using the squeeze-casting process and investigated the effect of volume % reinforcement on the mechanical properties of composites. The 304-type stainless steel of 0.3 mm in diameter was used as the reinforcement and the volume fraction was varied up to 40 %. The results showed that the reinforcement of stainless-steel wires significantly improved the tensile strength of the composites. The tensile strength of the composites increased with an increasing volume of stainless-steel wires in the matrix. However, the actual tensile strength was lower than the predicted tensile strength calculated using the rule of mixture. The interface bonding between the fiber and the matrix was inadequate and that caused fiber pullout during the tensile test. Several intermetallic iron-aluminides compounds such as Fe_3Al, FeAl, Fe_2Al_5, $FeAl_2$, $FeAl_3$, and Fe_2Al_7 were observed at the interface of the matrix and the reinforcement. Composites with a 40 % volume fraction of stainless-steel wires offered tensile strengths more than three times that of the aluminium matrix.

R. Baron et al.[27] discussed the effect of mechanical properties on steel and stainless-steel preform-reinforced aluminium composites prepared using the squeeze-casting process. A low-density power-metallurgy preform was used as the reinforcement. The microstructure of the composites revealed the presence of an aluminium and iron reaction phase around the metallic preform. The application of a load during the tensile test promoted premature failure by crack initiation at the interface of the matrix and the reinforcement. Stainless-steel preform-reinforced composites offered better mechanical properties over monolithic aluminium and steel preform-reinforced composites. Also, the ductility of the composites decreased with an increasing volume fraction of the reaction phase.

Coating on the reinforcement improves the interface bonding between the reinforcement and the matrix, wetting that in turn increases the mechanical properties of the composites.[29–39] Several researchers have extensively studied the effect of coating on a steel-fiber reinforcement in an aluminium alloy. D. Mandal et al.[39] investigated the mechanical properties of copper, nickel and uncoated short steel fibers reinforcement in aluminium produced by the stir-casting process. The electroless deposition method was used to prepare a copper and nickel coating on reinforcements. 500–800 μm length and 80–120 μm diameter of steel fibers were used as the reinforcement and 5 % of mass fractions of steel fibers were reinforced in aluminium. The results revealed that the addition of steel fibers significantly improved the mechanical properties of the composites compared to the matrix. The density, hardness, yield strength and ultimate tensile strength of the composite increased by reinforcing 5 % of mass fractions of steel fibers in the matrix. However, the addition of steel fibers decreased the ductility and increased the percentage of porosity in the castings. Copper-coated steel-fiber-reinforced composites exhibited better mechanical properties than the aluminium matrix, aluminium reinforced with nickel and uncoated steel-fiber composites. The fracture surface of the matrix showed dimple formation, which resulted in ductile fracture and fiber pull out, with dimples being observed in the composites. The copper-coated steel-fiber-reinforced composite showed dimples on the surface and coalesced rather than fiber pull out. This was attributed to the better interface bonding between the matrix and the reinforcement.

V. V. Ganesh et al.[40] investigated the mechanical properties of AA1050 aluminium alloy reinforced with galvanized iron wires. Some 2.5 % of the volume fractions of zinc coated galvanised iron wire with 0.8 mm diameter was reinforced in aluminium processed using casting process followed by hot extrusion. The results revealed that the composites exhibited better mechanical properties than the monolithic alloy. Micrographs of the composite revealed good interface bonding between the aluminium and the iron wires. The reinforcement of zinc-coated galvanised iron wires in aluminium increased the density, hardness, elastic modulus, yield strength and tensile strength. However, the ductility and coefficient of thermal expansion decreased with an increasing volume fractions of galvanized wires reinforcement.

It has been observed that very few studies have been carried out on aluminium alloy with steel wire mesh reinforcement. In this present work, zinc-coated steel-wire mesh was reinforced in LM6 aluminium alloy by the squeeze-casting process. The microstructure, hardness, tensile strength and ductility of composites were analysed and the fractured surface of a tensile specimen was examined using FESEM. The main objective of this paper is to investigate the mechanical properties of a squeeze-cast LM6 aluminium alloy reinforced with zinc-coated steel wire mesh at various angles of orientation.

2 EXPERIMENTAL PART

Commercially available zinc-coated steel-wire mesh with a chemical composition as given in **Table 1**, with a diameter of 304 μm, longitudinal and transverse distance

Table 1: Chemical composition of zinc-coated steel-wire mesh, in mass fractions (*w*/%)

Sample	C	Si	Cr	Mn	Ni	S	P	Cu	Zn	Fe
ZnFe	0.072	0.10	0.128	0.30	0.114	0.012	0.009	0.062	31.98	Bal

Table 2: Chemical composition of LM6 aluminium alloy, in mass fractions (*w*/%)

Sample	Si	Fe	Cu	Mn	Mg	Ni	Sn	Pb	Zn	Ti	Al
LM6	11.78	0.40	0.02	0.02	0.03	0.006	0.05	0.06	0.12	0.08	Bal

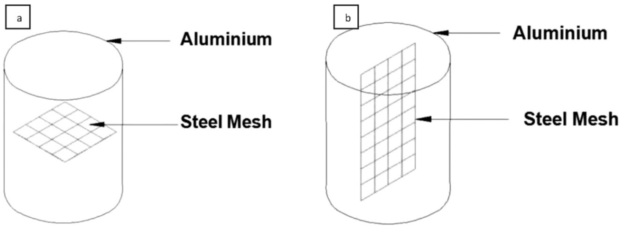

Figure 1: Schematic diagram of steel-wire mesh at various orientations in the aluminium-alloy casting: a) steel-wire mesh at 0°, b) steel-wire mesh at 90°

between the steel wires of 1590 μm, was used for the reinforcement. Steel-wire mesh was placed inside a preheated die at various orientations of (0, 45 and 90)°. The schematic diagram of the steel-wire-mesh reinforcement of the aluminium alloy is shown in **Figure 1**.

A modified universal testing machine with a 40-tonne capacity, as shown in **Figure 2**, was used for conducting the experiments. The die and punch were made of the SG400 spheroidal graphite iron and EN8 steel, respectively. A ceramic electric heater with a capacity of 400 °C was used to preheat the die. An electric induction furnace with a 5-kg capacity was used to melt the LM6 aluminium alloy.

The LM6 aluminium alloy with a chemical composition as listed in **Table 2** was melted in the electric induction furnace and the temperature was raised to 780 °C. The steel-wire mesh was placed inside the preheated die at various orientations of (0, 45 and 90)°. The melt was degassed with hexachloroethane tablets and a measured quantity of the LM6 aluminium alloy was poured into the preheated die, which was maintained at a temperature of 225 °C. A squeeze pressure of 125 MPa was applied during the solidification and the component was ejected subsequently, using an ejector pin. Cylindrical castings with a 60-mm diameter and 75-mm height, as shown in **Figure 3**, were prepared using this process.

Samples were prepared to investigate the microstructure and micro-hardness. The microstructure of the composites was analysed using an image analyser. The micro-hardness of the composites was measured using a micro-hardness tester (Model 3212 and Zwick hardness tester, USA) with a load of 0.2 kg. Tensile specimens were prepared using a wire-cut electrical discharge machine as per ASTM E8 standard, with a gauge length of 25 mm, width and thickness of 6 mm. The specimens were tested using an extensometer (Model TECSOL, TMC Engineering, India) and the average values of two tensile-test readings are shown in **Table 3**.

3 RESULTS AND DISCUSSION

3.1 Microstructure

Microscopic observations of the matrix and composites are shown in **Figure 4a** to **4d**. It is observed that the steel-wire mesh was reinforced in the aluminium alloy, showing better interface bonding between the steel wire and aluminium due to the presence of the zinc coating on the steel wires. The squeeze pressure during the solidification process made the aluminium matrix denser resulting in a fine microstructure.

3.2 Hardness

The hardness of the composites was observed at four locations in a sample and the average of hardness values was considered to plot the graph. A variation in the hardness of the composites against the distance between the steel wire and the matrix is depicted in **Figure 5**. It can be seen that the hardness of the composites increased with the increasing distance from the matrix to the steel wire. This is due to the incorporation of the zinc-coated steel-wire mesh into the aluminium matrix. Zinc dissolves in aluminium leading to solid-solution strengthening, which improves the interfacial bonding between aluminium and the steel wire that resists plastic deformation. Also, the squeeze pressure minimises the porosity, leading to a fine microstructure that also contributes to the improvement of the hardness. The maximum hardness values of (135, 96 and 61) VHN were observed for the steel wire, the interface between the steel wire and the matrix and the aluminium matrix, respectively.

Figure 2: Modified universal testing machine for squeeze casting

Figure 3: Sample castings prepared with squeeze casting

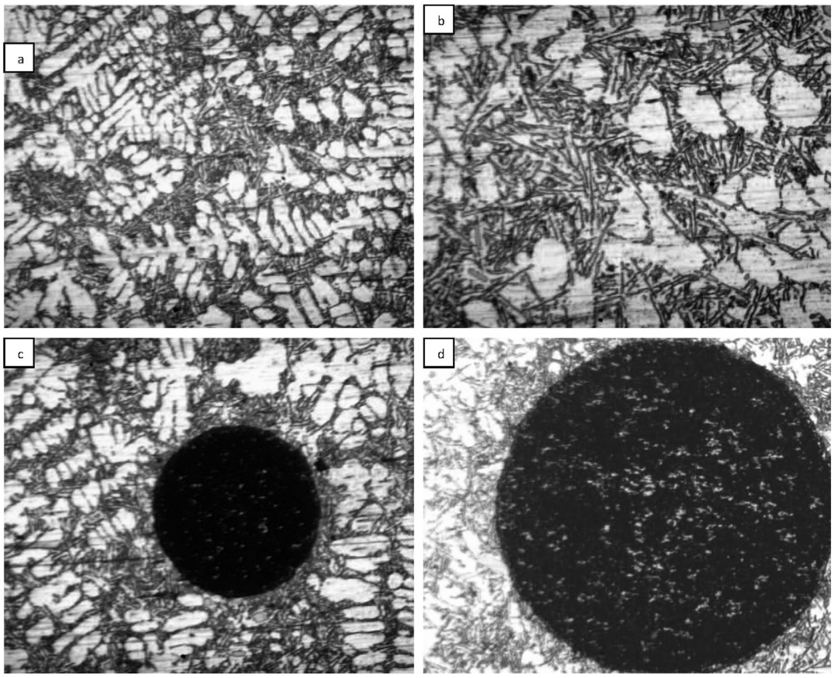

Figure 4: Optical micrographs of LM6 aluminium alloy reinforced with zinc-coated steel-wire mesh: a) LM6 matrix at 50×, b) LM6 matrix at 100×, c) LM6 matrix with a steel wire at 50×, d) LM6 matrix with a steel wire at 100×

3.3 Tensile strength

The tensile-strength values for the LM6 alloy and the composites are given in **Table 3**. The variation in the tensile strength of the composites against the orientation of the zinc-coated steel-wire mesh is shown in **Figure 6**. It is observed that the tensile strength of the composites increases with the increasing angle of orientation. The steel-wire mesh at the orientation of 90° allows the highest tensile strength compared to the 0° and 45° orientations. This is due to the reinforcement of the steel-wire mesh parallel to the loading condition; the matrix transmits the load to the steel-wire mesh, allowing a high tensile strength of 164 MPa. However, the steel-wire mesh at the orientations of 0° and 45° allows a low tensile strength compared to the matrix. This is due to the micropores at the interface of aluminium and the steel wire, which act as crack-nucleating points and reduce the tensile strength of the composites.

Table 3: Mechanical properties of the matrix and the composite with various angles of steel-wire-mesh orientation

Specimen code	Tensile strength (MPa)	% of elongation
LM6	148	23.75
LM6 – ZnFe – 0°	119	14.7
LM6 – ZnFe – 45°	141	15.95
LM6 – ZnFe – 90°	164	17.35

The ductility of the composites was measured based on the percentage of elongation as shown in **Table 3**. It is observed that the ductility of a composite decreases with the incorporation of the steel-wire mesh into the

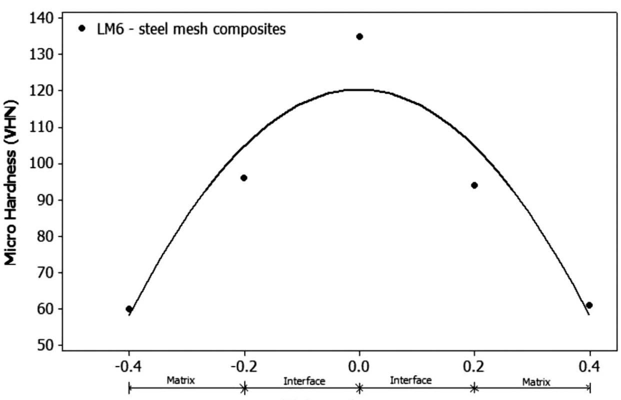

Figure 5: Variation of micro-hardness with the distance between the matrix and steel wire

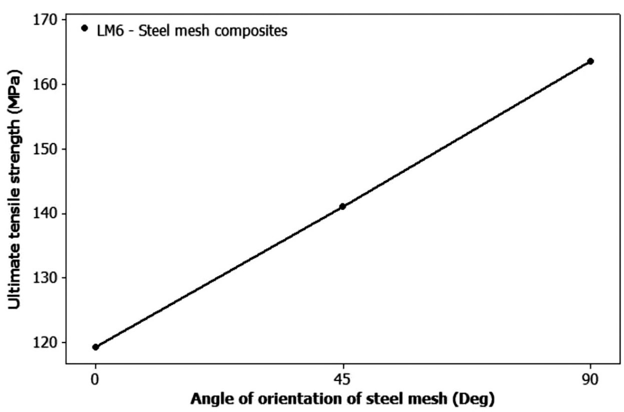

Figure 6: Variation of the tensile strength of the composites due to the angle of orientation

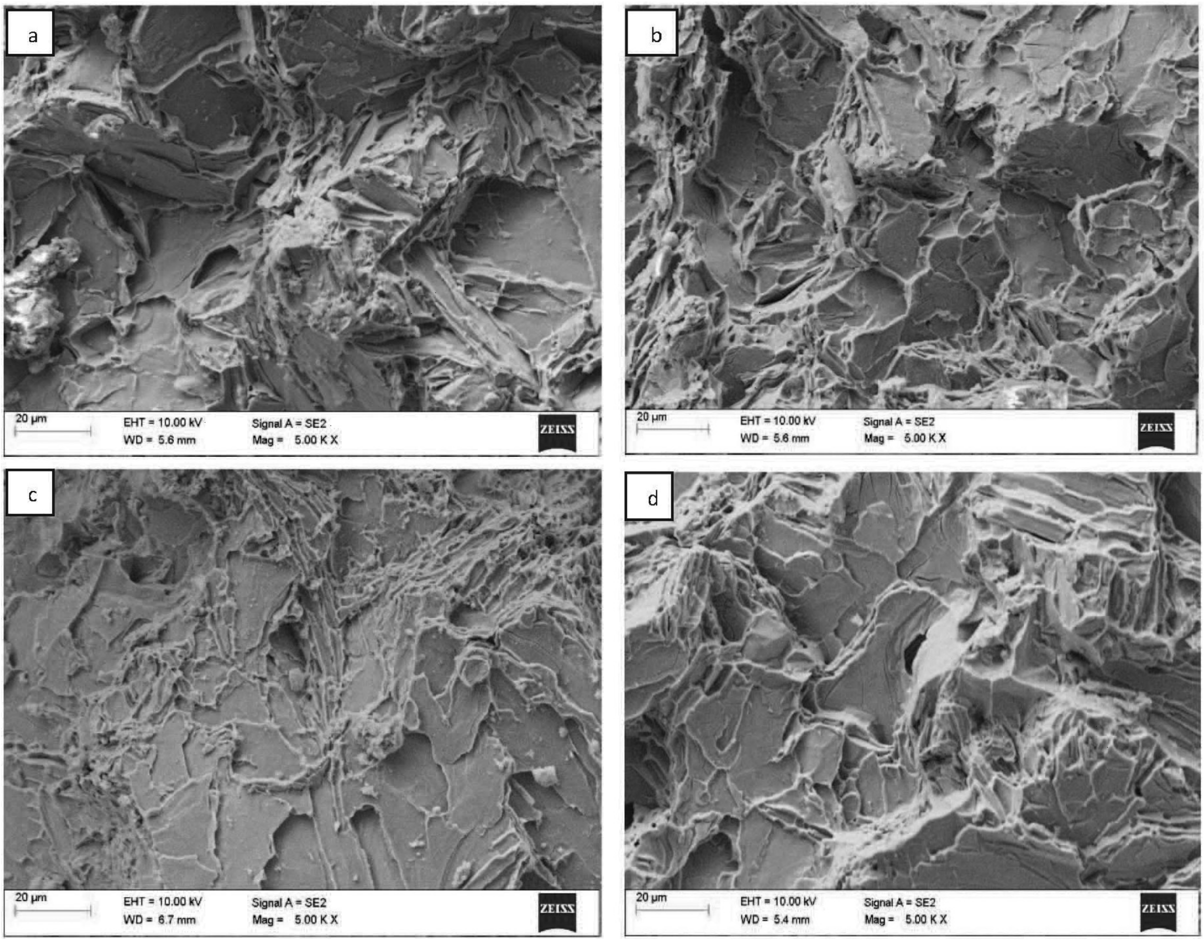

Figure 7: FESEM photographs of the fracture surfaces of different composites: a) LM6 matrix, b) LM6-ZnFe – 0°, c) LM6-ZnFe – 45°, d) LM6-ZnFe – 90°

aluminium alloy. The presence of micropores at the interface of aluminium and steel wire, the crack initiation at the interface and the propagation cause the failure of the composites.

3.4 Fracture surface

Figure 7 shows photographs of the fracture surfaces of the LM6 matrix and composites with orientations of (0, 45 and 90)°. A ductile fracture was observed in the matrix and composites during the tensile test. **Figure 7a** depicts the fracture surface of the LM6 matrix and the fracture occurs due to a dimple formation. **Figures 7b** to **7c** show the fracture surfaces of the zinc-coated steel-wire mesh at the orientations of 0° and 45°, respectively. The fracture mechanism is dominated by the steel wire pull-out due to the presence of the micropores and voids at the interface of steel and aluminium and dimple formation. The fracture surface of the zinc-coated steel-wire mesh at the orientation of 90° is shown in **Figure 7d**. Fracture is dominated by the steel wire pull-out, resulting from a broken steel wire rather than a dimple formation. R. Baron et al.[8] and R. B. Bhagat[9] and D. Mandal et al.[11] worked with stainless-steel wire/steel preform/steel fibres reinforced in an aluminium matrix by squeeze casting and stir casting and observed that a crack was initiated at the interface of the reinforcement and the matrix causing a fracture of the composite upon propagation.

4 CONCLUSIONS

Zinc-coated steel-wire mesh was reinforced at different orientations of (0, 45 and 90)° in the LM6 aluminium alloy by squeeze casting. The microstructures of the composites were analysed and the mechanical properties, viz., the hardness, tensile strength, ductility were investigated. From the above investigation, the following conclusions are made:

- The microstructures of the composites showed good interface bonding between aluminium and steel wire due to zinc coating of the steel wires.
- The hardness of the composites increased with the increasing distance from the matrix to the steel wire. The maximum hardness values of 135 VHN and 96 VHN were observed for the steel wire and the interface.

- The tensile strength of the composites increased with the orientation of the reinforcement. The maximum tensile strength of 164 MPa was observed for the steel-wire mesh at the angle of 90° orientation. The ductility of the composites decreased with the incorporation of steel-wire mesh into the aluminium alloy.
- The fracture surfaces of the composites caused steel-wire pull-outs and broken wires; and a dimple formation was observed in the matrix.
- This developed composite may be considered as a potential candidate to be used as a structural member in automobile, aerospace and marine applications because of its advantageous hardness and tensile strength.

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