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Machining studies of die cast aluminum alloy-silicon carbide composites

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Abstract: Metal matrix composites (MMCs) with high specific stiffness, high strength, improved wear resistance, and thermal properties are being increasingly used in advanced structural, aerospace, automotive, electronics, and wear applications. Aluminum alloy-silicon carbide composites were developed using a new combination of the vortex method and the pressure die-casting technique in the present work. Machining studies were conducted on the aluminum alloy-silicon carbide (SiC) composite work pieces using high speed steel (HSS) end-mill tools in a milling machine at different speeds and feeds. The quantitative studies on the machined work piece show that the surface finish is better for higher speeds and lower feeds. The surface roughness of the plain aluminum alloy is better than that of the aluminum alloy-silicon carbide composites. The studies on tool wear show that flank wear increases with speed and feed. The end-mill tool wear is higher on machining the aluminum alloy-silicon carbide composites than on machining the plain aluminum alloy.

Keywords: metal matrix composites; aluminum alloys; silicon carbide; die casting; milling; surface roughness

1. Introduction

Metal matrix composites (MMCs) combine a tough metallic matrix with a hard ceramic reinforcement with superior properties compared to conventional metallic alloys [1]. Aluminum, titanium, and magnesium alloys are commonly used as the matrix phase, and the most popular reinforcements are silicon carbide and aluminum oxide. Densities of most MMCs are approximately one third of steel, resulting in high specific strength and stiffness. These potentially attractive properties of MMCs, as well as the ability to operate at high temperatures, enable the MMCs to compete with super alloys, ceramics, and re-designed steel parts in several aerospace and automotive applications [2]. Compared to monolithic alloys, the wear resistances of MMCs are greatly enhanced by the introduction of a secondary phase in the form of abrasive ceramics into the ductile aluminum matrix [3]. The aluminum alloys reinforced with discontinuous ceramic reinforcements are rapidly replacing the conventional materials in various automotive, aerospace, and automobile industries [4].

The properties of MMCs are affected by the type and properties of the matrix, reinforcement, and interface. Matrix materials are usually lightweight materials, especially aluminum and its alloys. Ceramic reinforcements have been used in the form of particulates, whiskers, or continuous fibers. Particulate metal matrix composites (PMMCs) are more attractive than continuous fiber reinforced MMCs due to the higher ductility and lower anisotropy. Moreover, they are much cheaper, and they need simple processing methods.

Lloyd reported that the vortex mixing technique was suitable for the preparation of a ceramic particle dispersed aluminum composite [5], which was developed by Surappa and Rohatgi [6]. The stir casting involves the incorporation of ceramic particulates into liquid aluminum melt, and then the mixture solidifies together. Here, the crucial thing is to create good wetting between the particulate reinforcement and the liquid aluminum alloy melt. The simplest and most commercially used technique is the vortex technique or the stir casting technique. The vortex technique involves the introduction of pre-treated ceramic particles into the vortex of molten alloy created by the rotating impeller [7].

Microstructural inhomogeneities can cause notable parti-

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cle agglomeration and sedimentation in the melt and solidification during the stir casting process subsequently. Inhomogeneity in reinforcement distribution can also be a problem as a result of the interaction between the suspended ceramic particles and moving solid-liquid interface during solidification. Generally, it is possible to incorporate up to 30wt% ceramic particles in the size of 5-100 μm in a variety of molten aluminum alloys. The melt-ceramic particle slurry may be transferred directly to a shaped mould prior to complete solidification, or it may be allowed to solidify in billet or rod shape so that it can be reheated to the slurry form for further processing by using the die-casting or investment-casting technique. The process is not suitable for the incorporation of sub micron-size ceramic particles or whiskers. Another variant of the stir-casting process is compo-casting. Here, ceramic particles are incorporated into the alloy in the semisolid state [7]. Bronze-alumina composite was developed using the stir-casting method by Sornakumar and Senthilkumar [8].

The attractiveness of die casting is to make near net shape parts with tight tolerances requiring little or no machining. The most applied process of different die-casting processes is high-pressure die casting (HPDC) with high rates of production. The automotive industry uses an extensive range of aluminum HPDC parts, including transmission housings, cylinder heads, inlet manifolds, and engine sumps. This trend is increasing as the replacement of steel parts as lighter aluminum HPDC parts grows [9]. HPDC is a popular and cost-effective method for the mass production of metal components, in which physical dimensions must be accurately replicated, and the surface finish is very important. Approximately, half of all castings made worldwide from aluminum alloys are manufactured in this way, and these are used for a wide range of automotive parts and other consumer goods [10].

The demand of low tolerances and better quality products has forced the manufacturing industry to continuously progress in quality control and machining technologies. One of the fundamental metal cutting processes is end milling [11]. Milling is a machining process to generate machined surfaces by removing a predetermined amount of material progressively from the work piece. The milling process employs relative motion between the work piece and the rotating cutting tool to generate required surfaces. In some applications, the work piece is stationary, and the cutting tool moves, while in others, the cutting tool and the work piece move in relation to each other and to the machine. An important characteristic feature of the milling process is that each tooth of the cutting tool takes a portion of the stock in the form of small and individual chips [12]. The wide applications of computer numerical control (CNC) machine tools have significantly improved the machining efficiency and the product quality in the metal cutting industry. The milling operation is one of the most useful and yet complex machining processes. In particular, the end-milling process is commonly used for machining parts with complex surface geometries leading to variations in the depth and width of cut and, hence, the spindle load. The machining parameters, such as the feed rate and the spindle speed, are mostly selected off-line by experienced CNC programmers prior to the machining process. To avoid the potential machine overload and tool failure, CNC programmers tend to use conservative feed rate and spindle speed [13]. After the production of MMCs, they are to be machined to get net shape and better surface finish. The most widely used machining operations are turning and milling. A very limited study is available on the development of aluminum-based MMCs by a combination of the vortex method and the die-casting technique, and the milling of aluminum-based MMCs.

2. Experimental procedure

2.1. Development of aluminum alloy-silicon carbide composites by the vortex method and the pressure die-casting technique

The LM24 aluminum alloy as the matrix material and silicon carbide (SiC) with the average particle size of 16 μm as the reinforcement material were die cast. The aluminum alloy was melted in a graphite crucible at a controlled temperature protected with an argon gas atmosphere. The graphite stirrer was introduced into the crucible to perform the mixing process when the molten temperature reached 850°C. The stirring was carried out for 45 min at the rate of 200 r/min. Silicon carbide particles were preheated at 200°C and were introduced into the vortex created in the molten alloy. The internal surface of the die was applied with a water-based die coat before each casting, which acted as a lubricant between the molten metal and die and also prevented the adhesion between the die-cast metal and die. A 420-t cold chamber hydraulic-type die-casting machine was used to make castings. The pouring temperature of the molten mixture was 850°C, and molten metal was injected into the runner of the closed die up to the runner gate at the initial velocity of 0.23 m/s. Then the ram movement was given at 1.8 m/s for injection and simultaneously shot in the die. The molten mixture was poured into the plunger sleeve and forced into the die cavity with a pressure of 100 MPa. The shot accumulation force of 420 t was applied at the end of injection. The die was simultaneously cooled with demineralised water. Then the MMC was ejected from the die at 150°C, and it was allowed to cool in air. Thus, the different compositions of LM24 aluminum alloy-silicon carbide MMCs were developed by the new combination of the vortex method and the die-casting technique. The hardness of the specimen was determined using a Brinell hardness testing machine. The density of the specimen was determined using Archimedes' principles.

2.2. Milling experiments

The machining experiments of the aluminum alloy-silicon carbide composites were conducted in a milling machine by a milling process. End mills of M2 grade high speed steel (HSS) of 5 mm in diameter were used in the present work. The present market share of HSS milling cutters is 30%. The advantages of HSS compared with tungsten carbide and other harder cutting-tool materials are the higher toughness and the lower cost. Due to their high toughness and resistance to fracture, high speed steels are suitable especially for the high positive rake angle tools and for the machine tools with low stiffness. The milling tests were carried out at the speeds of 10, 20, and 30 m/min and the feed rates of 0.1, 0.3, and 0.5 m/min with a constant cut depth of 0.5 mm. The specification of the end mills used is ISO 1641: Part 1: 1978. The coolant used was kerosene. The surface roughness of the machined surface was observed using a stylus-type surface roughness tester. The wear of the end mills was studied using a toolmakers microscope.

3. Results and discussion

The microstructure of the plain LM24 aluminum alloy is presented in Fig. 1. The microstructure shows the interdendritic particles of eutectic silicon and $CuAl_2$ in a matrix of aluminum solid solution. The X-ray diffraction pattern of the plain LM24 aluminum alloy is given in Fig. 2. The hardness and density of plain LM24 alloy and the aluminum alloy-silicon carbide composites are presented in Table 1. The hardness of the aluminum alloy-silicon carbide composite increases with the increase in the amount of silicon carbide reinforcement and is higher than that of the plain LM24 aluminum alloy due to particulate hardening and the higher hardness of silicon carbide. The density of the aluminum alloy-silicon carbide composite increases with the increase in the amount of silicon carbide reinforcement and is higher than that of the plain LM24 aluminum alloy due to the higher density of silicon carbide.

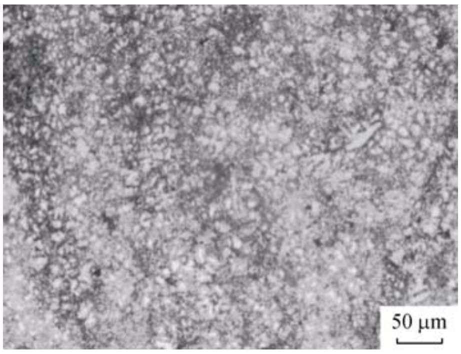

Fig. 1. Microstructure of the plain LM24 aluminum alloy.

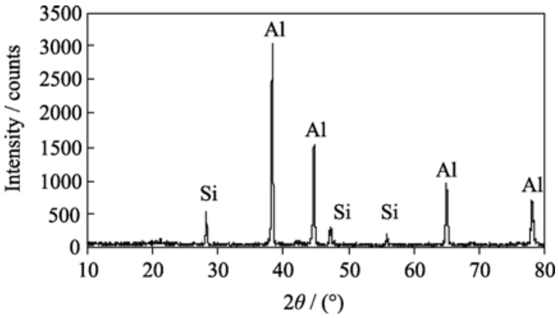

Fig. 2. XRD pattern of the plain LM24 aluminum alloy.

Table 1. Hardness and density of plain LM24 alloy and the aluminum alloy-silicon carbide composites

Material	Hardness, BHN	Density / ($g \cdot cm^{-3}$)
LM24	96	2.790
LM24+1wt% SiC	104	2.794
LM24+3wt% SiC	107	2.803
LM24+5wt% SiC	110	2.812

3.1. Effects of speed and feed on surface roughness

The ideal tool in machining can replicate its nose well on the work surface. The surface quality, which largely depends on the stability of the cutting nose and the dimensional accuracy, is controlled by the flank wear of tools [14]. The surface precision is usually based on two criteria, dimensional accuracy and surface roughness. Surface roughness is the measure of finer surface irregularities in the surface texture. Surface roughness generally plays an important role in wear resistance, ductility, tensile, and fatigue strength for machined parts and cannot be neglected in design. In end milling, surface roughness depends on the rotational speed of the end-mill cutter, feed rate, depth of cut, mechanical properties of the work piece being machined, and the amount and type of lubricant/coolant at the point of cutting. The effects of speed and feed on the surface roughness parameter (R_a) are presented in Figs. 3-5. At the cutting speeds of 10-30 m/min and the feed rates of 0.1-0.5 m/min, the surface roughness decreases with the increase of speed and feed.

The decrease in surface roughness with the increase in cutting speed is attributed to the increasing machining and burnishing effect between the end-mill tool and the milled surface. The increase in surface roughness with the increase in feed is attributed to the decreasing machining and burnishing effect, which is due to the decrease in the contact time between the end-mill tool and the work piece. The usage of coolant prevents the formation of the built-up edge of the end-mill tool and results in an excellent surface finish that is comparable to finish machining operations such as grinding or lapping.

The milled surface of the aluminum alloy-1wt% silicon carbide composite work piece at the cutting speed of 10 m/min and the feed of 0.1 m/min is presented in Fig. 6.

The milled surface of the aluminum alloy-1wt% silicon carbide composite work piece at the cutting speed of 10 m/min and the feed of 0.3 m/min is shown in Fig. 7.

The milled surface of the aluminum alloy-5wt% silicon carbide composite work piece at the cutting speed of 20 m/min and the feed of 0.1 m/min is presented in Fig. 8.

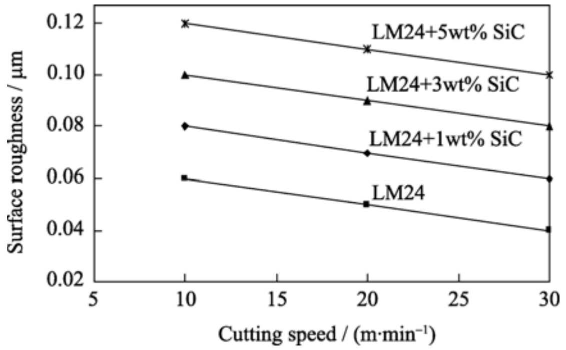

Fig. 3. Surface roughness (R_a) *vs.* cutting speed at a feed rate of 0.1 m/min.

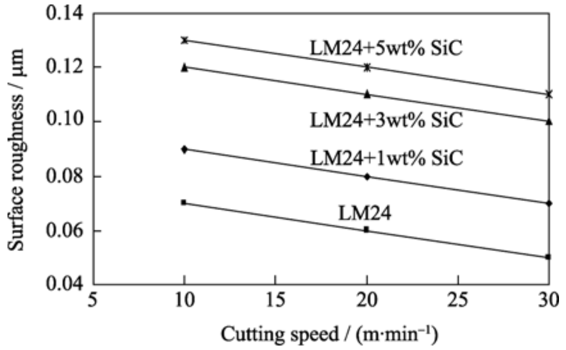

Fig. 4. Surface roughness (R_a) *vs.* cutting speed at a feed rate of 0.3 m/min.

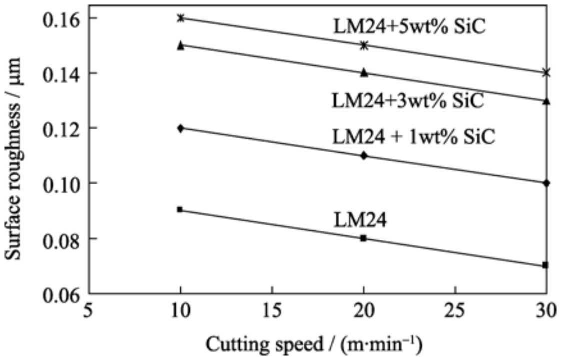

Fig. 5. Surface roughness (R_a) *vs.* cutting speed at a feed rate of 0.5 m/min.

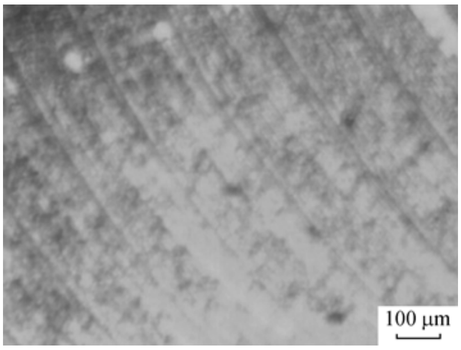

Fig. 6. Milled surface of the aluminum alloy-1wt% silicon carbide composite work piece.

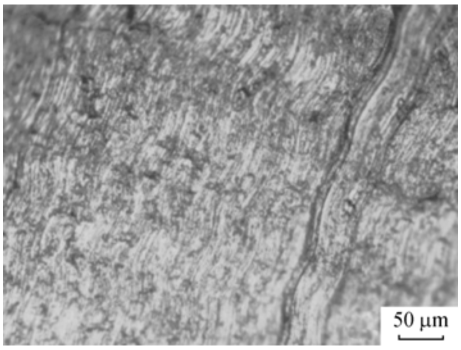

Fig. 7. Milled surface of the aluminum alloy-1wt% silicon carbide composite work piece.

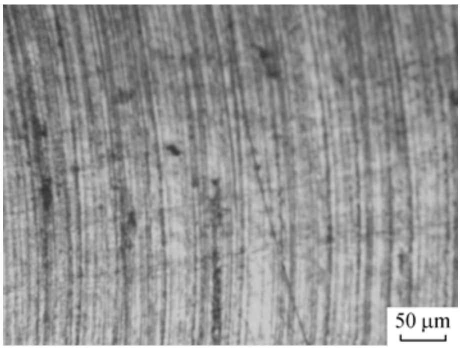

Fig. 8. Milled surface of the aluminum alloy-5wt% silicon carbide composite work piece.

3.2. Effect of silicon carbide particle reinforcement on surface roughness

The effect of silicon carbide particle reinforcement on surface roughness is presented in Figs. 3-5. During milling of an MMC, defects such as voids and cavities are formed on the surface due to tool-particle interactions, resulting in the pull-out/fracture and debonding of particles. The reinforcement particles in an MMC increase the tool-particle interactions and create the greater damage on the machined surface, which cause the inferior surface finish of the aluminum alloy-silicon carbide composites. The excellent surface finish of both the aluminum alloy-silicon carbide composite and the plain aluminum alloy is of the high quality finish machining process. The surface roughness increases with the SiC particle reinforcement.

3.3. Effects of cutting speed, feed, and particle reinforcement on end-mill wear

Flank wear is the most important tool wear occurring in machining operations. Flank wear is primarily attributed to the rubbing of the tool along the mechanical surfaces, caused by abrasive, diffusive, and adhesive wear mechanisms [15]. Among the different forms of tool wear, flank wear is the significant measure, because it affects the dimensional tolerance of work pieces. The dimensional accuracy of the work piece is controlled by the flank wear of tools [16]. Flank wear occurs on the relief face of the cutting tool which is generally attributed to the rubbing of the tool along the machined surface and, thus, affects the tool material properties as well as the work piece surface due to high temperatures. Abrasion, diffusion, and adhesion are the main wear mechanisms in flank wear [17].

The optical microscopy studies are conducted on the HSS end-mill tool qualitatively. It is observed that the harder SiC in the MMC abrades away the flank of the HSS end-mill tool with each cut. The flank wear increases with speed, feed, and SiC particle reinforcement. The rise of temperature adversely affects the wear resistance and hardness of the cutting tool. Increased heat causes dimensional changes in the work piece part being machined, making the control of dimensional accuracy difficultly. The mean temperature (T_m) in machining is proportional to the cutting speed (V) and feed (f) as

$$T_\mathrm{m} \propto V^a f^b,$$

where a and b are the constants which depend on the tool and work piece materials, respectively [18].

The end-mill tool wear is higher on machining the aluminum alloy-silicon carbide MMC than on machining the plain aluminum alloy, which is because the silicon carbide in the MMC is harder than the HSS end-mill tool. The general mechanisms of tool wear are abrasion, diffusion, oxidation, fatigue, and adhesion. Most of these mechanisms are accelerated at higher cutting speeds and the resulting higher cutting temperatures. The end-mill tool flank wear increases with the increase in the amount of particle reinforcement due to the higher abrasion of SiC particles.

4. Conclusion

Aluminum alloy-silicon carbide composites were developed using the vortex method and the pressure die-casting technique. Machining studies were conducted on the aluminum alloy-silicon carbide (SiC) composite work piece using high speed steel end-mill tools. The surface finish is better at higher speeds and lower feeds. The surface finish of the plain aluminum alloy is better than that of the aluminum alloy-silicon carbide composites. The surface finish values are very good, which allow the elimination of the costly final finishing machining operations such as grinding or lapping. The flank wear increases with the increase of speed and feed. The end-mill tool wear is higher on machining the aluminum alloy-silicon carbide MMC than on machining the plain aluminum alloy.

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