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ORIGINAL ARTICLE

Effects of aging heat treatment on machinability of alumina short fiber reinforced LM 13 aluminum alloy

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Abstract In this paper, the surface integrity (*R*a and *R*max) has been investigated with various aging heat treatment and machinability parameters in an aluminum-silicon based (LM–13) MMCs, produced by infiltration method. The composites have been subjected to heat treatment at different temperatures and times which was discussed in detail in an earlier publication (Altunpak and Akbulut, Teknoloji 8(4):331–339, 2005). In the milling of alumina short fiber reinforced LM–13 aluminum alloys, the surface integrity decreased when feed rate increased. It was found that increasing amount of fiber reinforcement and solutionizing temperature has a significant effect on the surface integrity and sub-surface damage of the materials. Increasing the solutionizing temperature and fiber reinforcement produced higher *R*a and *R*max values. Microhardness measurement indicated that the sub-surface damage and the hardness increased by increasing the feed rate and fiber content.

Keywords Machinability · MMCs · Saffil fiber · Aging · Surface roughness

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1 Introduction

Metal matrix composite (MMCs) are being used as replacement materials in various engineering applications. Although MMCs are often fabricated with near-net shape processing techniques, a number of secondary machining operations are always necessary [1]. For example Toyota has developed a 5% Al_2O_3 short fiber reinforced Al alloy diesel engine piston [2]. This piston needs secondary machining operations. But these composite materials differ from the conventional materials by the presence of harder and isolated reinforcements in the path of the tool during machining. This characteristic leads to difficulties in machining of these composites, primarily rapid wear of the cutting tools [3]. Several researchers have indicated that polycrystalline diamond (PCD) tools are the only tool material that is capable of providing a useful tool life during machining of MMCs. PCD is harder than Al_2O_3 and SiC and does not have a chemical tendency to react with the work piece material [1, 4, 5]. It is well known that machining causes various geometrical and metallurgical defects in the surface region. Mechanical properties such as creep and fatigue are greatly influenced by the condition of the surface [1]. As is well known, milling process has become one of the most promising advanced manufacturing technologies in the last 20 years [6]. But a very limited study is available in milling of these materials. Hence, it is important to understand the mechanism of machining. The good surface finish is produced when the particles are cut cleanly instead of being pulled from the matrix material. Many researchers reported that the surface roughness values decreases as the cutting speed increases [1, 4]. Therefore, maximum cutting speed was chosen in this study. To the best of the authors' knowledge, no research has yet been carried out to determine the effect of the cutting parameters on work piece surface integrity and sub-surface damage during the machining of Al/SiC particulate metal matrix composite [1, 7]. Barnes et al. reported that when drilling Al-SiC composites using PCD inserts, the heat treatment conditions of the matrix exerts a significant influence of machinability [8]. Most of these authors generally have used SiC reinforced MMCs for their investigation and very little work is reported on machining of alumina short fiber reinforced MMCs. Thus, it is necessary to study the effect of machining parameters and the heat treatments on the surface roughness of the MMCs.

In this paper, the effect of different aging heat treatment and feed rate on the surface roughness and sub-surface damage during the milling of alumina short fiber reinforced LM 13 Al alloy is investigated.

1.1 Experimental procedure

δ-Al_2O_3 (Saffil) reinforced Al-12Si (wt%) LM 13 aluminum composites formed by pressure infiltration methods were used. Different heat treatment parameters were studied to clarify the effect of the reinforcement on the matrix phase precipitation in these composites. In this study, test samples with dimensions of about 40×15×10 mm were produced in the same conditions. And then, a group of the composites were subjected to standard T6 heat treatment. The prior tests have not produced assessable differences with changing precipitation temperatures and times. Consequently, the composites were solution heat treated at 515°C, 535°C, and 555°C and subsequently subjected to aging heat treatment. Measurement of microhardness, bending strength with DSC, XRD, optical and scanning electron microscopy (SEM) studies show that the optimum heat treatment for unreinforced and Saffil fiber reinforced LM 13 alloys are very different. Since the aging kinetics is altering by introducing ceramic phases to the metal matrices the optimum aging conditions were determined for the composites that exhibited different amount of ceramic phases. Table 1 summarizes the hardness values obtained in different aging parameters [9]. The values of the microhardness measurements of the samples decreased at 555°C temperature. And grain boundary melting observed at this solution temperature. Maximum microhardness values of the composites were obtained at 535°C temperature in all conditions. The details of the experimental work are presented in an earlier publication [10]. Therefore, only the study of surface integrity and sub-surface damage will be presented here.

Machinability tests were performed with Johnford CNC apparatus by face milling machining technique. The machining experiments were carried out by using PCD inserts. The materials were machined with 1.0 mm depth of cut, cutting speed of 785 m min^{-1} (2,500 rpm), at four different feed rates; 50, 78, 126, and 200 mm min^{-1}. The cutting parameters were chosen to decrease surface roughness and minimize tool wear. Maximum cutting speed (2,500 rpm) was used. Higher cutting speeds could not be reached because of maximum rpm available. The surface roughness values of the machined samples were measured by Mahr surface profilometer. Table 2 summarizes the details of the experimental details.

Machinability tests were performed on the transverse direction to the fibers on the composite materials. After machining, some of machined unreinforced alloy and composites were investigated by using JEOL JSM 5600 scanning electron microscopy. The surface integrity and sub-surface damage has been analyzed on the samples that subjected to various aging heat treatment parameters depending on the feed rate and fiber volume content. The specimens were polished using a rotary polishing table with soft pads that were impregnated with fine diamond paste (1 µm). The microhardness of cross-sections per 10 µm (perpendicular to the machining direction) was analyzed using a Vicker's indentor at a load of 50 g and time of 30 s. Three observations (on average) were reported in each case.

2 Results and discussion

Figures 1 and 2 show surface roughness (*R*a, *R*max) of the composites as a function of different feed rates (cutting

Table 1 The hardness values of the composites after aging heat treatment conditions

Material	Solutionizing treatment (8 h)	Hardness (HV) after solutionizing treatment	Hardness (HV) after aging treatment (20 h at 161°C)
LM 13+10% Saffil	at 515°C	73	118
LM 13+10% Saffil	at 535°C	75	130
LM 13+10% Saffil	at 555°C	75	116
LM 13+20% Saffil	at 515°C	83	124
LM 13+20% Saffil	at 535°C	84	131
LM 13+20% Saffil	at 555°C	81	118
LM 13+30% Saffil	at 515°C	90	118
LM 13+30% Saffil	at 535°C	91	120
LM 13+30% Saffil	at 555°C	87	110

Table 2 Experimental specifications

Specifications	
Machine	Johnford milling
Work material	0, 10, 20 and 30 volume of δ-Al2O3 (average diameter and length=3 µm and 100–180 µm, Saffil fiber) reinforced Al-12Si (wt%) composites
Workpiece size (mm)	40×15×10
Tool materials	Polycrystalline diamond inserts (PCD)
The spindle speed (rev/min)	2500
Milling speed (m min^{-1})	785
Feed rate (mm min^{-1})	50, 78, 126, 200
Feed per tooth (mm/z)	0,0033, 0,0052, 0,0084, 0,0133
Depth of cut (mm)	1

speed=785 m min^{-1}, depth of cut=1 mm). With increasing feed rate when cutting speed and depth of cut were kept constant, surface roughness was determined. The surface roughness of composite materials were significantly decreased by increasing the feed rate. The best surface in the composites were obtained at 0.08 mm rev^{-1} feed rate. Also, no significant tool wear was observed in this study. This is attributed to a reduction in contact between the tool and abrading Al_2O_3 fibers at higher feed rates. Similar observations were reported by researchers. El-Gallab and Sklad reported that tool wear and surface roughness decreased by increasing feed rate when machining particulate reinforced MMC with [1, 11]. Tomac and Tonnessen attributed the increase in tool life at higher feed rates to the thermal softening of the composites [12]. High speed, low feed rate and low depth of cut are recommended for achieving better surface finish during turning of Al/SiC-MMC using rhombic uncoated carbide tool [13].

SEM investigations have revealed that cracks, scratches, and many significant plastic deformations have been observed over the machined surface of the composites.

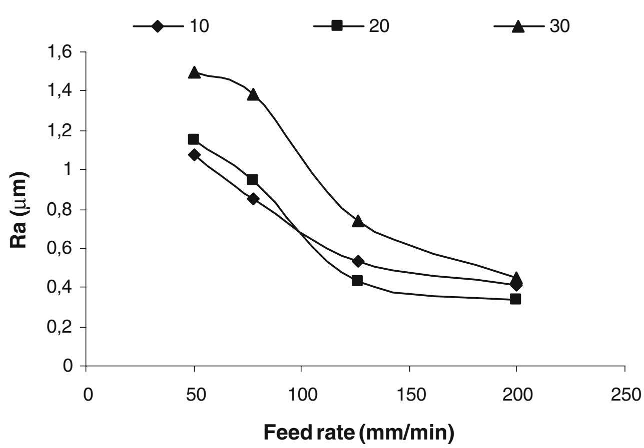

Fig. 1 Effect of feed rate on the surface roughness (R_a) of the machined workpiece of LM 13 composites solution treated at 535°C and subjected to aging treatment at 161°C for 20 h

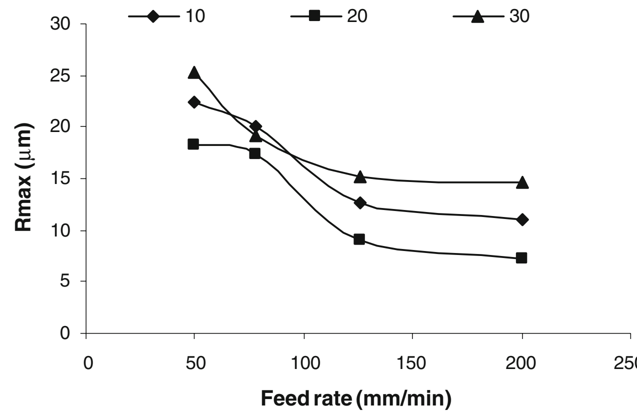

Fig. 2 Effect of feed rate on the surface roughness R_{max} (Peak to Valley) of the machined workpiece of LM 13 composites solution treated at 535°C and subjected to aging treatment at 161°C for 20 h

Figure 3 shows the pulled-out and fractured Al_2O_3 fibers on the machined surfaces of composites (the fiber marked by white single arrow). Some discontinuous grooves and scratches on the machined surface of composites could be attributed to the fractured fibers (Fig. 3, the regions marked by black single arrow). The presence of some big gaps on the surface of composites is also attributed to non-infiltrated areas on composites (Fig. 4, the regions marked by single arrow).

Increasing the amount of fiber reinforcement resulted in an increasing surface roughness of the matrix alloy. This is expected because of the increasing fiber content resulted in deeper and wider grooves. In this case especially an increase in the *R*max values were obtained. El-Gallab and Sklad [1] reported that *R*max was chosen rather than *R*a,

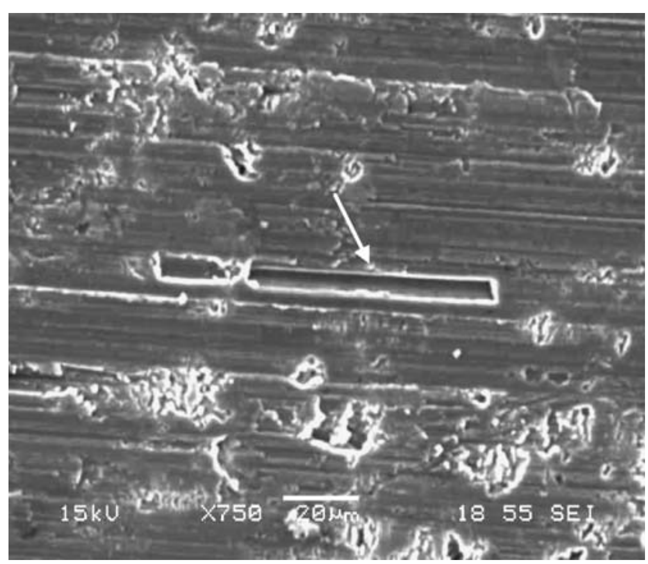

Fig. 3 SEM images of the machined surfaces of 10 vol% fiber reinforced matrix alloy (solution treated at 535°C and subjected to aging treatment, cutting speed=785 m min^{-1}, feed rate=200 mm min^{-1}, depth of cut=1 mm)

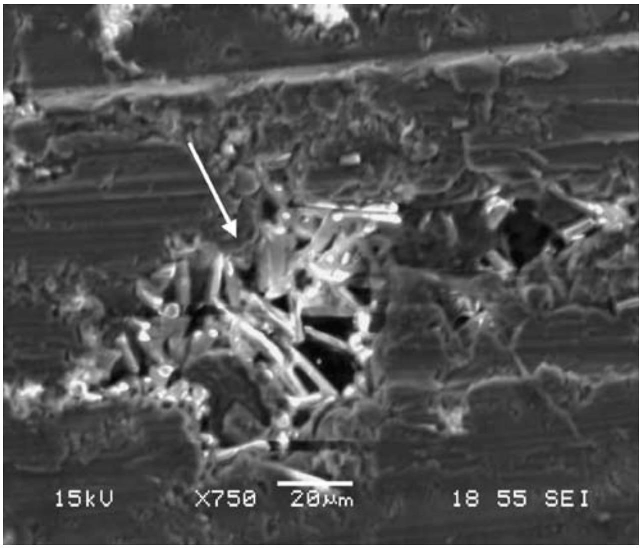

Fig. 4 SEM images of the machined surface of 30 vol% fiber reinforced matrix alloy that solution treated at 535°C and subjected to aging treatment (cutting speed=785 m min^{-1}, feed rate=200 mm min^{-1}, depth of cut=1 mm)

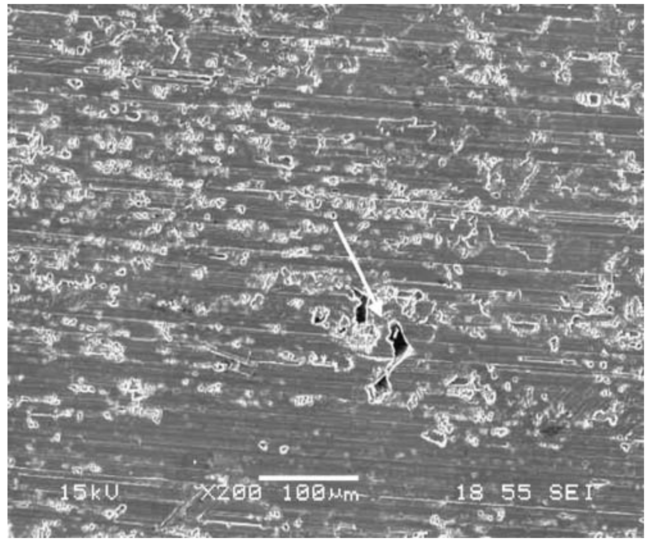

Fig. 6 SEM images of the machined surface of 10 vol% fiber reinforced matrix alloy that solution treated at 535°C and subjected to aging treatment (cutting speed=785 m min^{-1}, feed rate=200 mm min^{-1}, depth of cut=1 mm)

because the latter could give misleading results on surfaces that include fine grooves or cracks. The grooves that are formed could be attributed to SiC particles being pulled out of the composite material.

In Fig. 5, surface roughness is examined in the terms of increase in solution temperature. As a results of examination, increasing the solution temperature produced higher *R*a and *R*max values. It is attributed to the grain boundary melting and subsequent shrinkage (Fig. 6). According to a feed rate of 0.02 mm/rev, more plastic deformations and deep grooves were formed in SEM image of the machined surface at a feed rate of 0.08 mm/rev (Fig. 7, the regions marked by single arrow). In the previous study [10], although solutionizing temperatures of 555°C showed best solubility of the matrix alloy, the hardness values were obtained to be worse at this temperature. Grain boundary melting was observed at solution temperature 535°C and 555°C. Table 1 summarized some results [10, 9]. In this study, the surface roughness at 555°C deteriorates in all experiment. Tosun and Muratoğlu [12] reported that the over-aged conditions are not recommended for all type of drill and drilling parameters. Another study [14] has indicated that the roughness of the cut surface treated with T6 heat treatment (538°C for 8 h) is the best in machining of 365Al/0–20 wt% SiC composites.

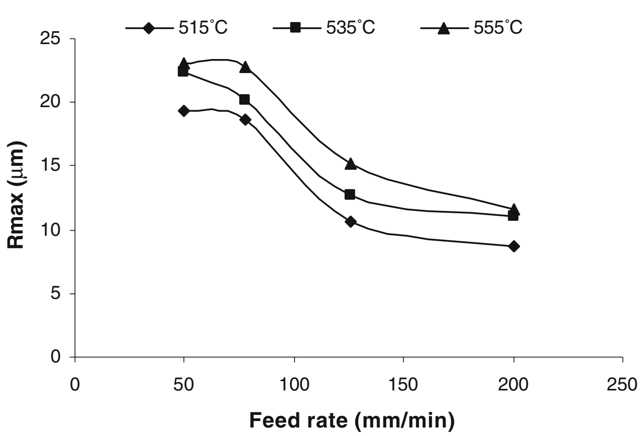

Fig. 5 Effect of feed rate on the surface roughness R_{max} (Peak to Valley) the machined surface of 10 vol% fiber reinforced matrix alloy that a) solution treated at 515°C b) solution treated at 535°C c) solution treated at 555°C and subjected to aging treatment (cutting speed=785 m min^{-1}, depth of cut=1 mm)

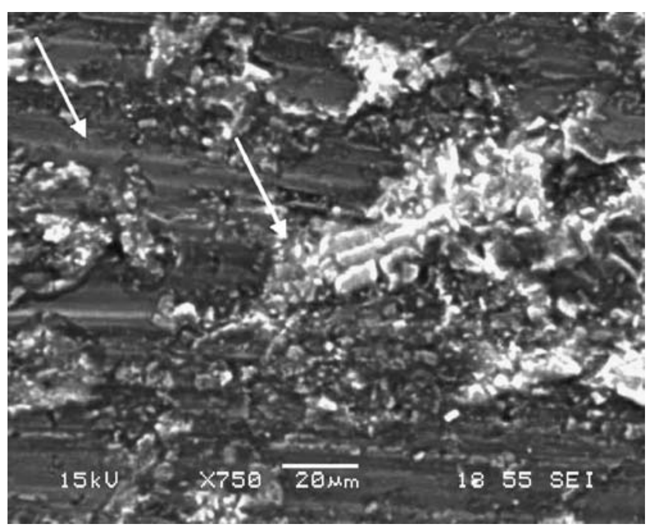

Fig. 7 SEM images of the machined surfaces of 20 vol% fiber reinforced matrix alloy (solution treated at 535°C and subjected to aging treatment, feed rate=200 mm min^{-1})

Increasing the feed rate which leads to plastic deformations resulted in an increasing sub-surface hardness of the machined surface. It can be seen from Fig. 8a–d that microhardness measurements in the machined cross-sections indicate that about 10–15 μm away from the cutting surface, the plastic deformation and the hardness significantly were increased by increasing the feed rate and fiber content. But in general, some microhardness values of 30 vol% fiber reinforced matrix alloy were lower than that of 20 vol% fiber reinforced matrix alloy. This attributed to the poor bonding resulted from porosity between matrix and fibers because of insufficient infiltration (Fig 4). Moving further away about 40–50 μm from the machined surface, the hardness starts to decrease. El-Gallab and Sklad attributed this to the reduction in the surface roughness with increase in the feed rate and the cutting speed. Increasing of the cutting speed, feed rate, and/or depth of cut were also resulted to increase in the depth of the affected layer [1, 11].

3 Conclusions

Milling tests were performed on alumina short fiber reinforced LM–13 aluminum alloy using PCD inserts. The influence solutionizing temperature and feed rate on surface roughness and sub-surface damage investigated. From the present work the following conclusions can be drawn:

1. Increasing the solutionizing temperature produced higher *R*a and *R*max values. Of the surface roughness values were obtained as to be worse at 555°C solutionizing temperatures. In milling of the composites, surface quality improved when feed rate increased.
2. In general, microhardness measurements of the machined cross-sections of the samples indicated that about 10–15 μm away from the cutting surface the plastic deformation and the hardness significantly increased by increasing the feed rate and fiber content.

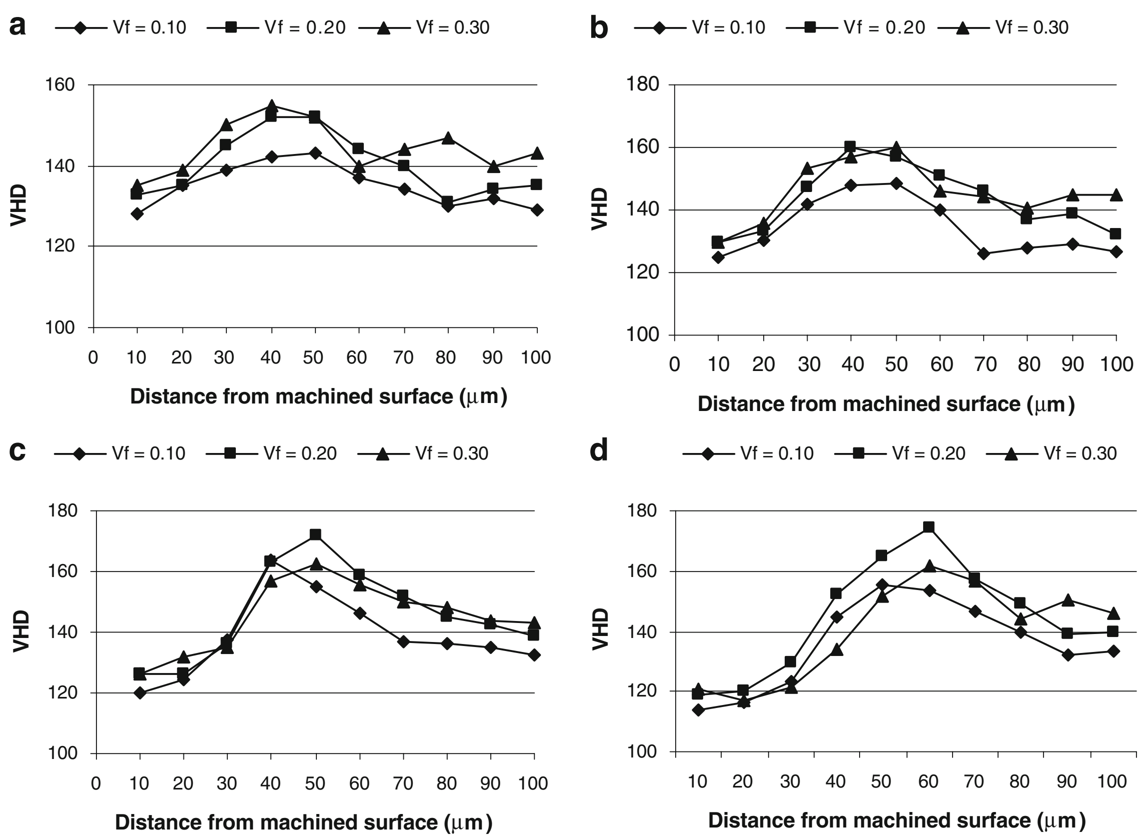

Fig. 8 Variation of microhardness of cross-section of machined surface **a** feed rate=50 mm min^{-1} **b** feed rate=78 mm min^{-1}, **c** feed rate=126 mm min^{-1}, **d** feed rate=200 mm min^{-1} (solution treated at 535°C and subjected to aging treatment)

3. In milling of the short fiber reinforced MMC, *R*max should chose rather than *R*a. Because *R*a could give misleading results.
4. The research findings can provide a suitable range of feed rate and useful solutionizing temperature in production of alumina short fiber reinforced aluminum composite applications such as piston, connecting rod, bicycle parts.

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