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ROLE OF Si ON MACHINED SURFACES OF Al-BASED AUTOMOTIVE ALLOYS UNDER VARYING MACHINING PARAMETERS

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Abstract: A morphological change due to Si contend into Al-based automotive alloys has been conducted on the characterization of machined surfaces in terms of roughness, temperature, chips formation as well as microstructure evaluation under different machining conditions. For this experiment, a shaper machine with HSS single point V-shaped cutting tool is used at different cutting speeds and depths of cut. The experimental results show that the surface roughness of the alloys decreases with the cutting speed and depth of cut but it is more prominent in the case of the cutting speed. This is because of a high cutting speed, which is more associated with the higher temperature and softening the work material leading to better surface finish. Higher Si added alloys also exhibit a better surface finish because the sample content is different fine and hard intermetallic due to ageing treatment, which also makes the alloys more brittle. For brittle and higher hardness, it produces a higher temperature during machining. During machining, relatively curly and short chips are formed by the high Si added alloy because of its low elongation properties. The fracture surfaces of higher Si added alloy display more crack propagation obtained by plate-like Si rich intermetallic.

Keywords: Al-Si alloys, roughness, temperature, chips, microstructure

1. INTRODUCTION

Al-Si-Cu-Mg alloys have widespread use in many industries such as automotive, transport, aviation and aerospace industries [1, 2]. They are well suited for manufacturing light-weight, highly loaded automotive components like cylinder blocks, cylinder heads, pistons and valve lifters. This is due to the fact that they have a high strength to weight ratio [3, 4].

While casting this type of Al-Si automotive alloys, elements such as Cu and Mg are normally found in alloys as minor elements. Moreover, Ni, Cr and Zn are often used as minor elements along with Cu and Mg, which can further improve the material properties [5-8]. In addition to that, trace elements such as Zr, Ti, Ce, Sc etc. may be added to the alloy to participate in the grain refinement process. An addition of these elements also contributes to an improvement of the thermal stability of the alloys [9, 10]. Cu and Mg not only enhance material strength but they also participate in the age hardening process of the Al-Si alloy. The reason for such a response may be attributed to the formation of Al_2Cu and Mg_2Si intermetallics [11]. The most important element for these types of alloys is Si. An addition of Si increases many properties such as strength, wear, corrosion resistance and castability for these alloys. Si also participates in the age hardening behaviour of these Al-Si automotive alloys. Furthermore, the strength of the alloy seems to improve with the increasing amount of Si content for a certain level. Some research has been conducted to investigate the level of the alloying elements of Cu and Mg in Al-Si alloys to achieve optimum properties. It is reported that about 2.0wt% of Cu attains the most favourable properties of the alloys. In the case of Mg, this is between 0.5 and 1.0wt%. On the other hand, the Si content to cast Al-Si alloys is in the range from 5 to 23 wt%. When

12-13wt% Si is present in the alloys, it is known as an eutectic alloy. Below and over this percentage, the terms are used of hypoeutectic and hypereutectic alloys respectively [5].

Since the Al-Si-Mg-Cu alloys are used in the manufacturing of different parts of automobile, aerospace sectors, these alloys have to be machined for imparting proper shapes to them. Machinability depends on many considerable parameters such as the feed, speed, cutting force, depth of cut, microstructure, strength etc. of the materials. It is found that the tool traverse speed is the most dominant parameter followed by the axial force and the reinforcement ratio [12]. Machinability also depends from the change of microstructures due to an addition of different elements. The amount of these alloying elements also plays an important role in the machinability of the alloys [13]. Heat generation and chips formation during machining could have effects on the surface quality of the materials. Heat generated during machining could result in the softening of the material and, thus, lowered cutting forces. Again, shorter chips are always expected because continuous chips sometimes stick with the tool, cause damage to the surface quality and unexpected injury may occur [14].

It is a well stablished fact that variation of silicon in Al-Si automotive alloys leads to a greater degree of refinement of the eutectic silicon followed by primary silicon, which changes the morphology of the matrix. The main concern of this study is the effect of the morphological change on the machinability in terms of surface quality, heat generation, chips formation as well as microstructural observations of Al-based automotive alloys.

2. EXPERIMENTAL PROCEDURE

Commercial purity aluminium (Al99.750), copper (Cu99.997), magnesium (Mg99.80) and Al-50 wt% Si master alloy ingots were used for preparing the Al-Si-Cu-Mg alloys with varying levels of Si. Where the amounts of Cu and Mg were maintained at a constant level. Other elements like Fe, Sn, Pb, Ni etc. were present in the alloys as trace impurities. The main constituents of the five alloys analysed with the use of a Shimadzu PDA 700 optical emission spectrometer were as follows:

– Al-0.2Si-2.2Cu-0.8Mg,
– Al-3.5Si-2.2Cu-0.8Mg,
– Al-6.1Si-2.1Cu-0.8Mg,
– Al-12.7Si-2.2Cu-0.8Mg,
– Al-17.9Si-2.2Cu-0.8Mg.

The experimental alloys were melted in a clay-graphite crucible using a natural gas-fired pit furnace. Borax as a degasser was also used during melting to prevent the oxidation of the alloys. Casting was done in a mild steel mould preheated at 250°C whose size was 20×200×300 in millimetres. The melting temperature was maintained at 780±15°C with the help of an electronic controller. Next, the homogenized melts under stirring at 700°C were poured in that preheated mould. The cast alloys were homogenized at 450°C for 12 hours and air cooled to relieve internal stresses. The homogenized samples were solutionied at 535°C for 2 hours followed by salt water quenching to obtain a super saturated single phase region. The solution treated alloys were aged at 200°C for four hours to achieve peak aged condition for the maximum strength [15, 16]. For this purpose, an Electric Muffle Furnace ranging 900±3.0ºC was used.

Machining operation was carried out with the help of a 3HP GEMCO heavy duty 16 inches capacity shaper machine on the samples aged sized 20x150x150mm. The HSS single point V-shaped cutting tool with an angle of 55º was used. For machining, the depth of cut considered was 0.5, 1.0, 2.0 and 4.0 mm and the stroke per minute was 11, 23, 48 and 70 to maintain the cutting speed of 3.6, 7.6, 15.9 and 23.2 m/min, respectively. The feed rate and the stroke length were kept constant throughout the experiment at 0.254 mm/stroke and 200.0 mm, respectively. The tool geometry with the machining conditions used in this study is presented in Table 1. After each cut, the average surface roughness (Center Line Average Roughness, R_a) of the surface machined was measured. Attempts were also made to measure the surface temperature of the sample with the help of infrared thermometer ranging -32ºC–520ºC during machining. The surface roughness of the surfaces machined was measured with a surface roughness-measuring instrument (Talysurf). All the data of surface roughness presented was calculated as the average of ten readings taken. The photographs of the chips machined for all the alloys were taken using a DSLR camera in an as-received condition. The micrographs of the different surfaces machined were taken with a USB microscope. The experimental set-up is shown in Fig. 1.

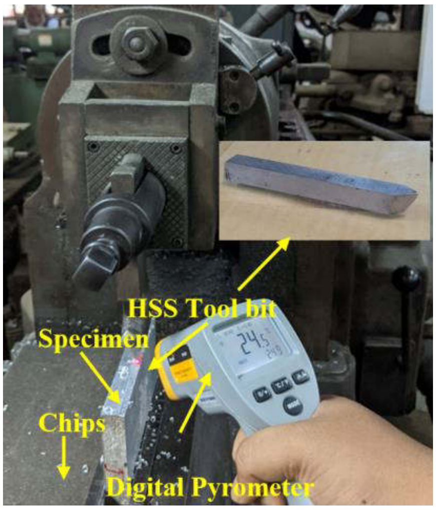

Fig. 1. Photograph of the machining setup for shaping the surface

Tab. 1. Tool geometry and machining condition

V-shaped tool, °	55
Back rake angle, °	5
Clearance angle, °	8
Tool nose radius, mm	0.8
Feed rate, mm/stroke	0.254
Depth of cut, mm	0.5, 1.0, 2.0 and 4.0
Cutting speed, m/min	3.6, 7.6, 15.9 and 23.2

3. RESULTS AND DISCUSSION

3.1. Surface roughness

Machining was performed with a shaper machine at different cutting speeds and depths of the cut on the experimental alloys. The results obtained from these experiments are plotted in the following graphs. Figures 2 to 5 show the variation of surface roughness with the cutting speed at different depths of the cut for the different Si added automotive experimental alloys. Based on the figures, it is evident that the roughness of the surface machined decreases with the cutting speed. In all the cases, higher Si added alloys demonstrated lower surface roughness. This may be attributed to the fact that higher cutting speeds produce higher temperatures because the material taking away is more aggressive. As a result, this softens the materials that improve the cutting process and consequently diminish surface roughness [17]. Moreover, when the cutting speed is low, a subsurface material fracture occurs, which contributes to increasing the surface roughness; by raising the cutting speed this effect disappears. Higher Si addition to the alloy makes the alloys brittle through the creation of different intermetallics. During machining, these alloys produce shorter chips as a result of minimum friction between the tool, chips as well as workpieces. Minimum friction improves the surface quality of the alloys as increased Si means shorter chips formation. Some variations are observed in the case of the 17.9Si added alloy. This is so because beyond the eutectic composition, the amount of blocky shape primary silicon increases in the alloy and, during machining, there may particle pull-out as a result of a higher surface roughness [2].

It is a well stabilised fact that surface roughness increases with an increase of the depth of the cut due to the thermal load and vibration on the machine tool. Furthermore, higher friction and tool wear lead to higher surface roughness. However, in this study, some variations are observed regarding the surface roughness because of higher temperature produced by the higher dept of the cut that has more influence on the surface finishing [18]. As discussed earlier, these types of alloys consist of different intermetallics, and intermetallics change their properties with the contact of heat. Microstructural change may occur through the formation of precipitates followed by precipitate and grain coarsening of the alloys [5].

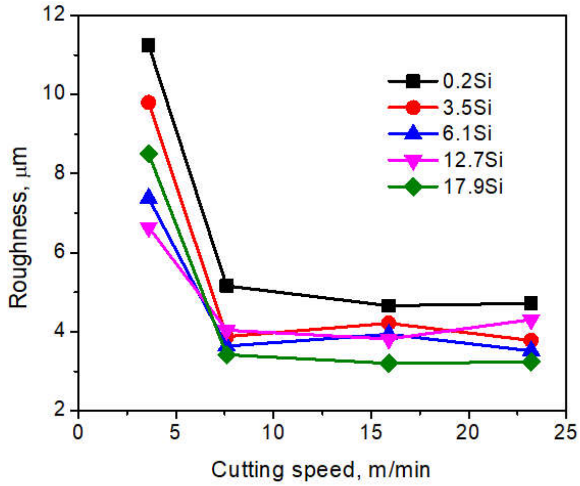

Fig. 2. Variation of surface roughness with cutting speed at 0.5mm depth of cut

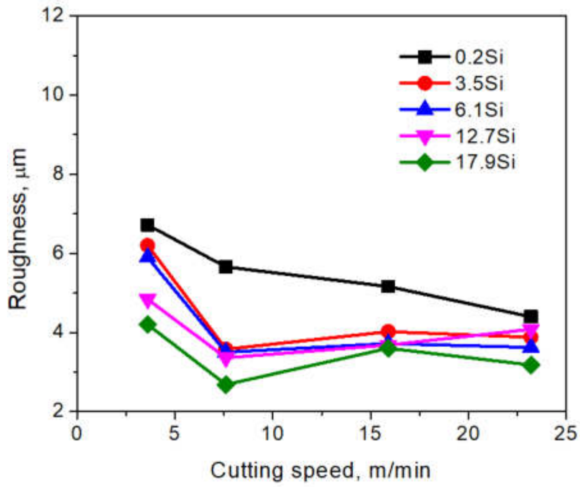

Fig. 3. Variation of surface roughness with cutting speed at 1.0mm depth of cut

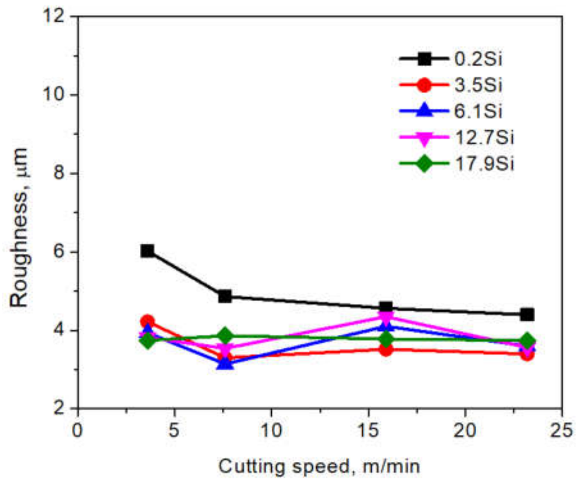

Fig. 4. Variation of surface roughness with cutting speed at 2.0 mm depth of cut

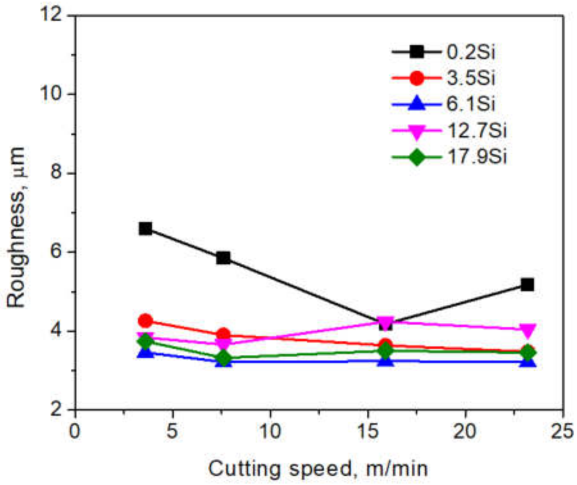

Fig. 5. Variation of surface roughness with cutting speed at 4.0 mm depth of cut

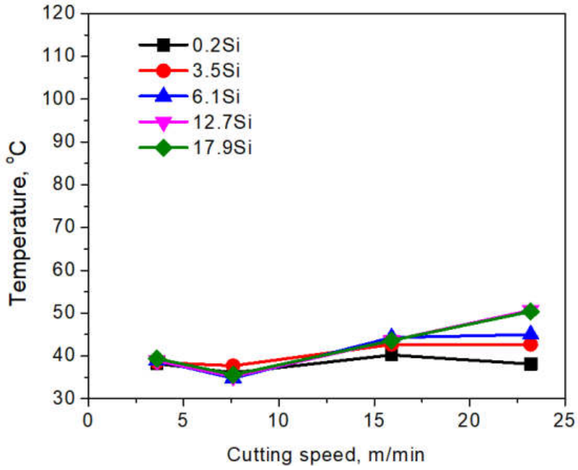

Fig. 6. Variation of surface temperature with cutting speed at 0.5 mm depth of cut

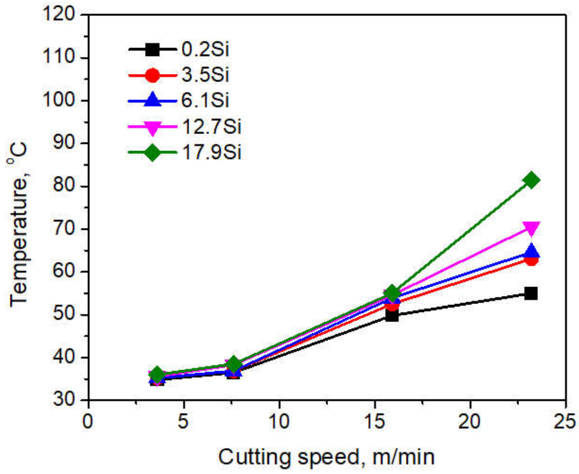

Fig. 7. Variation of surface temperature with cutting speed at 1.0 mm depth of cut

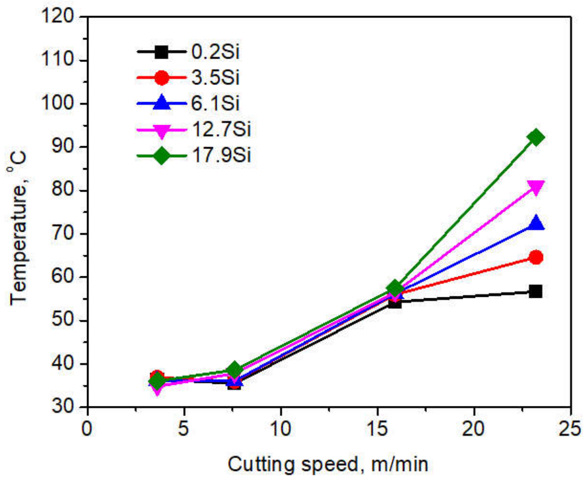

Fig. 8. Variation of surface temperature with cutting speed at 2.0 mm depth of cut

3.2. Surface temperature

Figures 6 to 9 display the variation of surface temperature of the experimental alloys as a function of the cutting speed during machining under different depths of cut. For all the depths of cut, the surface temperature increases with an increase of the cutting speed. The depth of the cut also has an impact on the increase of the temperature but the influence of the cutting speed is more prominent for all the alloys. The smallest rise in the temperature is identified for 0.2Si alloy for all the depths of cut, while an interesting phenomenon is observed for higher Si added alloys. By increasing the cutting speed, the deformation rate of the workpiece increases accordingly to produce a higher strain rate and to further strengthen the material, which is unfavourable for the side flow. At the same time, a higher cutting speed may cause a shorter time for heat dissipation inside the primary shear zone and generate more heat due to friction, which may cause the cutting temperature to increase. When the depth of the cut is increased to some extent, the chip section and friction of the chip-tool is increased, which leads to an increase in the temperature [19].

The content of Al-based automotive alloys includes different elements such as Si, Cu, Mg, Fe along with melting impurities. Due to ageing treatment, the content of the samples aged results in different types of intermettalics but the common Al_2Cu, Al_2CuMg, Mg_2Si and Al_5FeSi phases are responsible for a higher hardness. A higher amount of Si in the alloys produces higher Si-rich intermettalics as a result of the variation of higher hardness. As the higher Si added alloy achieved higher hardness, all the cases produce relatively higher temperatures [5]. In addition, as discussed earlier, beyond the eutectic composition, 17.9Si creates more primary Si in the matrix. It is very hard and brittle, so it produces higher temperatures during machining.

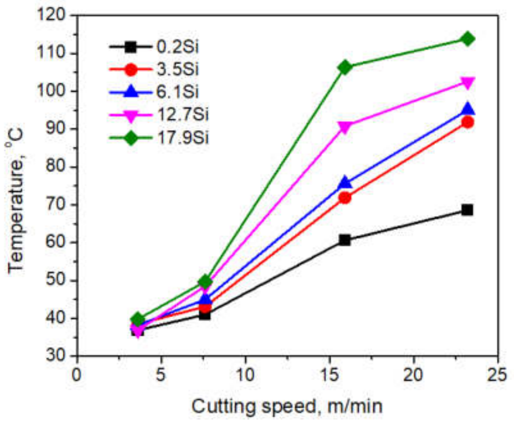

Fig. 9. Variation of surface temperature with cutting speed at 4.0 mm depth of cut

3.3. Photographs of the chips

Figure 10 shows the photographs of chips formed at different depths of cut and cutting speeds. When 0.2Si and 17.9Si added alloys are machined at 0.5 mm depth of cut and 3.6m/min cutting speed, relatively curly chips are observed in the case of 17.9Si added alloy (10. a1 and b1). This is because of lower elongation of the materials as Si decreases the ductility of the materials [7, 20]. When the 4.0 mm depth of cut is used, a similar nature is observed for both materials but the thickness is higher (10. a2 and b2). When the materials are cut at a higher speed at 23.2 m/min and the depth of cut 0.5 mm, long chips are observed (10. a3 and b3). A higher cutting speed produces higher heat, and this makes the materials relatively soft and reduces the brittleness as a result of longer chips being generated. In the case of 4.0 mm depth of cut, higher thickness along with long chips are also observed (10. a4 and b4). The Si effects by showing a relatively small size of the chips are observed both in the cases of a higher cutting speed for the 17.9Si added alloy. Yet, it is evident that increasing the cutting speed causes the formation of cracks on the chips and it is more prominent for higher Si added alloys. The chip formation during machining starts with an initiation of a crack at the free surface of the work piece which further spreads towards the cutting edge of the tool. The crack rapidly comes to a close where plastic deformation exists under a higher level of compressive stresses. The chip segment caught up between the tool rake face and the crack is pushed out while the material in the plastic region just below the base of the crack is displaced along the tool rake face thus forming saw-toothed chips [21]. Higher Si added alloys reduce its ductility through the formation of Si rich intermetallics and hence higher propagation of cracks on the chips. A higher cutting speed produces a rapid impact force on the chips so the intermetallics accelerate the crack propagation.

3.4. Optical microscopic observation

Figure 11 shows the optical microstructure of the surfaces of 0.2Si and 17.9Si added alloys before and after machining at different depths of the cut and cutting speeds. Before machining, smooth and with no plastic deformation surfaces are observed for both alloys (11. a1 and b1). Without Kellers etch and Kroll’s reagent, this type of microstructure does not provide much information. However, for polished surfaces, they display some different tones for different alloying elements as present in the alloys. The tone turns into lighter and darker. It depends on the amount of elements present in the alloys. However, dark spots became more prominent on the surface of 17.9Si added alloy because of an increase with Si percentage beyond the eutectic composition of 12.6% Si, the primary Si particles blocky-like structure accumulate in the Al matrix [22].

The micrographs of the surfaces machined of 0.2Si and 17.9Si added alloys after machining at 0.5 mm depth of the cut and 3.6m/min cutting speed consist of different cracks and a more uneven surface along with the cutting direction (11. a2 and b2). In the case of the 4.0mm depth of the cut, the surface scenario completely changes by showing the absence of cutting direction, but some cracks are presents on the surface (11. a3 and b3). At a low cutting speed and a low depth of the cut, the surfaces of the material are very similar in their nature by being relatively brittle. The areas created by crack propagation are evident. Normally, during machining, the total heat generated at the tool-work piece interface may be distributed to the chip in 80%, to the tool in 10%, and the rest to the work piece. Under machining at a low cutting speed, the temperature between the machining interfaces is more sufficient to create an unstable larger built-up edge and also the chips fracture readily produce a rough surface, and this may cause an adhesive wear on the tool. Once more, with machining at a low depth of the cut of 0.5mm and 23.2m/min cutting speed, the surface machined generated consists of well-defined uniform feed marks running perpendicular to the tool feed direction (11. a4 and b4). Machining at a 4.0mm depth of the cut under 23.2m/min cutting speed, the alloy surfaces put on show some variations, which is particularly true of the 0.2Si alloy (11. a5 and b5). With increasing the cutting speed, more heat will be generated that may produce more deformation and micro-pits. The 0.2Si added alloy affected easily its higher ductility. The deformation of feed marks occurs as a plastic flow of the material during the cutting process. The plastic flow of the material on the surface machined results in higher roughness and superior residual stress [23]. As the cutting speed increases, the friction between the tool and the chip will increase and when this becomes large enough to source a shear fracture in the vicinity of the tool tip, a built-up edge is formed.

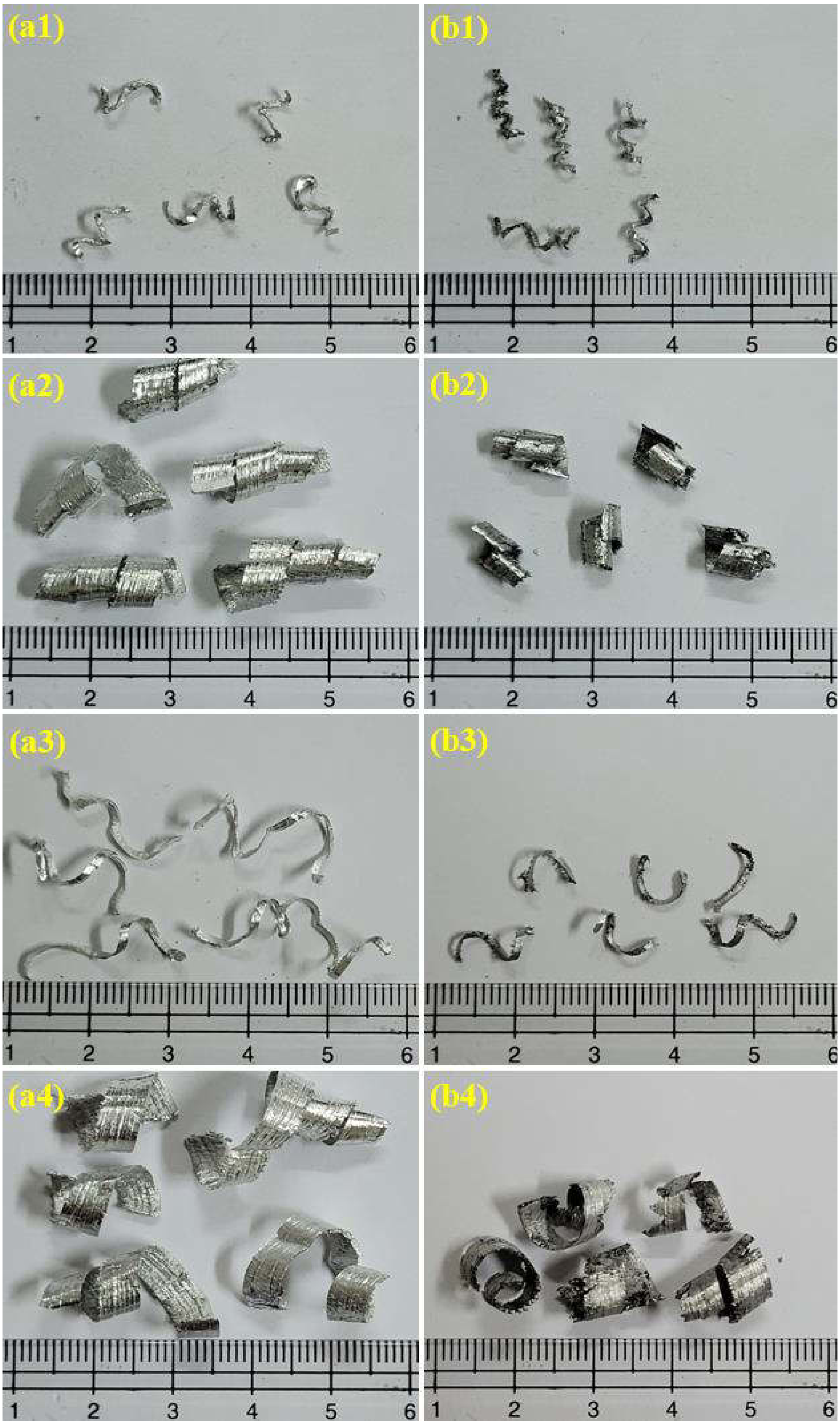

Fig. 10. Photo micrograph of the chips generated due to machining at different cutting speeds and depths of the cut (a1) 0.2Si alloy 3.6m/min at 0.5mm (b1) 17.9Si alloy 3.6m/min at 0.5mm, (a2) 0.2Si alloy 3.6m/min at 4.0mm (b2) 17.9Si alloy 3.6m/min at 4.0mm (a3) 0.2Si alloy 23.2m/min at 0.5mm, (b3) 17.9Si alloy 23.2m/min at 0.5mm,, (a4) 0.2Si alloy 23.2m/min at 4.0mm, (b4)) 17.9Si alloy 23.2m/min at 4.0mm

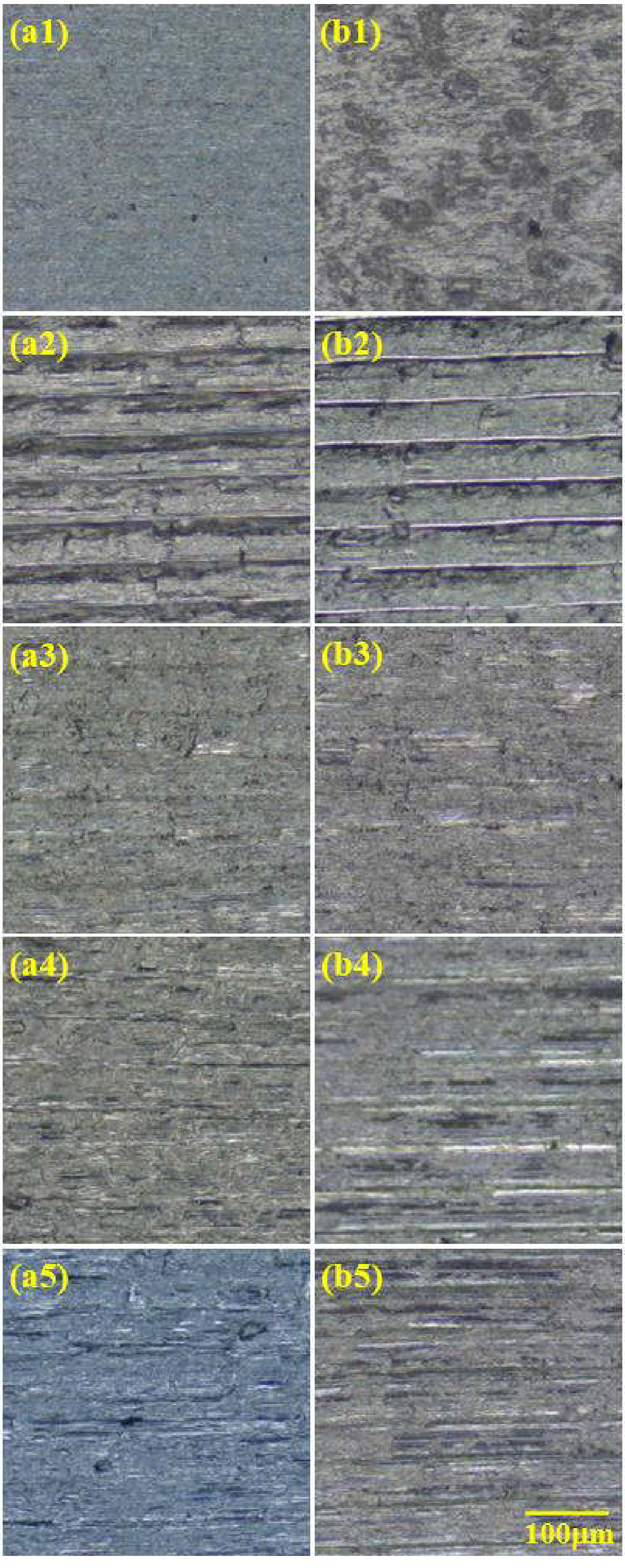

Fig. 11. Optical microstructure of the surface generated before machining (a1) 0.2Si (b1)) 17.9Si, after machining at 3.6m/min cutting speed and 0.5mm depth of the cut (a2) 0.2Si (b2) 17.9Si, at 3.6m/min cutting speed and 4.0mm depth of cut (a3) 0.2Si (b3) 17.9Si, at 23.2m/min and 0.5mm depth of cut (a4) 0.2Si (b4) 17.9Si and at 23.2m/min cutting speed at 4.0mm (a5) 0.2Si (b5) 17.9Si alloy

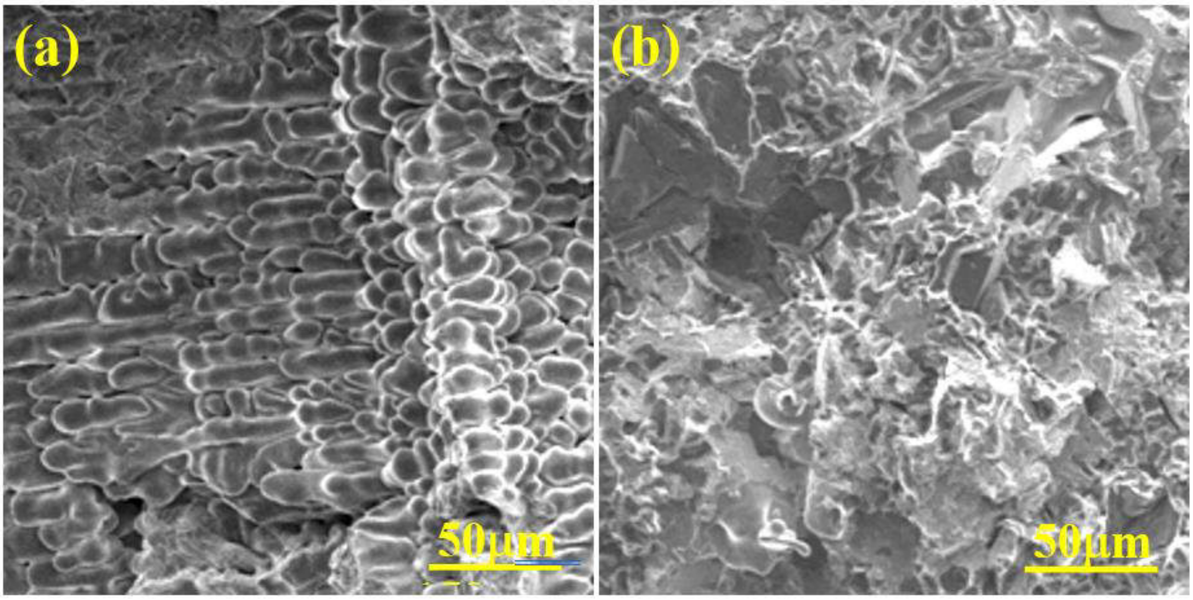

Fig. 12. SEM fracture surfaces of (a) 0.2Si alloy (b) 17.9Si at peak aged condition 175°C for 240 minutes

3.5. SEM fracture surface

Figure 12 shows the fracture appearance of the 0.2Si and 17.9Si added automotive alloys examined using an SEM analysis. Two alloys display some difference to their mode of fracture. The low Si 0.2Si added alloy shows the most common fracture mode like an intergranular fracture along with grain boundaries (Figure 12a). Some dimple morphology with ductile α-phase fracture is observed, which indicates a mixed fracture. The fracture surfaces of 17.9Si added alloy as reported in Figure 12b show an evidence of more crack propagation obtained by the enormous cleavage of Si rich intermetallics. A higher quantity of Si forms a large amount of these intermetallics since plate-type shapes and very brittle which spread the cracks. These types of alloy consist of different types of intermetallic phases of different shapes and sizes, yet plate-type shapes intermetallics are very harmful as they may destroy the mechanical properties [24, 25].

4. CONCLUSIONS

In the present work, the influence of Si on the machinability of heat-treated Al-based automotive alloys was studied with the aid of a shaper machine, and the following conclusions can be proposed.

1. Higher cutting speeds and depths of the cut produce better surface finish of the alloys but this is more significant for the cutting speed. At the same time, a high cutting speed is more associated with a higher cutting temperature and softening the work material leading to better surface finish.
2. Higher Si added alloys include different types of Si rich intermetallics which make the material hard and brittle, and this produces a higher temperature during machining.
3. These intermetallics also help to create small chips, which leads to a lower roughness. High Si added alloys also form relatively curly and short chips during machining because of their low elongation properties. Fracture surfaces of higher Si added alloy display more crack propagation obtained by plate-like Si rich intermetallics.

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