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Characterization of Machined Surfaces of Al-based Automotive Alloys with Different Levels of Si Content under Up Milling and Down Milling Operation

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Abstract: This paper aims to investigate and compare the characteristics of machined surfaces and chips formation of aluminium-based automotive alloys with varying silicon content. The milling operations are performed using horizontal milling machine under two peripheral up milling and down milling methods with an HSS slab milling cutter. The experiment has conducted for different cutting speeds in dry condition while the depth of cut and machining feed are kept constant throughout the evaluation. The study reveals that the down-milled surface has higher hardness and better surface finish resulting in lower roughness as the cutting force is compressive in nature. On the contrary, the up-milled surface has lower hardness and micro cracks on it, which resulted in relatively higher surface roughness as the cutting force is tensile shear in nature. In addition, the surface hardness increases with the increment of silicon content in the alloys for both milling methods for the presence of hard Si rich intermetallics. The chips produced during up milling are shorter whereas the chips produced during down milling are longer for creation of higher temperature and pressure. Higher Si added alloy shows the curly like chips for its lower elongation behaviour. Fracture behaviour of higher Si alloy also confirms crack propagation obtained by the massive cleavage of the brittle and plate-types Si rich intermetallics.

Keywords: Milling operation, Roughness, Hardness, Chip formation, Microstructure

1. Introduction

Silicon added Al-based alloys are commonly used in automotive and transport industries as these alloys are promising candidates for manufacturing light-weight, highly loaded automotive components like cylinder blocks, cylinder heads, pistons and valve lifter etc. [1-3]. The low density of Al and the excellent strength-to-weight ratio reduces weight some extend in practical applications [4, 5]. To achieve the novel properties primary aluminium are alloyed with the chemical elements like copper, zinc, manganese, silicon, magnesium, iron, etc. Among most common aluminium alloys used in automotive industry, Al-Si alloys are the most in-demand alloys [6]. The strength of Al-Si Alloy increases with the addition of Si due to the formation of hard Si phase intermetallics into the Al matrix. Normally the Si content varies between 5 to 23wt% in this type of cast alloys. The eutectic composition of Al-Si alloy contains 12.6% Si, which is used for medium strength automotive components. Hypoeutectic Al-Si alloy containing lower than 12.6% Silicon is suitable for manufacturing low strength components whereas hypereutectic Al-Si alloys containing more than 12.6%

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Si are generally more suitable for heavy structures [7, 8]. Alloying elements are generally added to get better properties of the metals. It increases or reduce different properties as a substance to improve one property may have inadvertent effects on other properties [9, 10]. The amounts of these alloying elements also play an important role on the properties. Machinability is one of the major considering properties of the materials [11].

Since these alloys are fairly strong yet light weighted, they are used frequently in the development of various components in the automotive, transportation, aviation and aerospace sectors. Therefore, machining is essential in several cases. Some researchers have experimentally investigated the machinability of Al-Si alloys [12-14]. However, the effect of machinability on the surface characteristics by varying the percentage of Si in Al-Si automotive alloys is not fully understood yet specially in milling operation. In this study, the effect of varying the percentage of Si on the machinability in terms of surface roughness, surface hardness, chips formation as well as microstructural characteristics of Al-Si automotive alloys has been investigated. Two types of milling like up milling and down milling operation were used under different cutting speeds to observe and compare the different behaviour related the machinability during the procedure.

2. Experimental procedure

Five Al-based automotive alloys were casted by wt% where Si varied at different level as

- *Alloy 1: Al-0.2Si-2Cu-1Mg,*
- *Alloy 2: Al-3.5-2Si-2Cu-1Mg,*
- *Alloy 3: Al-6.12Si-2Cu-1Mg,*
- *Alloy 4: Al-12.7Si-2Cu-1Mg,*
- *Alloy 5: Al-17.9Si-2Cu-1Mg.*

These alloys were casted by melting aluminium (Al99.750), copper (Cu99.997), magnesium (Mg99.80) and the master alloy of Al–50%Si. These were melted in a graphite crucible using a natural gas-fired pit furnace. Casting was done in preheated at 250°C mild steel mould, which size was 20 x 200 x 300 in millimetre. The experimental alloys chemical composition was evaluated through a shimadzu pda 700 optical emission spectrometer, as reported earlier. The cast alloys were homogenized in a Muffle furnace at 450°C for 12 hours and air cooled to relieve internal stresses. The homogenized samples were solutionized at 535°C for 2 hours followed by salt water quenching to get 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]. In this purpose an Electric Muffle Furnace ranging 900± 3.0°C was used.

The samples of dimension 20 mm × 150 mm × 150 mm were machined in a horizontal milling machine with the help of a high-speed steel slab milling cutter, which setup is exposed in Fig. 1. Both up milling and down milling was performed on the alloys. During milling operation, the cutting speed was varied for each sample while maintaining a constant depth of cut of 1.0 mm and a constant feed rate of 9.5mm/min. At the same time as the milling operation underwent the chips generated were collected into a styrofoam container. Tool geometry with the cutting conditions used in this study is presented in Table 1. The centre line average roughness Ra of the machined surface was measured with Tylor-Hubson surface roughness tester. The roughness was measured five times at different points of the machined surface and the average value was taken. Pictures of the machined surface are taken using a USB microscope to observe the cutting pattern of the machined surface for both up milling and down milling. From the pre-collected 4/5 ideal chips were selected and their photomicrographs were taken using a DSLR camera. The hardness of the machined surface was also taken using a Rockwell Hardness testing machine named Zwick hardness tester where 1/8th inch ball in B scale was used.

Table 1: Tool Geometry and Cutting condition

Cutter Diameter (mm)	76.2
Cutter Height (mm)	101.6
Cutter Helix angle (degree)	20
Cutter Rake angle (degree)	8
Cutter Teeth (no.)	16
Feed (mm/min)	9.5
Depth of Cut (mm)	1.0
Cutting Speed (m/min)	7.9, 12.9, 14.8, 18.9
Cutting Condition	Dry

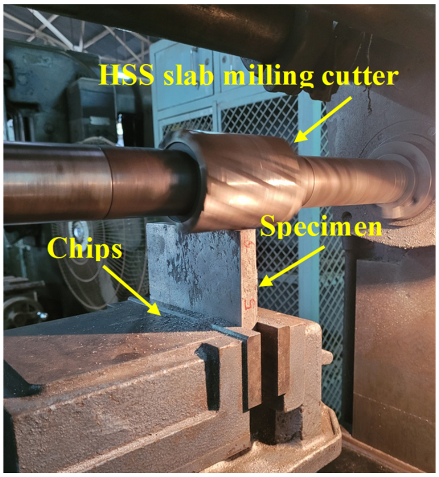

Figure 1: Photograph of the experimental setup

3. Results and Discussions

The variations of surface roughness at different cutting speed by varying Si content in Al-Si automotive alloys for up milling and down milling are shown in Figure 2 and 3 respectively. In both cases, the considered depth of cut was 1.0 mm. In case of up milling process it is evident from Figure 2 that, for a constant cutting speed, surface roughness of the alloys increases with the increase of Si percentage in the alloys. It is because of higher Si forms the higher different size and shapes Si-rich intermettalics and make available of porosity and blow holes into the alloys. Similarly Figure 3 shows the variation of surface roughness of the experimental alloys at different speeds for down milling operation. Similar results are observed from this figure but the intensity of surface roughness is different for different Si added alloys at different the cutting speed. Furthermore, it is evident that for a given alloy, surface roughness increases as cutting speed is increased. Higher cutting speed means the creation of high temperature and pressure, which result in coarsening of the grains and different intermetallics result in rougher surfaces [17]. These pressure and temperature also affect the cutting tool's material and it wears faster, so has an effect on surface roughness.

By comparing Figure 2 and 3, it is clear that, for both up milling and down milling process, surface roughness increases with the addition of Si but the increment is more distinguishable for up milling compared to down milling. This can be attributed to the fact that during any machining operation, build up edge is created on the surface of the metal. These built up edges are responsible for increasing surface roughness [18]. Built up edges deteriorate surface finish and are simply not desirable during metal cutting. In up milling, the cutting force is a tensile force, which means that the cutter applies a tensile force that shears the surface. This in turn, produces more built up edges. For this reason, surface finish quality is comparatively inferior and more distinguishable for up milled surface. On the other hand, the cutting force in down milling is a compressive force. This means the cutter applies an inward force on the surface, which in turn compresses the built up edges produced by the previous cutting edge of the cutter. Thus, in down milling the number of built up edges are less, which leads to a smoother and better quality surface [19].

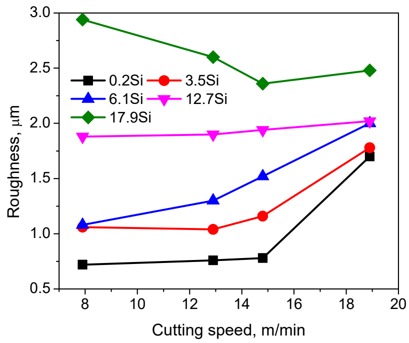

Figure 2: Variation of surface roughness with cutting speed at 1mm depth of cut for up milling

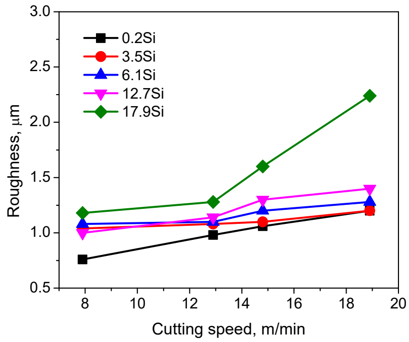

Figure 3: Variation of surface roughness with cutting speed at 1mm depth of cut for down milling

Figure 4 and 5 depict the difference in surface hardness for experimental Al-based automotive alloys at different cutting speeds under up milling and down milling process. It can be seen from the graph that for up milling machining process, the hardness increases with the cutting speed for all of the alloys to some extent, which is then followed by a downward turn after a certain cutting speed (Figure 4). Once more, Figure 5 represents the alike variation of hardness of the alloys with cutting speed under down milling operation but the strength is dissimilar. The reason for this, during machining temperature and pressure are created on the surface. Alloying elements like Si, Mg, Cu, Fe etc. form different intermetallic thus increase the strength of the alloys [20]. When the cutting speed is raised further, more temperature and pressure is produced on the surfaces of the alloys. As a result, the intermetallic precipitates start to coarsen, which causes the hardness to decrease. Higher Si added alloys contain higher portion of Si rich intermetallics, which are relatively thermally stable and cause the minimum softening of the alloys at higher cutting speeds. Another interesting fact is that, down milled surface exhibits better quality in case of hardness values than up milled surface. This is because during down milling, the cutting tool applies a compressive force, which acts similar to a cold rolling operation and thus raises the hardness of the surface further. By comparing Figures 4 and 5,

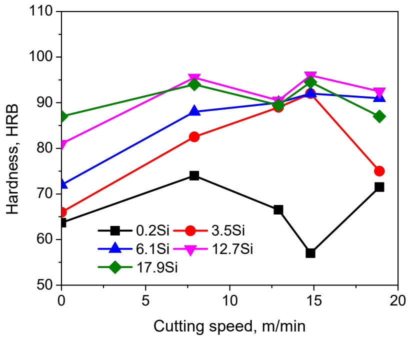

Figure 4: Variation of surface hardness with cutting speed under up milling operation at 1mm depth of cut

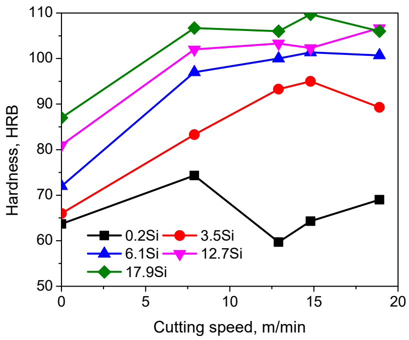

Figure 5: Variation of surface hardness with cutting speed under down milling operation at 1mm depth of cut

it becomes evident that the hardness of the alloys rises as the Si percentage rises. The reason is - as Si percentage in the alloys increase, the formation of Si rich intermetallics increase, which in turn raises the hardness of the alloys [17].

Chip formation:

Figure 6 shows photo micrographs of chips created during up milling and down milling operation. The flat like chips are produced under up milling process at the cutting speed 18.9 m/min for 0.2Si alloy but the same machining condition 17.9Si alloy provides the curly nature of chips (Figure 6a and 6b). It is occurred due to lower elongation of the materials. It is well known that addition of Si into this type of alloys increases the tensile strength with the expenses of elongation [21, 22]. When the 0.2Si and 17.9Si alloys are gone through the down milling process the chips are relatively extended in size with the curly nature for 17.9Si alloy (Figure 6c and 6d). The cause for this is, during down milling the cutting tool applies compressive force on the surface, which produce heat and pressure and acts like the hot rolling operation. That is why during down milling thin and longer chips are formed. On the contrary, during up milling, the cutting tool applies a tensile shear force and form smaller and flat chips.

Microstructural Observations:

In Figure 7, the microstructural images of the machined and non-machined surfaces are shown. Before marching the polished surfaces of 0.2Si and 17.9Si automotive alloys show the smooth surfaces (Fig. 7a and 7b). However, the dark spots became more prominent on the surface of 17.9Si added alloy. This is due to the fact that as Si percentage increases, Si particles accumulate in certain regions where the dark spots become visible [23].

Again from Figure 7, it can be observed that the machined surfaces are uneven and rough. The surfaces made by up-milling are noticeably more rutted than those created by down-milling (Fig. 7c and 7d). This is because during up-milling the cutter applies tensile force, which generates a rougher surface along with the cracks into the alloys surfaces. During down-milling, the surface undergoes compressive cutting force, this in turn diminishes the built up edges produced during machining and provides a smoother surface (Fig. 7e and 7f). Compact nature of surfaces is also seen for both the alloys [19, 24].

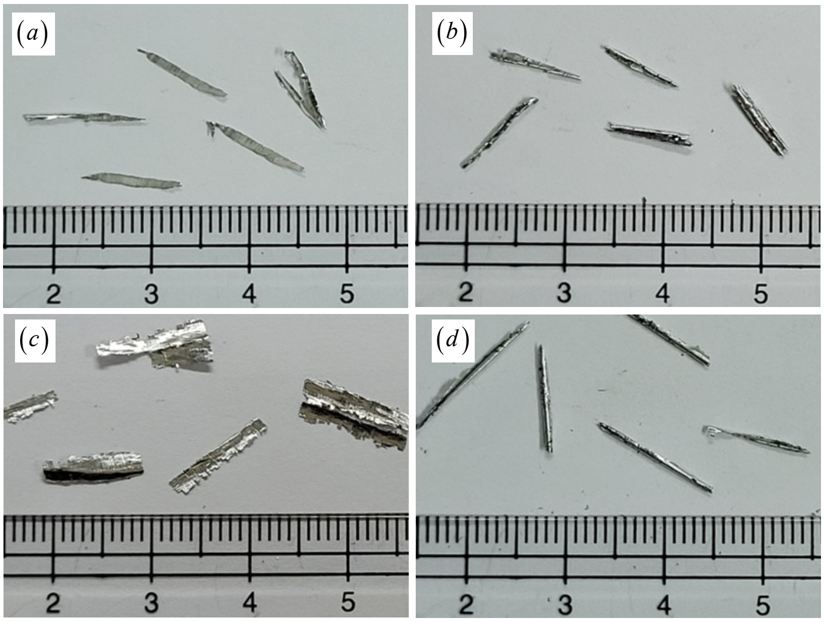

Figure 6: Photo micrograph of the chips generated due to machining at 1 mm depth of cut and 18.9 m/min cutting speed under up milling (a) 0.2Si alloy (b) 17.9Si alloy and under down milling (c) 0.2Si alloy (d) 17.9Si alloy

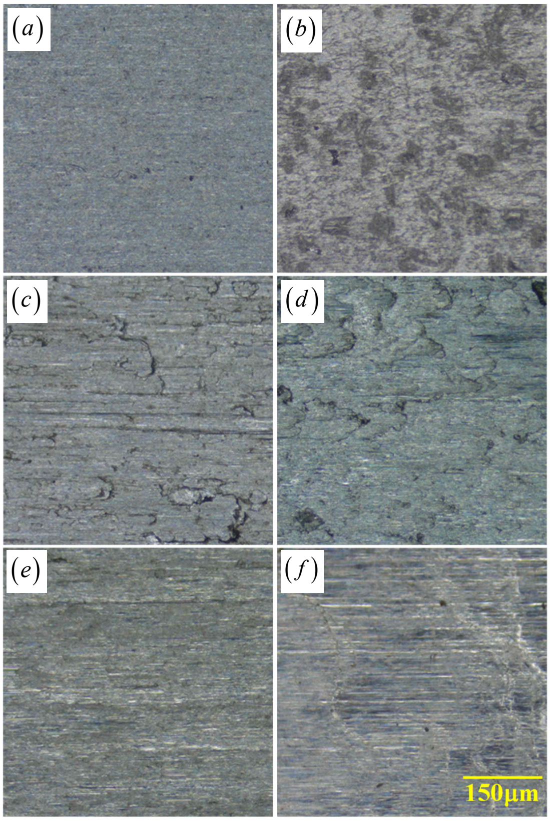

Figure 7: Optical microstructure of the surface before machining (a) 0.2Si alloy, (b) 17.9Si alloy and surface generated due to machining at 1 mm depth of cut and 17.9 m/min cutting speed under up milling (c) 0.2Si alloy (d) 17.9Si alloy and under down milling (e) 0.2Si alloy (f) 17.9Si alloy

SEM fracture surface:

For better understanding the mode of fracture of the 0.2Si and 17.9Si added automotive alloys were examined using SEM as presented in Fig. 8. It can be observed that the fracture mode of the two alloys are more different. Low 0.2Si added Al-Cu-Mg automotive alloy shows the most common fracture mode like intergranular fracture along with grain boundaries (Figure 8a). Some dimple morphology with ductile α-phase fracture is observed, which indicate a mixed fracture. The figure also demonstrated that the plane of the fracture dependent on the orientation of the grain. In general mode of fracture observed in Figure 8b the SEM fractography images of 17.9Si added alloy exhibits more crack propagation offered by the massive cleavage of the brittle and plate-type shapes Si rich intermetallics. Since the Si content increased into the alloys, a large amount of these intermetallics expected, which spread the cracks. The quantity of cleavage facets also augmented into fracture surfaces. There are different types of intermetallic phases observed in this type of alloys as it contents different level of alloying elements but plate-type shapes intermetallics are the most damaging to mechanical properties [25, 26].

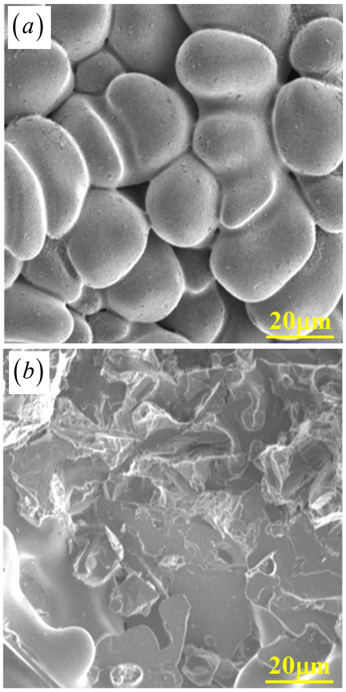

Figure 8: SEM fracture surfaces of aged (a) 0.2Si alloy (b) 17.9Si alloy

4. Conclusions

Based on the study of different level of Si content Al-based automotive alloys under up milling and down milling operation the following conclusions can be drawn:

Surface roughness increases with the percentages of Si into the alloys for both the upmilling and down milling methods because of the formation of Si-rich intermetallics as well as augmentation of porosity and blow holes. These intermettalics also play important role on the hardness of the alloys.

During downmilling, the surface undergoes compressive cutting force, this in turn diminishes the built up edges produced during machining and provides a smoother surface along with higher hardness than that of upmilling.

The surface roughness and hardness both are found to be proportional to cutting speed for higher temperature, which are caused by the modification of different intermetallics in the alloys.

Higher Si added alloy produces the chips of curly nature due to lower elongation of the materials. The chips are relatively extended in size when machined under down milling process as the cutting tool applies compressive force on the surface than up milling, the cutting tool applies a tensile force. As a result, more cracks are observed on the surfaces made by upmilling than on the compressed surface created by downmilling.

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