

## EFFECT OF SILICON CONTENT ON MACHINABILITY OF Al-Si ALLOYS

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### ABSTRACT

In this study the effect of the change in the amount of Silicon (Si) occurring in Al-Si alloys on mechanical and machinability properties of the alloy was investigated. The change in mechanical properties and microstructure, which depends on the increase in Si percentage, and the effects of this change on Flank Build-up (FBU), wear on the cutting edge, surface roughness, and machinability were also studied. Alloys in different ratios of Si (i.e. 2 to 12 wt %), were employed in the study. The specimens for tests were obtained by casting into metal moulds. The results obtained from experimental studies indicate improved mechanical properties and machinability, depending on the rise in Si percentage in Al-Si alloys. It is also observed that the increase in Si percentage enhanced surface quality.

**Keywords:** machining, cutting force, mechanical properties, Al-Si alloys

## INTRODUCTION

Today, aluminium alloys are commonly used in numerous industries, predominantly in transport, automotive, aerospace and aviation industries [1-8]. The most important properties of aluminium alloys; in addition to aluminium alloys being plentiful in nature, its facility to produce, machine, and mould, being lightweight and its improvable mechanical properties also increase the place of use and the importance of these alloys even more in today's industries [9-12].

Some aluminium alloys are quite important materials used in the manufacturing of various parts, predominantly in automotive, transport, aviation and aerospace sectors, in order to lower emissions that are harmful to the environment (SO<sub>x</sub>, CO<sub>2</sub>, and NO<sub>x</sub> emissions) and to use energy resources efficiently through weight decreases [2, 3-6]. Within this scope, among the significant aluminium alloys most commonly used in today's industries is Al-Si alloys [4, 7, 8, 10]. It is observed that the studies conducted on aluminium alloys generally focus on such subjects as microstructure and mechanical properties analyses, hardness and creep properties

analysis, porosity formation, ageing characteristics and surface roughness analyses.

As a result of our literature reviews, studies that investigate the effect of the change in Si percentage in Al-Si alloys on cutting forces (on machinability) and that also analyse wear on cutting edge and Flank build-up (FBU) are non-existent. Al-Si aluminium alloys containing Si% in different ratios (including Silicon in the ratios of 2 to 12 wt%) were used in this study. In the study, the effects of the change in Si% amount on microstructure, XRD, mechanical properties, cutting forces (machinability), chip formation, wear on the cutting edge, and Flank Build-Up (FBU) were investigated. Within this scope, this study bears an original quality.

## EXPERIMENTAL PROCEDURE

### Microstructural, XRD and mechanical properties

Al-Si alloys containing Si at variable rates (from 2% Si to 12% Si) were used in the experimental study. Experimental samples were obtained by casting in Metal moulds. In obtaining the experimental samples, pure aluminium (Al-8E,

99.8%) and eutectic Etial 140 alloy with 12.5% Si content (12.5%Si, 0.6%Fe, 0.4%Mn, 0.1%Cu, 0.1%Zn, 0.1%Mg, 0.1%Ni, 0.1%Ti, 0.1%Pb content) were used. Melting processes were carried out with an induction furnace (35 KW Inductotherm). For the casting samples, when molten metal reached the temperature of ~720°C, it was kept at this temperature for 30min and then was cast in metal moulds. Moulds were designed so as to obtain 4 cylindrical samples in each mould for casting the experimental samples. At the end of casting, at least 16 cast samples were obtained from each of the alloys. Diameter of experimental samples taken from the mould was 24mm and length was 200mm. In order to modify primer Si crystals with sharp corners that might occur due to fast cooling in the mould during the casting of Al-Si alloy (eutectic) containing 12%Si, phosphor bronze (CuSn<sub>3</sub>) was added to molten alloy at ppm level (20g in 0.002g/7400g pot). Mould filling time of casts was established as 8-10sec. Chemical compounds of Al-Si alloy experimental samples used in the experiment are given in Table 1.

In the experimental study, 6 experimental samples (with a diameter of 15 mm and a thickness of 10mm) were prepared from each series to be used in microstructure analyses of Al-Si alloys. Sample surfaces were cleaned by sanding (with emery papers starting from 200 grits up to 1200). Surfaces of samples used in microstructure analyses were polished with diamond abrasives (6µm, 3µm, and 1 µm diamond paste, respectively). Sample surfaces were etched (for 20-25 seconds) with the prepared etching solution (Keller solution 2%HF, 3%HNO<sub>3</sub>, 95%H<sub>2</sub>O). Microstructural surveys were conducted on the metallographic samples by optical microscopy (LV150 Nikon Eclipse). The hardness values of the samples were determined by the Vickers hardness test (HV) with a load of 0.1N and 10N by using microhardness tester (Shimadzu HVM-2). At least ten hardness measurements were carried

**Table 1.** Chemical composition of the studied Al-Si alloys

Al-Si Alloys	Si	Zn	Mn	Cu	Fe	Al
2%Si	2.15	0.02	0.01	0.01	0.04	rest
4%Si	4.28	0.02	0.01	0.01	0.04	rest
8%Si	8.12	0.02	0.01	0.01	0.04	rest
12%Si	11.70	0.02	0.01	0.02	0.05	rest

wt %, “Al” refers to Aluminum content and “Si” refers to Silicon content of the alloy.

out on each sample. XRD (X-ray diffraction analyses) (Panalytical-Empyrean) were carried out under Cu K $\alpha$  radiation with an incidence beam angle of 2°. The microstructures of the samples were examined using optical microscopy (OM) and scanning electron microscopy.

Tensile tests were carried out. Data on the tensile strengths of alloys (Ultimate Tensile Strength-UTS) and elongation % (El%) values were obtained from tensile tests. Samples used in the tensile tests were prepared in compliance with ASTM E 8 M-99 standards. Tensile test data were established by averaging 6 samples. Tensile tests were carried out at room temperature (20°C) (Shimadzu Autograph AGS-J 10 kN Universal Tester). The strain rate used for tensile testing was  $1.1 \times 10^{-3} \text{ s}^{-1}$ .

### Machining properties

Machinability tests were carried out on CNC turning lathe (2.2 KW Boxford 250). Turning procedures were conducted under dry machining conditions by using Polycrystalline Diamond (PCD-Taegutec CCGT 120408 FL K10) cutting edge and by orthogonal cutting method. Data on cutting forces established in the study were obtained by measuring with a specially designed and produced strain-gauge (Fig. 1).

In machinability experiments, changes in the cutting speeds were measured (by keeping the chip section fixed) at varying cutting speeds of Al-Si alloys Data on the machinability of alloys based on the changes in cutting forces were prepared in graphics. Data on surface roughness values (Ra-µm) formed depending on the changes in alloy properties and machining parameters (Mitutoyo SJ210) were obtained. Before commencing the machinability experiments, cylindrical turning procedure was carried out in order to clean the surfaces of samples. After the sample surfaces were

**Table 2.** Machining parameters and conditions used during the test

Operations	turning				
Feed rate (f, mm.rev <sup>-1</sup> )	0.10 (constantly)				
Depth of cut (DoC, mm)	0.5				
Cutting speed (m.min <sup>-1</sup> )	56, 112, 168				
Cutting & coolant	orthogonal, dry cutting				
Workpiece materials	Al-Si Alloys (from 2% to 12% Si)				
Cutting tool	Taegutec CCGT 120408 FL K10				
$\alpha$	$\Gamma$	$\lambda$	$\epsilon$	$\kappa$	$r_e$
7°	5°	0°	80°	50°	0.8

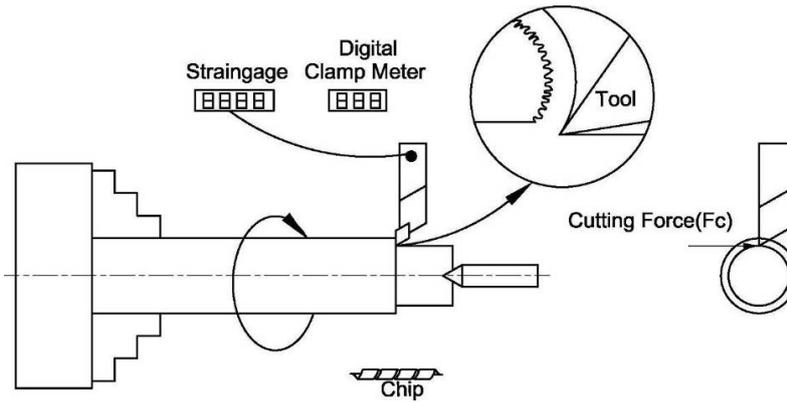


Fig. 1. Schematic representation of experimental set-up with strain

cleaned, (following the pre-cleaning chip was removed by decreasing the diameter of samples from 24 mm to 20 mm) then experiments for measuring cutting forces were conducted. In machinability experiments, feed rate was kept fixed ( $0.10 \text{ mm}\cdot\text{rev}^{-1}$ ). Machining parameters used in the experimental study are given in Table 2.

## EXPERIMENTAL RESULTS AND DISCUSSION

### Microstructural, XRD and mechanical properties

Microstructure images of Al-Si alloys used in the study can be found in Figure 2(a-d). When examined Figure 2(a-d), it was observed that the silicon in microstructure was distributed inside the structure, became significant/increased (Fig.

2d) depending on the Si% amount in the alloy. In Figure 3, XRD pattern belonging to Al-Si alloys. Microstructure images and XRD pattern obtained in this study is in compliance with literature [1, 8-11, 13].

Data on mechanical properties of Al-Si alloys used in the experiment can be observed (Fig. 4 and Fig. 5). The hardness of the analysed alloys was observed as in an order on a gradual increase from Al-Si containing 2%Si to Al-Si alloy containing 12%Si (Fig. 4).

While the lowest hardness value was obtained from Al-Si alloy containing 2%Si as  $45.7\text{HV}_{10}$ , the highest hardness value was obtained as  $68.4 \text{ HV}_{10}$  from the Al-Si alloy containing 12%Si. Depending on the increase in Si amount in the alloy, an increase ( $\sim 50\%$ ) was observed in the hardness of the alloy containing 12%Si (compared to the alloy containing 2%Si. The reason for the alloy to manifest an increase in hardness depending on

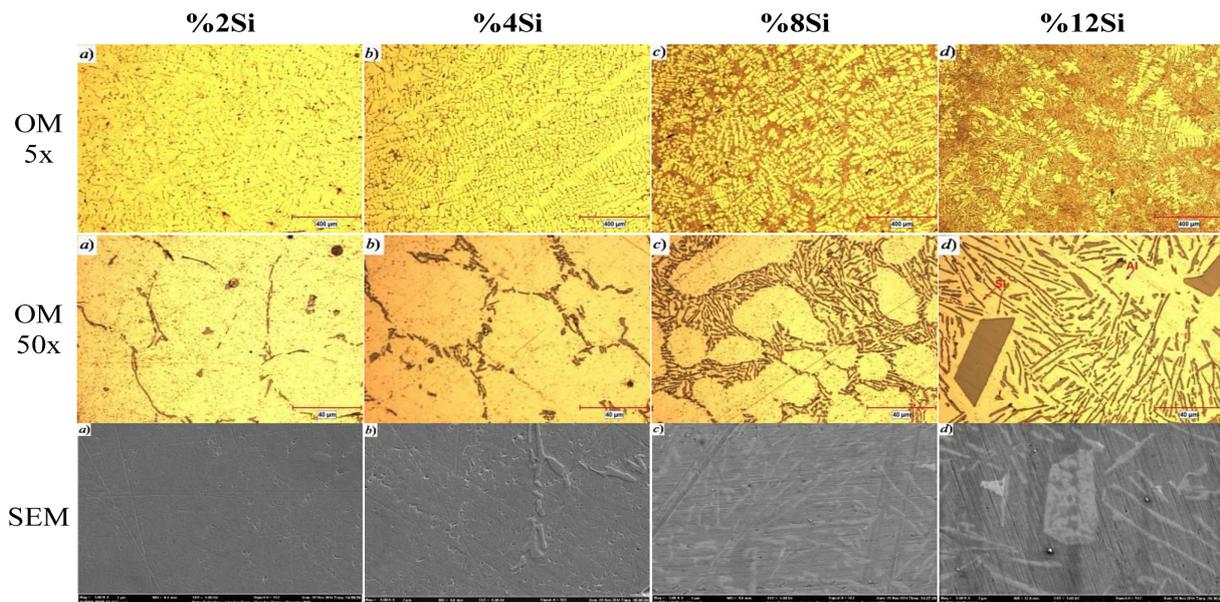


Fig. 2(a-d). Optical Micrographs and SEM of (a) 2%Si, (b) 4%Si, (c) 8%Si, (d) 12%Si Al-Si alloys

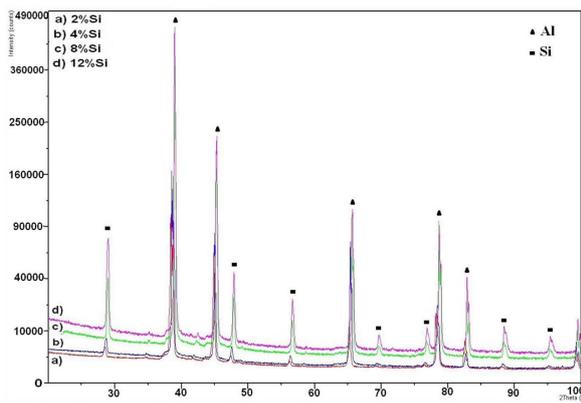


Fig. 3. XRD patterns of Al-Si Alloys

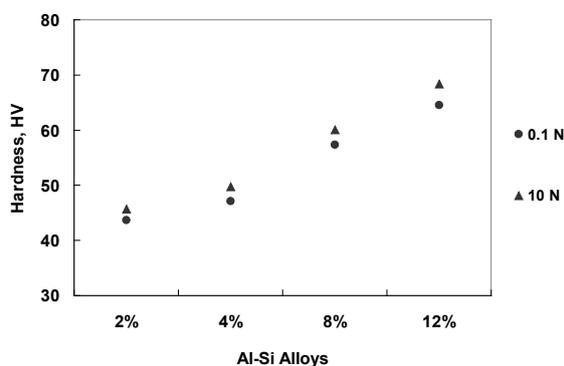


Fig. 4. Hardness (HV) of Al-Si alloys

the amount of Si% in alloy was believed to be the effect of Si observed/found in microstructure depending on the addition of Si.

In the conducted experimental study, data obtained from tensile tests of Al-Si alloy samples are observed in the graph in Figure 5. As it can be observed from the graph, UTS values increased depending on the rise in Si amount in alloy, however, EL% decreased.

### Machining properties

In the conducted machinability experiments, chip section was kept fixed at different

cutting speeds and thus data on cutting forces of Al-Si alloys were obtained (Fig. 6). It was observed in the study that machinability of alloys increased depending on the increase in Si% amount in the alloy (Fig. 6). In the experiment, it was found that cutting forces at lower cutting speeds were higher and that cutting forces decreased depending on increases in Si% amount in alloy (Fig. 6). While the highest cutting force value in machinability experiments (at all cutting rates) was obtained from Al-Si alloy containing 2%Si, the lowest cutting force value (at all cutting rates) was found in the Al-Si alloy containing 12%Si (Fig. 6). Cutting forces (at all cutting rates) were ordered in a gradual decrease starting from Al-Si alloy containing 2%Si down to the alloy containing 12%Si (Fig. 6). While the cutting force value was measured as 34.7N in Al-Si alloy containing 2%Si at the lowest cutting rate (at 56m/min), it was measured as 21.9N in Al alloy containing 12%Si. With the increase in cutting rate (to 168 m/min), it was measured as 21.4N in Al-Si alloy containing 2%Si and as 17.9N cutting force in Al-Si alloy containing 12%Si. Therefore, when comparing the machinability of alloys containing 2%Si and 12%Si, an increase was observed in the machinability of alloy containing 12%Si.

Decrease in cutting forces depending on the rise in the Si% amount in alloy manifests the effect of Si in alloy. Depending on the Si amount in alloy, it may be noted that silicon observed in the microstructure becoming significant/increasing facilitated chip breaking [9–14] thus showed an impact in a form of a decrease in cutting forces. From this point of view, it may be noted that the machinability of alloy increased depending on the rise in Si amount in alloy in Al-Si alloys. Cutting forces were also observed as higher at lower cutting rates. The reason for this was the build-up of

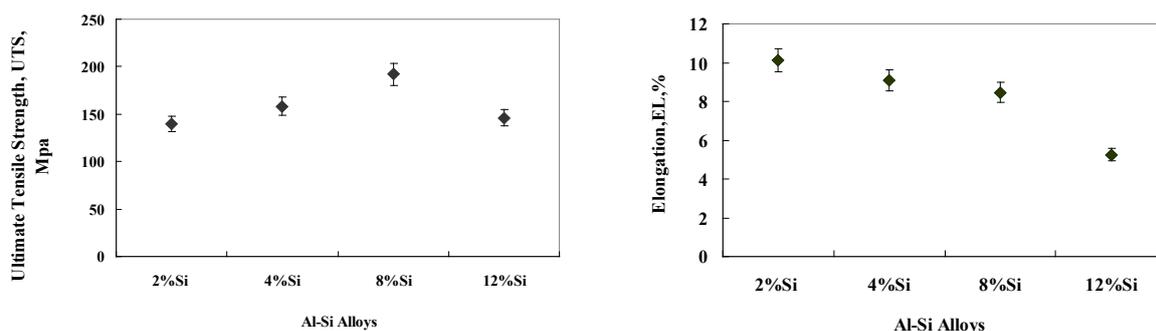


Fig. 5. Tensile tests of Al-Si alloys: UTS (left) and %EL (right)

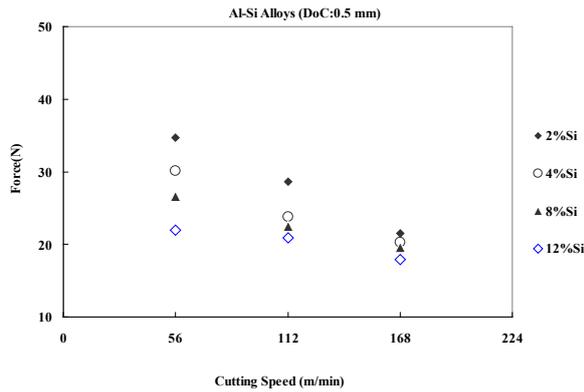


Fig. 6. Relationship between cutting forces and Al-Si alloy compositions (DoC:0.5 mm, f:0.10 mm/rev)

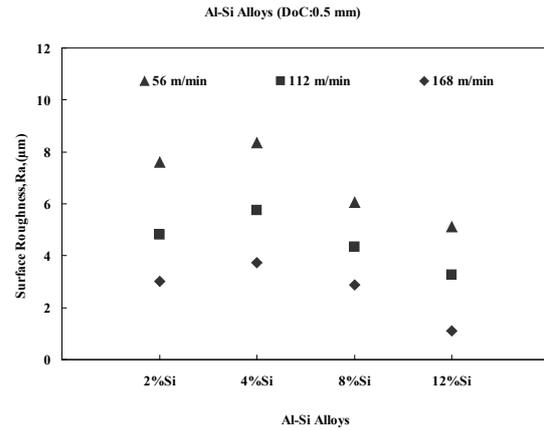


Fig. 7. Relationship between surface roughness and cutting speeds of Al-Si alloys (DoC:0.5 mm)

chips as a result of dislocation build-up at lower cutting rates (deformation hardening/work hardening) [15-20].

Data on surface roughness of alloys used in the experiment are observed in Figure 7. Surface roughness values were ordered manifesting a decrease beginning from the alloy containing 2%Si down to Al-Si alloy containing 12%Si. It was observed in the study that surface roughness values decreased (finer surfaces were obtained) depending on the rise in Si amount in the alloy in Al-Si alloys and on the increase in cutting rate (from 2%Si to 12%Si).

When examined in the study chips obtained from processing the samples (Fig. 8), chip lengths changed depending on the Si amount in the alloy and on the rise in cutting rate. It was observed that Si found in microstructure was effective in chip formation depending on the increase in the Si% amount in alloy. When comparing chips obtained from Al-Si alloy

containing 12%Si with others, chips were observed as formed at shorter lengths (showing brittle breaking behaviour and discontinuous chip formation) as a result of chips manifesting more brittle/fragile behaviour (thanks to Si) due to alloy being harder. From this point of view, it may be noted that the increase in Si amount in Al-Si alloys affects chip lengths to be shorter.

Images of the surfaces of cutting edge used in the experiment are observed in Figure 9. Flank Build-up (FBU) was observed on cutting edge surfaces due to dry adhesion between the work piece and cutting edge surface (Fig. 9). It was observed that this build-up (FBU) was more on the cutting edge belonging to Al-Si alloy containing 2%Si and that it spread more broadly on continuous chip surface (Fig. 9a). In the alloy containing 12%Si, chip build-up (FBU) was observed as lower, however, wear occurred at the tip more and was deeper (Fig.

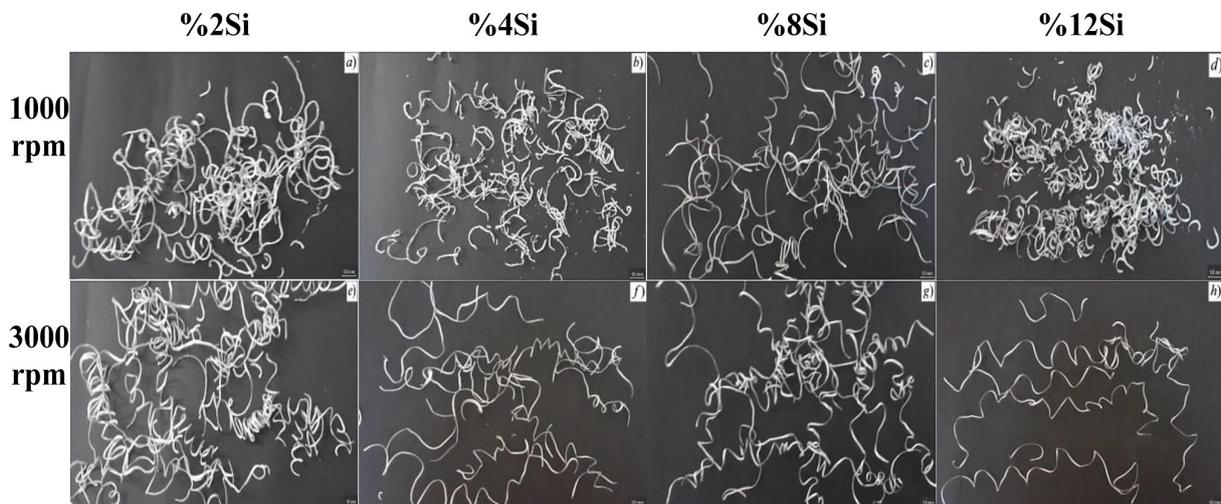


Fig. 8(a-h). Chip formation of Al-Si alloys ( $V_c$ :56-168 m/min, DoC:0.5 mm, f:0.10 mm/rev)

9h). FBU was observed to occur on the tip surface of the cutting edge from the wider surface towards the narrower surface depending on the increase in Si% amount in alloy (Fig. 9). A similar case occurs due to a rise in the cutting rate.

In the experimental study, mechanical properties and machinability of alloys were observed to increase depending on the Si% amount in Al-Si alloys (Fig. 4-6). It was found that chip breaks were facilitated and that this showed an effect in a form of a decrease in cutting forces thanks to the rise in Si% in alloy (due to the effect of Si). Especially in Al-Si alloy containing 12%Si, the occurrence of lower cutting force shows that Si in the structure has a positive effect on the machinability of Si [13-15].

It was observed that cutting forces were greater at lower cutting rates. The reason for cutting forces being greater at lower cutting rates may be noted as chip build-up (FBU) adhesion on cutting edge due to increase in dislocation build-up (deformation hardening/work hardening effect) [15-17] and local heating due to friction. From this point of view, Si presence in Al-Si alloys (increase in Si% amount) shows an effect in the form of decreasing cutting forces and machinability increases depending on the former.

It was observed in the study that a rise in Si amount in Al-Si alloys had a positive effect on mechanical properties and machinability properties of the alloy. The data obtained from the previous sections of the study (Fig. 2-5) and data obtained from the mechanical test results (Fig. 6-9) machinability section support each other. The data obtained from the study are in compliance with literature [1-14].

## CONCLUSIONS

The below-mentioned results were obtained from the experimental study:

1. Mechanical properties of Al-Si alloys were observed as increased depending on the Si% amount in Al-Si alloys used in the experiment. On the other hand, EI% decreased.
2. It was observed that the increase in Si% amount in the Al-Si alloys (Si observed in microstructure becoming significant) had an effect in the form of a decrease in cutting forces. Machinability of Al-Si alloys increased depending on the decrease in cutting forces.
3. Cutting forces were observed as higher at lower cutting speeds. Cutting forces were observed to decrease along with the increase in cutting speed. The highest cutting force were found to occur in the alloy containing 2%Si.
4. In Al-Si alloys, surface roughness values were observed as on a decrease (finer surfaces) inversely due to increase in Si amount in alloy. Surface roughness values were observed as higher (rougher surfaces were formed) at lower cutting speeds.
5. Increase in Si% amount in alloy was observed to have an effect on chip formation. Chips were observed to form at shorter lengths depending on the increase in Si% amount in alloy and cutting speed. Chips were observed to form at shorter lengths in Al-Si alloy (containing 12%Si) at higher hardness due to the effect of silicon chips were formed at longer lengths in 2%Si alloys.

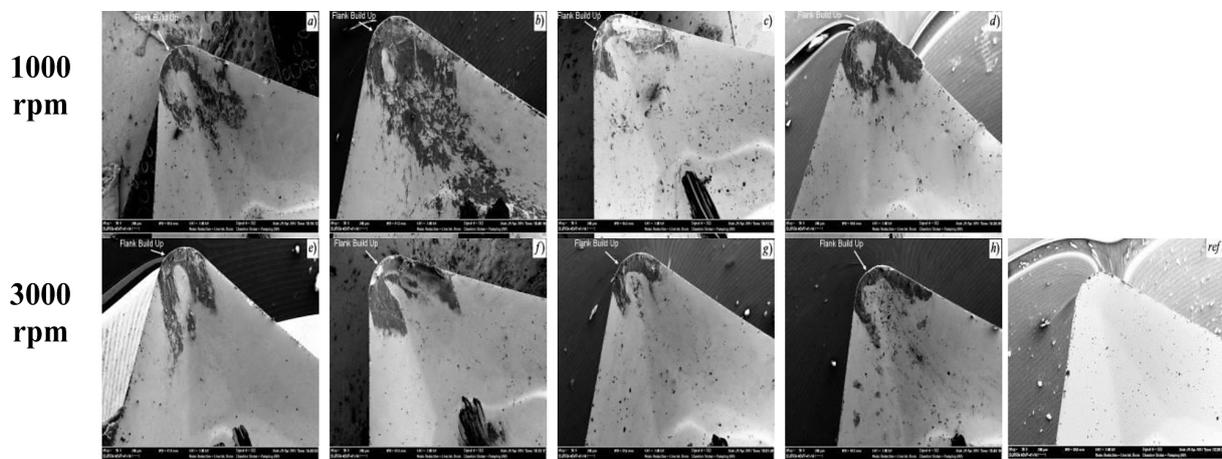


Fig. 9(a-h). SEM image of cutting tool tip used for machining of Al-Si alloys ( $V_c:56-168$  m/min, DoC:0.5 mm, f:0.10 mm/rev)

6. It was observed that the increase in Si amount affected Flank Build-up (FBU formation on cutting tool edge and on cutting forces formation. It was observed that FBU spread on the cutting edge surface at lower cutting speeds, and that FBU formation was higher in Al-Si alloy containing 2%Si that had higher ductility.

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