

Effect of Si content on machinability of Al-Si alloys

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Abstract

This study investigates the effect of the change in the amount of Si found in Al-Si alloys on mechanical properties and machinability properties of the alloy. The way the microstructure and the mechanical properties change depending on the increase in the %Si amount in the alloy and the effects of such changes on Flank Build-up (FBU), wear in the cutting edge, surface roughness, and machinability were analysed. To this end, alloys with varying amounts of silicon (i.e., 2 to 12 wt.% Si) were used in the study. Experimental samples were obtained by casting in sand moulds. It was observed in the study that, in Al-Si alloys, the mechanical properties and machinability of alloys increased depending on the rise in %Si in the alloy, that cutting forces decreased, and accordingly, machinability increased. It was also observed in the study that the increase in the %Si amount raised the surface quality (decrease in surface roughness).

Key words: machining, cutting force, mechanical properties, Al-Si alloys

1. Introduction

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

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_x , CO_2 , and NO_x emissions) and to use energy resources efficiently through weight decrease [2, 3–6].

Within this scope, among the significant aluminium alloys most commonly used in today's industries are aluminium-silicon (Al-Si) alloys [4, 7, 8, 10]. It is observed that the studies conducted on aluminium alloys generally focus on such subjects as microstructure analysis, porosity formation, ageing characteristics, mechanical properties, roughness, and creep characteristics analysis. As a result of our liter-

ature reviews, studies that investigate the effect of the change in %Si amount in Al-Si alloys on cutting forces (machinability) and that also analyse wear on cutting edge and Flank build-up (FBU) are non-existent.

Al-Si alloys containing %Si at variable rates (that include silicon at rates ranging from 2 to 12 %) 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.

2. Experimental procedure

2.1. Microstructural, XRD, and mechanical properties

Al-Si alloys containing Si at variable rates (from 2 to 12 % Si) were used in the experimental study. Experimental samples were obtained by casting in sand 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 %

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Table 1. Chemical composition of the studied Al-Si aluminium alloys (in wt.%)

Alloys	Si	Zn	Mn	Cu	Fe	Al
Al-2%Si	2.14	0.02	0.01	0.01	0.04	Rest
Al-4%Si	4.12	0.02	0.01	0.01	0.04	Rest
Al-8%Si	8.32	0.02	0.01	0.01	0.04	Rest
Al-12%Si	11.50	0.02	0.01	0.02	0.05	Rest

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 in an induction furnace (35 KW Inductotherm). For the casting of samples, when molten metal reached the temperature of $\sim 720^\circ\text{C}$, it was kept at this temperature for 30 min and then was cast in sand moulds. Sand moulds were prepared by adding 2.5 % sodium silicate (water glass) resin to dry silica sand of 90–110 AFS grain thickness. This blended sand was mixed in a mixer, and then moulds were obtained by hardening with the prepared CO_2 after the mould gap of the sand was given shape. 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 12 cast samples were obtained from each of the alloys. The diameter of experimental samples taken from the mould was 24 mm, and length was 200 mm. 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_5) was added to molten alloy at ppm level (20 g in 0.002 g/7400 g pot). Mould filling time of casts was established as 8–10 s. Chemical compounds of Al-Si alloy experimental samples used in the experiment are given in Table 1.

In the experimental study, 5 samples (with a diameter of 15 mm and a thickness of 10 mm) were prepared from each series to be used in microstructure analysis 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 analysis were polished with diamond abrasives (6, 3, and 1 μm diamond paste, respectively). Surfaces of samples were etched (for 20–25 s) with the prepared etching solution (Keller solution 2 % HF, 3 % HNO_3 , 95 % H_2O). 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 0.1 and 10 N by using microhardness tester (Shimadzu HMV-2). At least ten hardness measurements were carried out on each sample.

Tensile tests were carried out. Data on the tensile strength 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

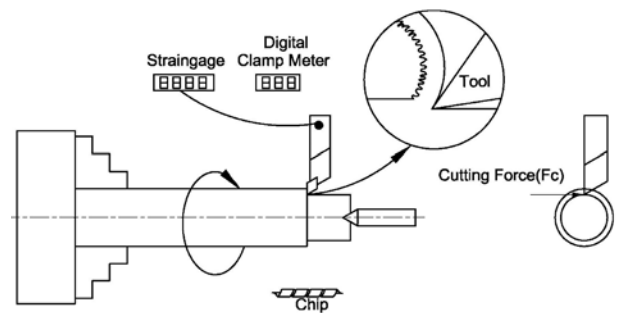


Fig. 1. Schematic representation of experimental set-up with strain.

standards. Tensile tests were carried out at room temperature (20°C) (Shimadzu Autograph AGS-J 10 kN Universal Tester). Tensile test data were established by averaging the 5 samples. The strain rate used for tensile testing was $1.1 \times 10^{-3} \text{ s}^{-1}$.

XRD (X-ray diffraction analysis) (Panalytical-Empyrean) was carried out under $\text{Cu K}\alpha$ radiation with an incidence beam angle of 2° . The microstructure of the samples was examined using optical microscopy (OM) and scanning electron microscopy.

2.2. 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 the 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, R_a (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 had been cleaned, (following the pre-cleaning

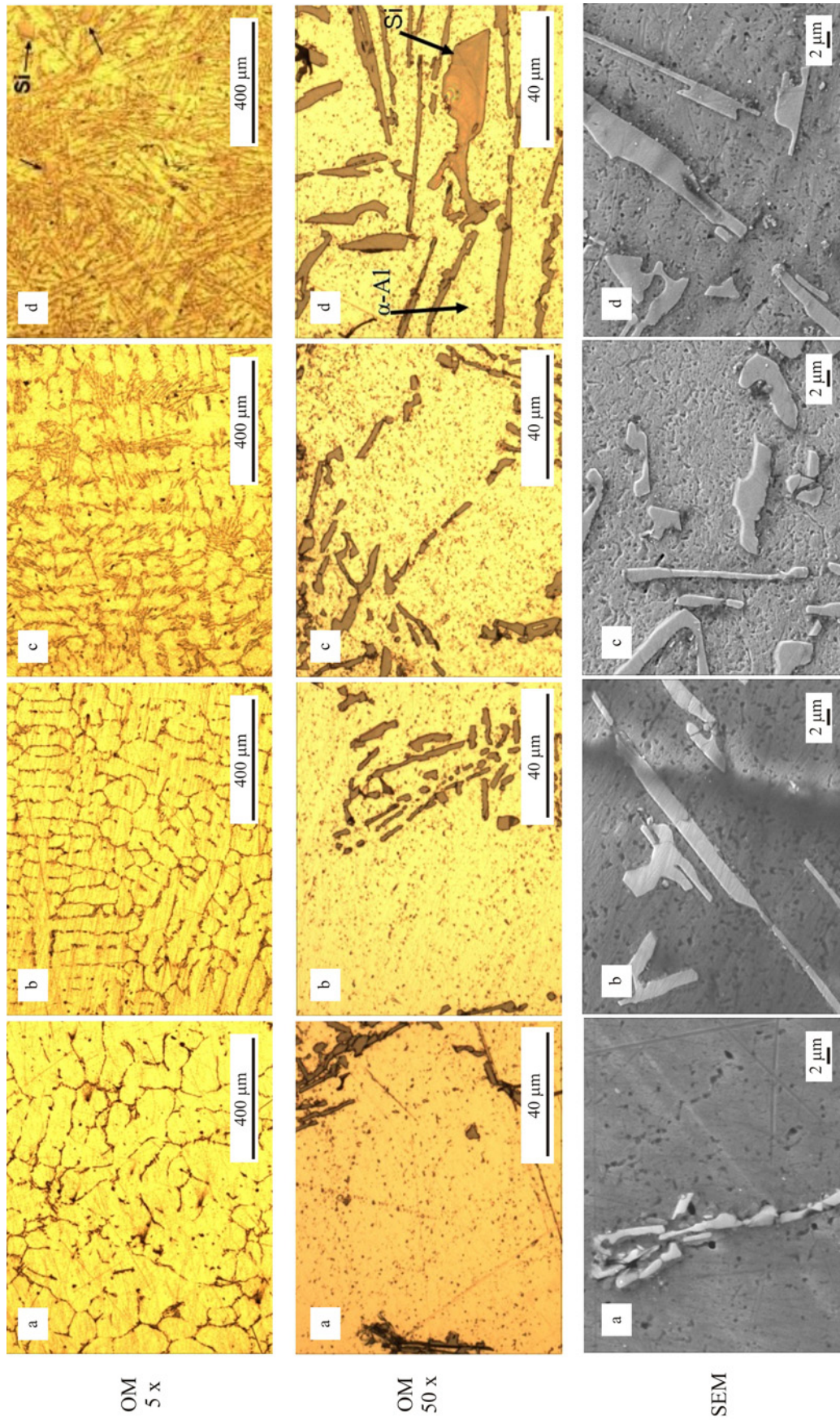


Fig. 2. Optical micrographs of (a) 2 % Si, (b) 4 % Si, (c) 8 % Si, (d) 12 % Si Al-Si alloys.

Table 2. Machining parameters and conditions used during the test

Operations	Turning
Feed rate, f (mm rev ⁻¹)	0.10 (constantly)
Depth of cut, DoC (mm)	0.5
Cutting speed (m min ⁻¹)	56, 112, 168
Cutting & coolant	Orthogonal, dry cutting
Workpiece materials	Al-Si aluminium alloys (from 2 to 12 % Si)
Cutting tool	Taegutec CCGT 120408 FL K10

α	γ	λ	ε	κ	r_ε
7°	5°	0°	80°	50°	0.8 mm

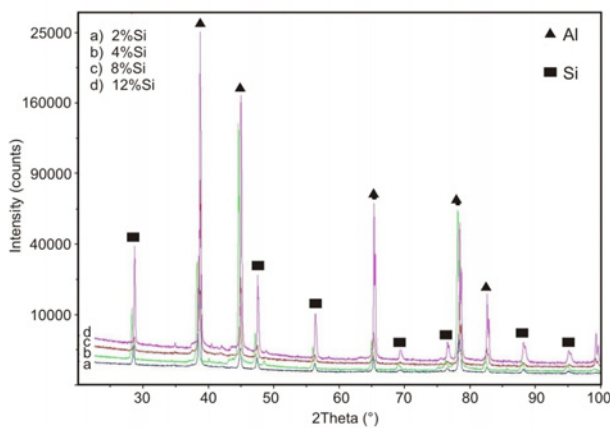


Fig. 3. XRD patterns of Al-Si alloys.

chip was removed by decreasing the diameter of samples from 24 to 20 mm) experiments for measuring cutting forces were conducted. In machinability experiments, the feed rate was kept fixed (0.10 mm rev⁻¹). Machining parameters used in the experimental study are given in Table 2.

3. Experimental results and discussion

3.1. Microstructural, XRD, and mechanical properties

Microstructure images of Al-Si alloys used in the study can be found in Figs. 2a–d. When examining Figs. 2a–d, it was observed that the silicon in microstructure was distributed inside the structure, and became significant/increased (Fig. 2d) depending on the %Si amount in the alloy. In Fig. 3, XRD pattern belongs to Al-Si alloys. Microstructure images and XRD pattern obtained in this study are in compliance with the literature [1, 8–11, 13].

Data on mechanical properties of Al-Si alloys used in the experiment can be observed (Figs. 4 and 5). When checking the hardness values of the analysed

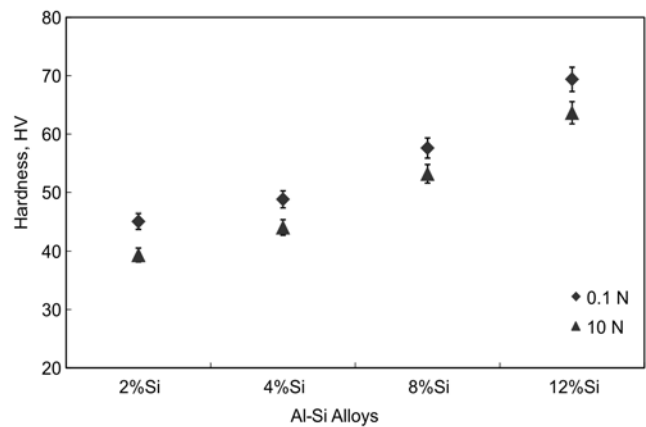


Fig. 4. Hardness (HV) of Al-Si alloys.

alloys, hardness was observed as in the order of 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 for Al-Si alloy containing 2 % Si as 39.3 HV, the highest hardness value was obtained as 63.6 HV for the Al-Si alloy containing 12 % Si. Depending on the increase in Si amount in the alloy, an increase (~62 %) 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 the amount of %Si in the 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 on the graph in Fig. 5. As can be observed from the graph, UTS values increased depending on the rise in Si amount in the alloy. However, El% decreased.

3.2. Machining properties

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

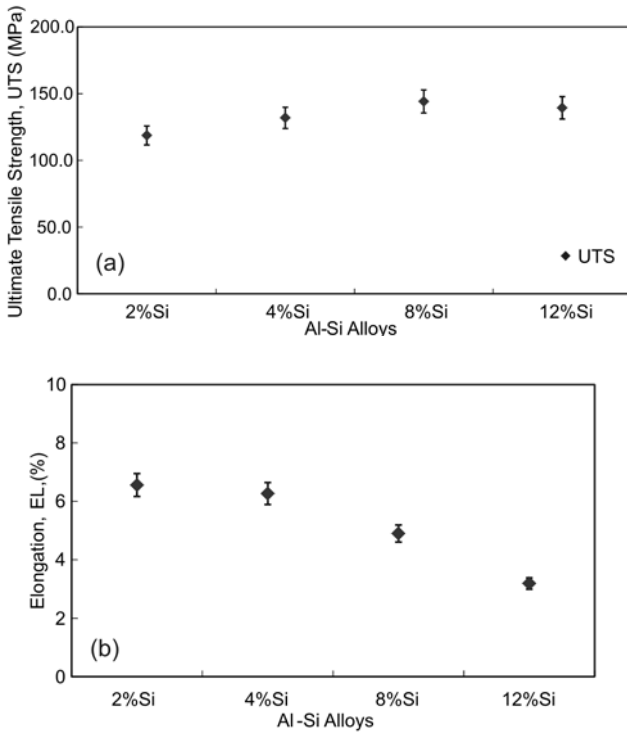


Fig. 5. Tensile tests of Al-Si alloys: (a) UTS and (b) %EL.

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 the increase in %Si amount in the 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 45 N in Al-Si alloy containing 2 % Si at the lowest cutting rate (at 56 m min^{-1}), it was measured as 27.1 N in Al alloy containing 12 % Si. With the increase in cutting rate (to 168 m min^{-1}), it was measured as 34.9 N cutting force in Al-Si alloy containing 2 % Si and as 19.9 N cutting force in Al-Si alloy containing 12 % Si. Therefore, when comparing the machinability of alloys containing 2 and 12 % Si, an increase ($\sim 60 \%$) was observed in the machinability of an alloy containing 12 % Si.

The decrease in cutting forces depending on the rise in the %Si amount in alloy manifests the effect of Si in the alloy. Depending on the Si amount in the alloy, it may be noted that silicon observed in the microstructure becoming significant/increasing facilitated chip breaking [9–14] thus showed an impact in the 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 Al-Si alloys. Cutting forces were also observed as higher at lower cutting rates. The reason for this was the build-up of chips as a result of dislocation build-up at lower cutting rates (deformation hardening/work hardening) [15–20].

Data on the surface roughness of alloys used in the experiment are presented in Fig. 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

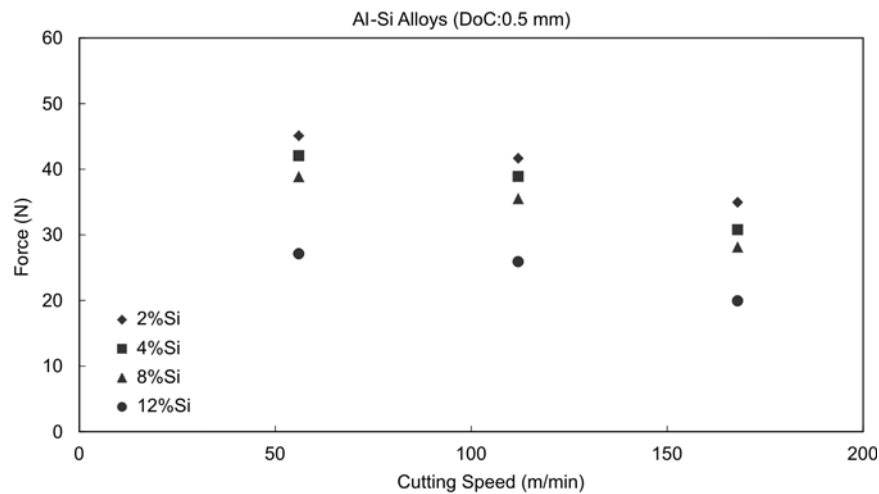


Fig. 6. Relationship between cutting forces and Al-Si alloy compositions (DoC = 0.5 mm, $f = 0.10 \text{ mm rev}^{-1}$).

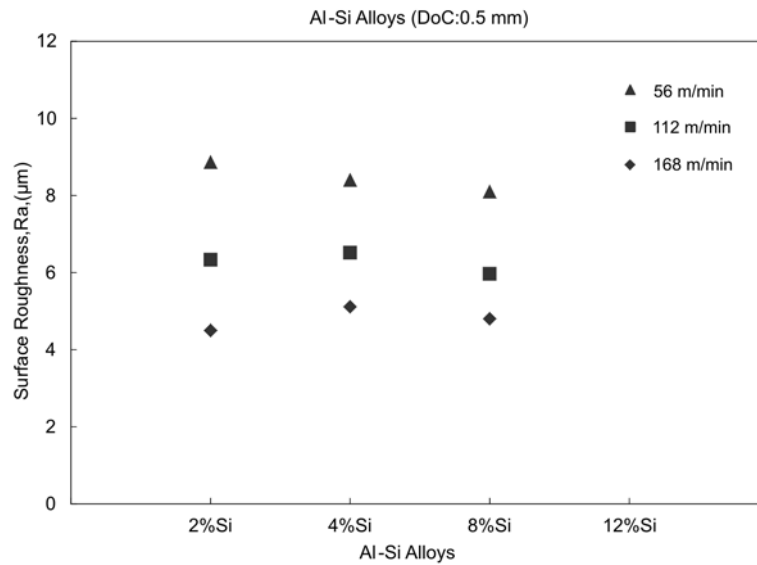


Fig. 7. The relationship between surface roughness and cutting speeds of Al-Si alloys (DoC = 0.5 mm).

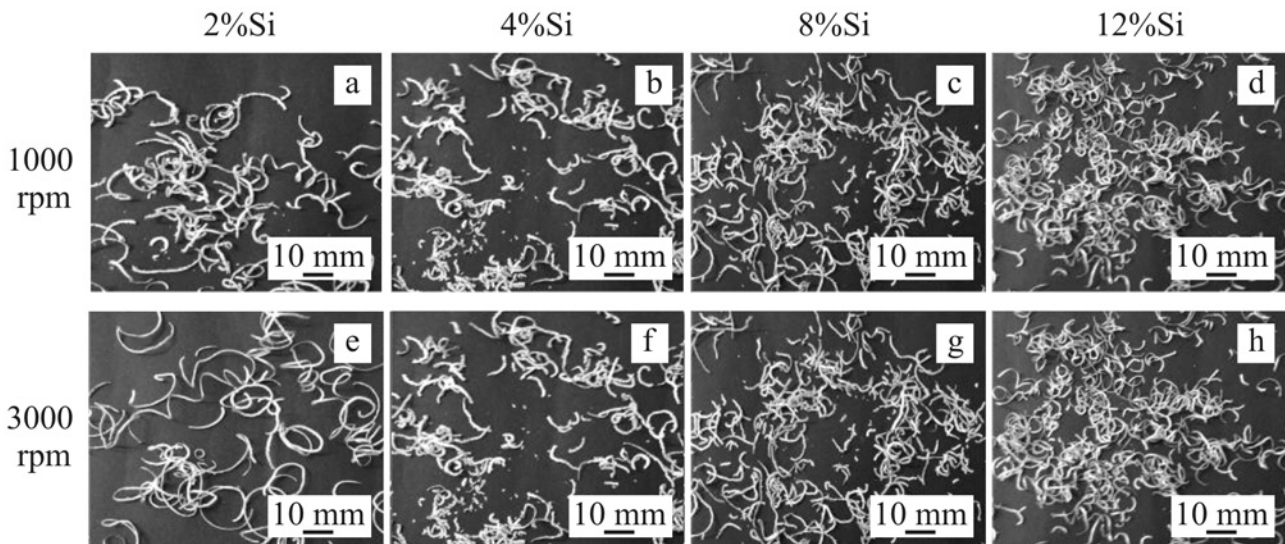


Fig. 8. Chip formation of Al-Si alloys ($V_c = 56\text{--}168 \text{ m min}^{-1}$, DoC = 0.5 mm, $f = 0.10 \text{ mm rev}^{-1}$).

Al-Si alloys (from 2 to 12 % Si) and on the increase in cutting rate.

When examining chips obtained from processing the samples (Fig. 8), chip length 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 the 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 length to be shorter.

Images of the surfaces of cutting edge used in the experiment are presented in Fig. 9. Flank Build-up (FBU) was observed on cutting edge surfaces due to dry adhesion between the workpiece 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 a 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. 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 the alloy (Fig. 9). A

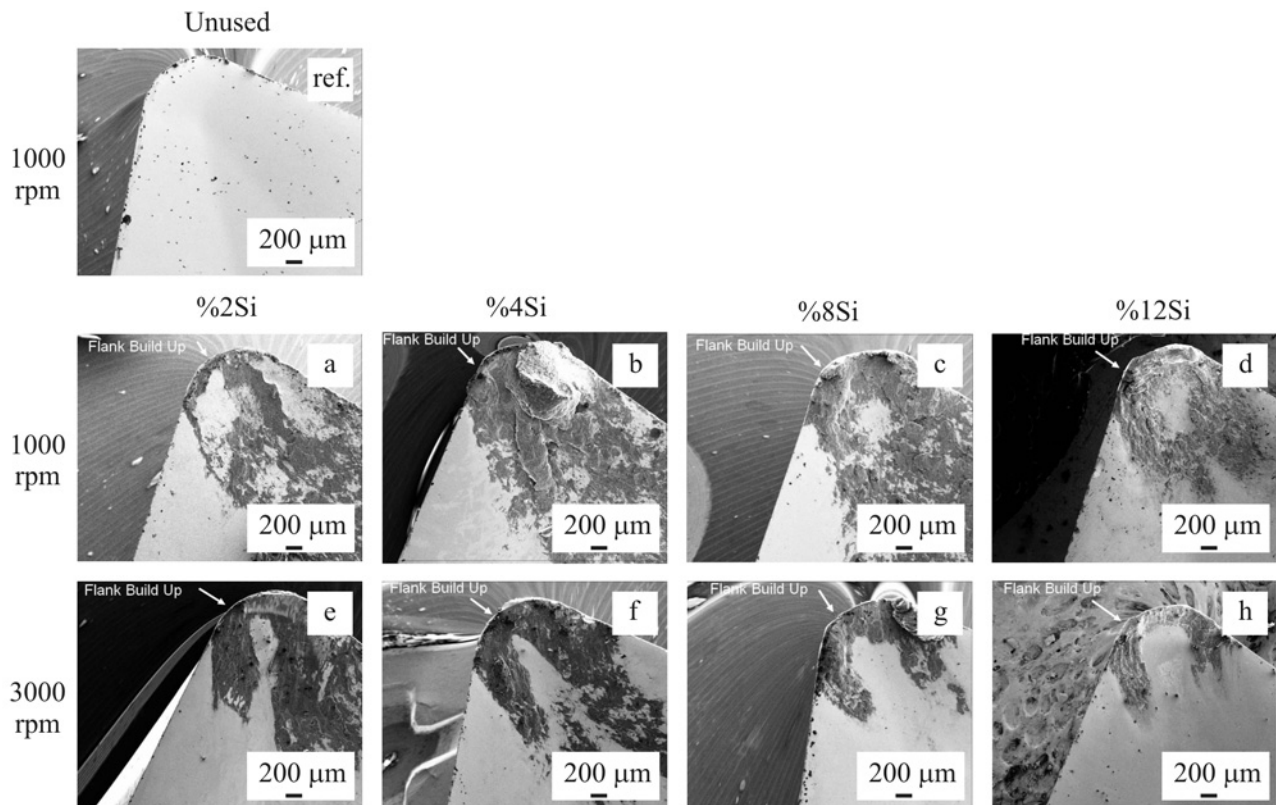


Fig. 9. SEM image of cutting tool tip used for machining of Al-Si alloys ($V_c = 168 \text{ m min}^{-1}$, $\text{DoC} = 0.5 \text{ mm}$, $f = 0.10 \text{ mm rev}^{-1}$).

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 (Figs. 4–6). It was found that chip breaks were facilitated and that this showed an effect in the 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, 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 an 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. Data obtained from the previous sections of the study (Figs. 2–5) and data obtained from the mechanical test results (Figs. 6–9) machinability section sup-

port each other. Data obtained from the study are in compliance with the literature [1–14].

4. Conclusions

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

- Mechanical properties of alloys were observed as increased depending on the %Si amount in Al-Si alloys used in the experiment. On the other hand, $EI\%$ decreased.

- It was observed that the increase in %Si amount in the alloy (Si observed in microstructure becoming significant) had an effect in the form of a decrease in cutting forces. Machinability of alloy increased depending on the decrease in cutting forces.

- 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 was found to occur in the alloy containing 2% Si.

- In alloy, surface roughness values were observed as on a decrease (finer surfaces) inversely due to an increase in Si amount in the alloy. Surface roughness values were observed as higher (rougher surfaces were formed) at lower cutting speeds.

– The 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 formed at longer lengths in 2 % Si alloys.

– 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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