Effect of Si Content on Machinability of Al-Si Alloys Casted Sand and Metal Moulds

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Abstract: This study investigates the effect of metal and sand moulds casting (solidification or cooling rate) and increase of %Si content in Al-Si (Aluminium-Silicon) cast alloys on mechanical properties and machinability properties. The effect of cooling was analysed by casting the experimental samples in metal and sand moulds. Al-Si cast alloys with varying rates of Silicon (%Si) content (from 2% up to 12%) were used in the study. It was observed that the metal and sand moulds casting (cooling rate) of Al-Si alloys and mechanical properties (hardness and strength) increased depending on the %Si content in the alloy and that cutting forces formed during machining gradually decreased and thus machinability increased. Also noted in the study was the increase in the cooling rate and surface quality (Ra) of alloys (surface roughness value decreased) depending on the rise in %Si amount.

Keywords: Machinability, cutting force, mechanical properties, Al-Si alloys, Surface Roughness

1.INTRODUCTION

Today, aluminium alloys find numerous fields of use in many industries predominantly in automotive, transportation, aviation, and aerospace industries [1-8]. Among the most significant properties of aluminium alloys are as follows: ease of manufacturing, ease of castability, light weight, and ability to improve mechanical properties. Especially their light weight and mechanical properties open to improvement expands the areas of use and their importance in today's industries [2,3,5,6]. Various aluminium alloys occupy a very significant space in lowering environmentally damaging emissions (SO_X, CO_2, and NO_X emissions) and efficient use of energy resources through decreasing weight especially in automotive, transportation, aviation, and aerospace industries [3,5]. For this reason, these alloys are quite an important structural material preferred in the manufacturing of numerous parts used in these sectors [1-6]. Among the important aluminium alloys in this field is Aluminium-Silicon (Al-Si) alloys [6,7]. Therefore, a plethora of researches are carried out on various aluminium alloys [3,6-12].

This study investigates the effect of metal and sand moulds casting (casting condition, cooling rate) and increase of %Si content in Al-Si cast alloys on mechanical properties and machinability properties. Studies that investigate the effect of casting condition and cooling rate and %Si content in alloy in Al-Si aluminium alloys on machinability are quite scarce and insufficient. For this reason, this study investigates the impact of cooling rate on mechanical properties and machinability properties by conducting casting in metal and sand moulds. In addition, the effect of alloy components on mechanical properties and machinability in Al-Si alloys containing %Si at varying degrees were analysed through both casting methods. By analysing the microstructure and mechanical properties of these alloys, the impact of the change in %Si amount on cutting forces, surface roughness (Ra), Flank Build-up (FBU) and chip formation were investigated. In this context, this study bears a unique quality.

2.MATERIALS AND METHODS

Microstructural and Mechanical Properties

Experiment samples used in the study were obtained by casting in sand and metal moulds at the same time. Al-Si alloys containing Si at varying rates (from 2%Si to 12%Si) were used in the study. The effect of casting condition and cooling rate was studied by casting Al-Si alloys with the same alloy components in both sand moulds and metal moulds at the same time. These samples were maintained in sand and metal moulds for the same duration (~30 minutes) (and in same environments, same casting condition).

For obtaining experiment samples, pure aluminium (Al-8E at 99.8% purity) 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. Pure Aluminium and Etial 140 purchased from Nova Metal Co., Turkey. Melting procedures were conducted in induction furnace (35 KW Inductotherm). Casting of samples were carried out by casting in sand and metal moulds simultaneously following keeping molten metal for 30 minutes after it reached ~730°C. In sand moulds, mixture was prepared by adding 2.5% sodium silicate (water glass) water clear casting resin in 2.5% silica sand with 90-110 AFS grain size. This sand mixture was fed into mixers for ~30 minutes, and after the mould cavity of the prepared sand was moulded, moulds were obtained by hardening with CO_2 gas. Metal moulds were made from GG25 material. Metal moulds and sand moulds were designed so as to obtain 4 cylindrical samples in each mould following casting the test samples. At the end of casting process, 12 experiment samples were obtained from each mould and Al-Si alloy. Diameter of experiment samples removed from the mould was 25mm and the length was 200mm. In casting Al-Si alloy (eutectic) containing 12% Si, phosphor bronze ($CuSn_5$) ppm level (20g in 0.002g/7400g pot) was added in molten alloy for the modification of primer Si crystals that may form due to fast cooling in mould. Mould filling time of casts were established as 8-10 seconds. Chemical components of Al-Si alloy used in the experiment are given in Table 1.

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

(Wt %, "Al" refers to Aluminum content and "Si" refers to Silicon content of the alloy).

Al-Si Alloys	Si	Zn	Mn	Cu	Fe	Al
2%Si	2.1	0.02	0.01	0.01	0.04	Rest
4%Si	4.2	0.02	0.01	0.01	0.04	Rest
8%Si	8.1	0.02	0.01	0.01	0.04	Rest
12%Si	11.8	0.02	0.01	0.02	0.05	Rest

In the experimental study, 3 test samples (at 12mm diameter and 10mm thickness) from each Al-Si alloy were prepared to be used in microstructure analyses. Surfaces of these samples were cleaned by sanding (with emery papers ranging from 120 up to 1200 grits). Then, surfaces of these samples were polished by diamond abrasives (6µm, 3µm and 1µm diamond paste, respectively). Surfaces of samples were etched (for 20~25 seconds) 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 (OM) (LV150 Nikon Eclipse) and scanning electron microscopy (SEM). The hardness values of the samples were determined by the Vickers hardness test (HV) with a load of 10N 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 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 tests were carried out at room temperature (20ºC) (Shimadzu Autograph AGS-J 10 kN Universal Tester). Tensile test data were established by averaging the 7 samples. The strain rate used for tensile testing was 1.1×10^{-3} s^{-1}.

Machining Properties

Machinability tests were conducted on CNC turning lathe (DMG CTX Alpha300). Turning procedures were carried out under dry processing conditions by using Polycrystalline Diamond (PCD) (Taegutec CCGT 120408 FL K10) cutting edge. Data obtained from the study on cutting forces were produced by measuring with a specially designed and manufactured strain-gauge (Fig.1).

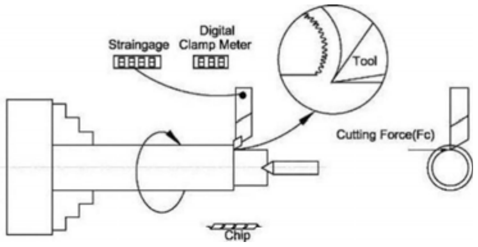


Fig.1 Schematic representation of experimental set-up with strain

In machinability experiments, changes in the cutting forces of Al-Si alloys were measured at varying cutting rates (by keeping chip section fixed). Data on the machinability of alloys were prepared as graphs in accordance with changes in cutting forces. Surfaces of samples taken from casting were cleaned before commencing machinability experiments. Feed rate was kept at a fixed rate (0.10mm.rev^{-1}) in machinability experiments. Data on surface roughness of alloys (Ra-µm) were then obtained (Mitutoyo SJ210). Machining parameters used in the experimental study are given in Table 2. Data formed by changes in cooling rate, alloy properties, and machining parameters were prepared as graphs.

Table 2 Machining parameters and conditions used during the test.

Machining Parameters and Conditions	
Operations	: Turning
Feed rate (*f, mm/rev*)	: 0.10 (*Constantly*)
Depth of Cut (*DoC, mm*)	: 0.5
Cutting Speed (*m/min*)	: 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

α	γ	λ	ε	κ	r_ε
7^o	5^o	0^o	80^o	50^o	mm

3.RESULTS AND DISCUSSION

Microstructural and Mechanical Properties

Microstructure images of Al-Si alloys used in the experimental study are given in Fig.2(a-d). When analysed Fig.2(a-d), it was observed that silicon was dispersed, became evident/increased in microstructure due to increase in %Si content in alloy and to cooling rate (Fig.2d). Microstructure images obtained in this study are in concordance with the literature [1,13].

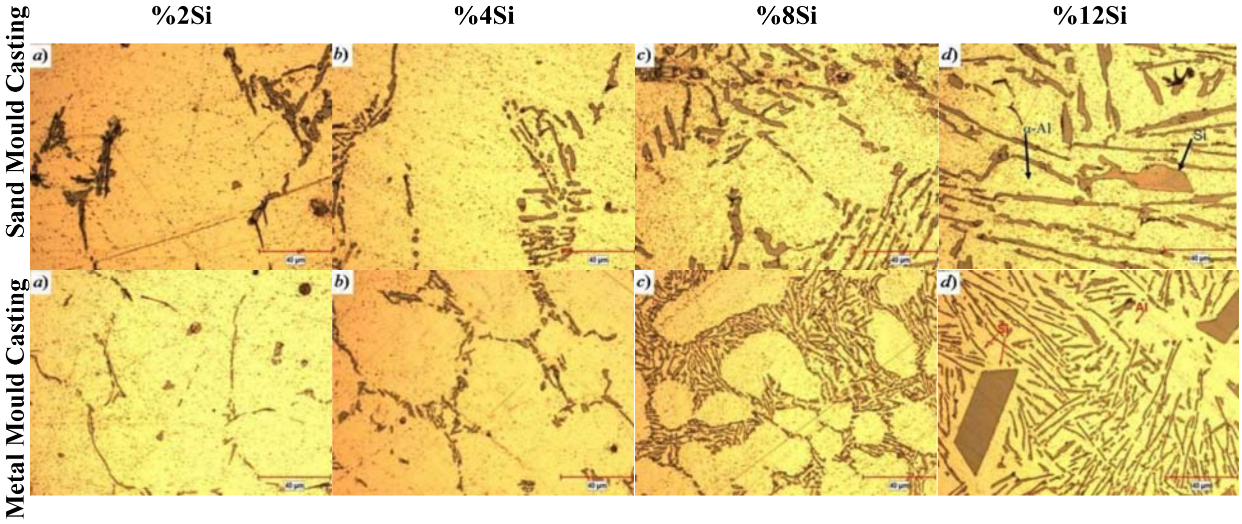


Fig.2 (a-d) Optical Micrographs (OM 50x) of (a)2%Si, (b)4%Si, (c)8%Si, (d) 12%Si Al-Si alloys

Data on mechanical properties of Al-Si alloys used in the experiment (hardness (Fig.3) and strength (Fig.4)) are shown. When checked the hardness values of analysed alloys (Fig.3), it was observed that the hardness of alloys removed from the metal mould was higher (compared to sand mould). Hardness values of alloys ranged in a gradually increasing order beginning from Al-Si containing 2%Si up to Al-Si with 12%Si content (Fig.3) (Similar was observed in both moulds). Higher hardness of samples from the metal mould (compared to sand moulds) shows the effect of cooling rate on hardness (Fig.3). It is possible to note that the hardness of Al-Si alloys increase depending on the rise in cooling rate (Fig.3). In addition, the hardness of alloys increased (sequentially) depending on the rise in %Si amount in alloy. The reason for this is believed to stem from the effect of Si observed/found in microstructure depending on the increase in %Si.

While the lowest hardness value (in both moulds) was obtained from Al-Si alloy containing 2%Si, the highest hardness value was received from alloy containing 12% Si (Fig.3). Hardness of alloy containing 12%Si was observed to increase (compared to alloy containing 2%Si) (~65%in sand mould and metal mould) depending on the rise in Si amount in alloy. It is similar in both moulds. In experiment samples removed from sand mould, while the lowest hardness value was obtained from Al-Si alloy containing 2%Si as 39.5 HV_{10}, the highest hardness value was taken from Al-Si alloy containing 12%Si as 59.9 HV_{10}. In experiment samples removed from metal mould, while the lowest hardness value was obtained from Al-Si alloy containing 2%Si as 45.8 HV_{10}, the highest hardness value was taken from Al-Si alloy containing 12%Si as 68.8 HV_{10} (Fig.3).

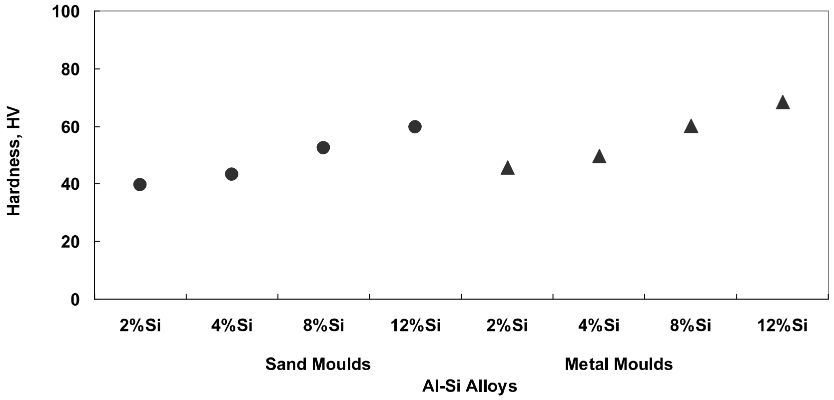
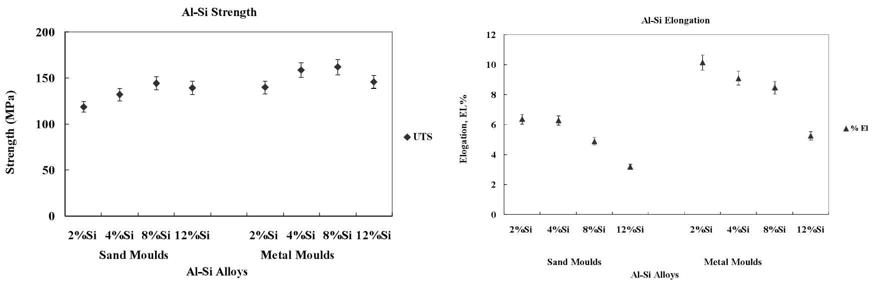


Fig.3 Hardness (HV) of Al-Si alloys

Data obtained from tensile tests in the experimental study are given in graph form in Fig.4a-b. As can be observed from the graph, UTS values increased parallel to the rise in the cooling rate of Al-Si alloys and the rise in %Si content in alloy. On the other hand, %El was observed to decrease. UTS values of samples from metal mould were higher (compared to samples from sand mould) (Fig.4a).

While the lowest UTS value (in both moulds) was obtained from Al-Si alloy containing 2%Si, the highest hardness value was received from alloy containing 12% Si (Fig.4a). When checked the %El values, the highest %El value (in both moulds) was obtained from Al-Si alloy containing 2%Si (Fig.4b). The lowest %El values were observed in alloys containing 12% Si (in both moulds). While the lowest UTS value was established as 118.7 MPa in Al-Si alloy containing 2%Si in experiment samples removed from sand mould, the highest UTS value was obtained from Al-Si alloy containing 12%Si as 139.3MPa (Fig.4a). Similarly, while the lowest UTS value was established as 139.7MPa in Al-Si alloy containing 2%Si in experiment samples removed from metal mould, the highest UTS value was obtained from Al-Si alloy containing 12%Si as 145.9MPa (Fig.4a).



(a) UTS (b)%EL

Fig.4 Tensile Tests of Al-Si alloys (a) UTS and (b) EL%

Machining Properties

In the machinability study, data on cutting forces of Al-Si alloys were obtained (by keeping chip section fixed) at varying cutting speeds (Fig.5.). In the experimental study, cutting forces were observed to decrease due to the increase in cooling rate (Fig.5). From this point of view, the fact that cutting forces of samples from metal mould (compared to samples from sand mould) manifested the positive effect of cooling rate on machinability.

It was also observed that there was a drop in cutting forces due to the increase in %Si content in alloy (in both moulds) (Fig.5). In experiments, while the highest cutting force values (in both moulds) were established in Al-Si alloy containing 2%Si, the lowest cutting force value was obtained from Al-Si alloy containing 12%Si (Fig.5). From this viewpoint, the fact that cutting forces drop due to the increase in %Si content in alloy (in both moulds) shows the effect of Si in alloy. Depending on the Si amount in alloy, it may be noted that silicon observed in microstructure becoming evident/increasing facilitated the chip breaks [13-18], thus had a decreasing effect on cutting forces. Therefore, machinability of alloys was improved.

In addition, cutting forces manifested a decrease in experiments (in both moulds) due to the rise in cutting speed. Cutting forces showed a decreasing range in all cutting speeds beginning from Al-Si alloy containing 2%Si down to the alloy containing 12% alloy (Fig.5). The reason for cutting forces being higher at lower cutting speeds was believed to be due to chip build-up as a result of dislocation deposit at lower cutting speeds (deformation hardening/work hardening) [15-20].

In samples from sand mould, while the cutting force value was measured as 45.1N in Al-Si alloy containing 2%Si at the lowest cutting speed (at 56m/min), it was established as 29.5N in Al alloy containing 12%Si. Following the increase in cutting speed (rise to 168 m/min), cutting force was measured as 38.2N in Al-Si alloy containing 2%Si and as 21.5N in Al-Si alloy containing 12%Si. Accordingly, machinability of alloy containing 12%Si is higher (compared to alloy containing 2%Si).

In samples from metal mould, while the cutting force value was measured as 34.7N in Al-Si alloy containing 2%Si at the lowest cutting speed (at 56m/min), it was established as 22.9N in Al-Si alloy containing 12%Si. Following the increase in cutting speed (rise to 168 m/min), cutting force was measured as 24.5N in Al-Si alloy containing 2%Si and as 17.8N in Al-Si alloy containing 12%Si. Accordingly, machinability of alloy containing 12%Si is higher (compared to alloy containing 2%Si). In the study, it may be noted from data obtained in this phase that cutting forces decreased and machinability increased due to rise in Si amount in Al-Si alloy and cooling rate.

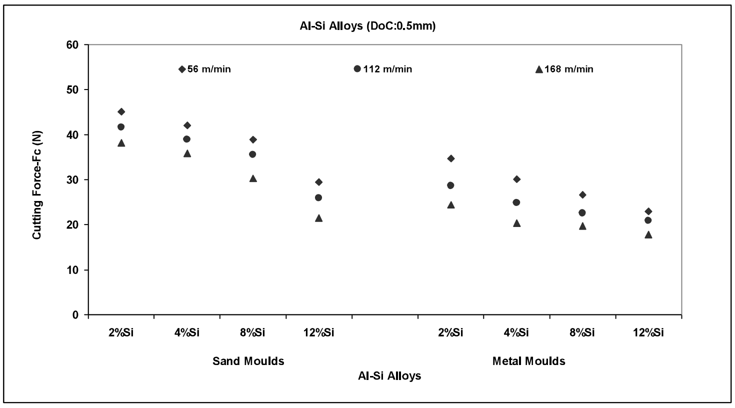


Fig.5 Relationship between cutting forces and Al-Si alloy compositions (*DoC:0.5 mm, f:0.10 mm/rev*).

Data on surface roughness (Ra) values of alloys used in the experiment is given in Fig.6. Surface roughness values of alloys from metal mould were observed as lower (surface with higher sensitivity). Surface roughness values ranged from alloy containing 2%Si down to Al-Si alloy containing 12%Si manifesting a decrease. From this viewpoint, a drop was observed in surface roughness values (surfaces with higher sensitivity were obtained) in Al-Si alloys due to increase in Si content in alloy and to increase in cooling rate and cutting speed (from %2Si to %12Si).

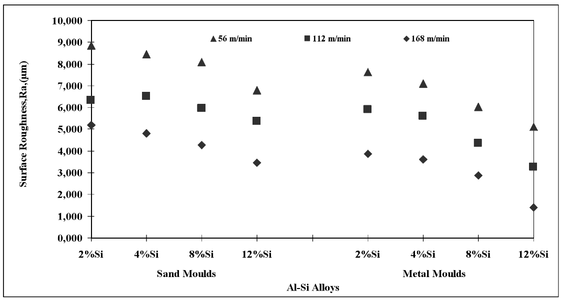


Fig.6 Relationship between surface roughness and cutting speeds of Al-Si alloys (*DoC:0.5 mm, f:0.10 mm/rev*).

When analysed the chips formed during the machining of samples in the study (Fig.7), chip formation was observed to change due to increases in cooling rate, %Si content in alloy, and to rise in cutting speed. It may be noted that the rise in

Si content and cooling rate in Al-Si alloys had an effect on chip lengths being shorter. From this point of view, Si found in microstructure has an impact on chip formation due to a rise in %Si content of alloy and cooling rate.

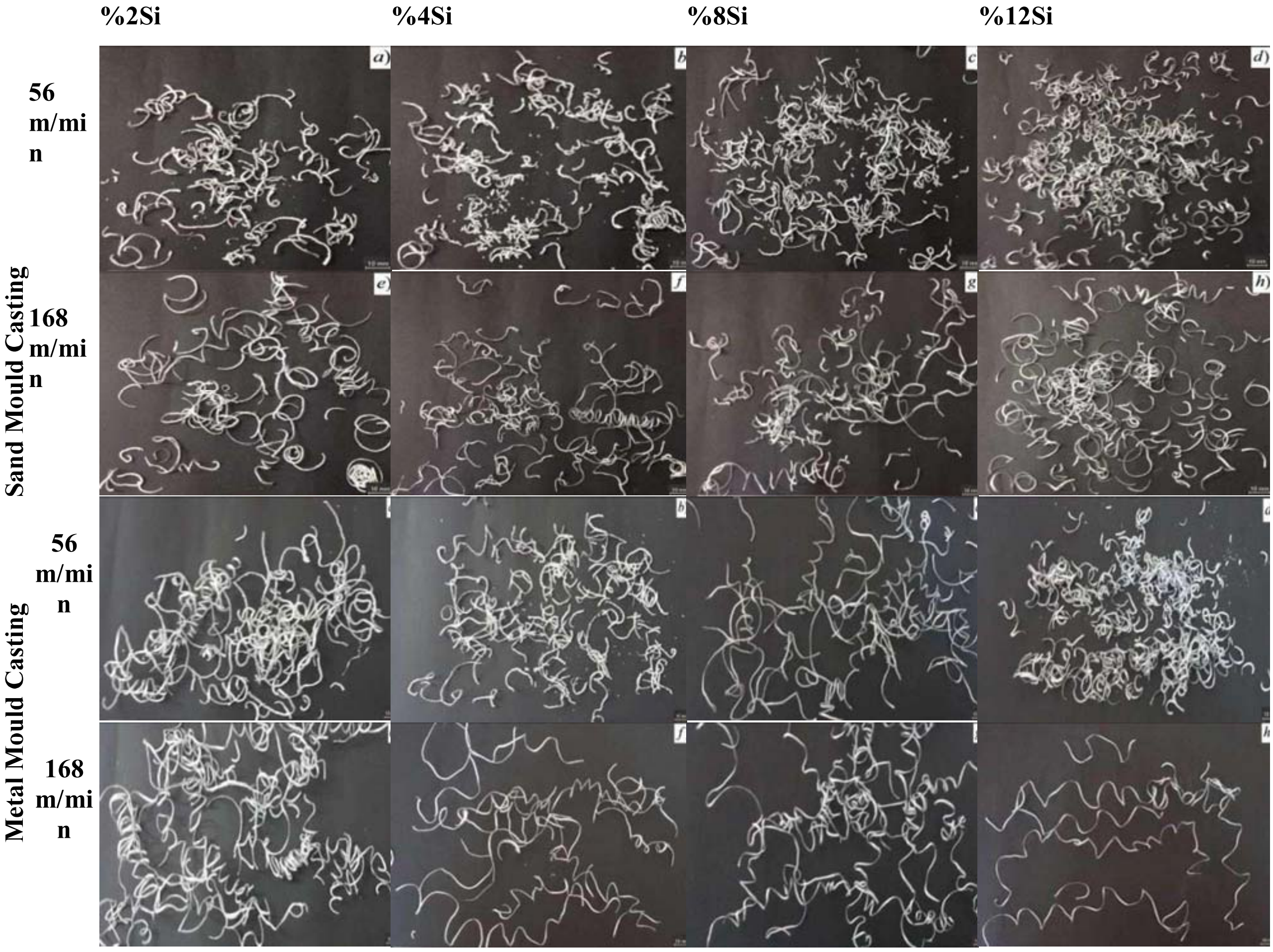


Fig.7(a-h) Chip formation of Al-Si alloys (V_c:*56-168 m/min,* DoC:0.5 mm, f:0.10 mm/rev)

Images on cutting edged surfaces used in the experiment are shown in Fig.8. Depending on the increase in %Si content in alloy and on cooling rate, FBU was observed to form on the cutting edge from the broader surface toward the narrower surface of the edge (Fig.8). Similar occurs with the increase in cutting speed. Flank Build-up (FBU) formation was observed on cutting edge surfaces between the work piece and cutting edge surface due to dry adhesion (Fig.8). The said build-up (FBU) was found to occur more on the cutting edge of Al-Si alloy containing 2%Si and to spread on yield surfaces to a wider area (Fig.8a). It was also observed in the alloy containing 12%Si that flank build-up (FBU) was less; however, wear occurred further to the edge and deeper (Fig.8h).

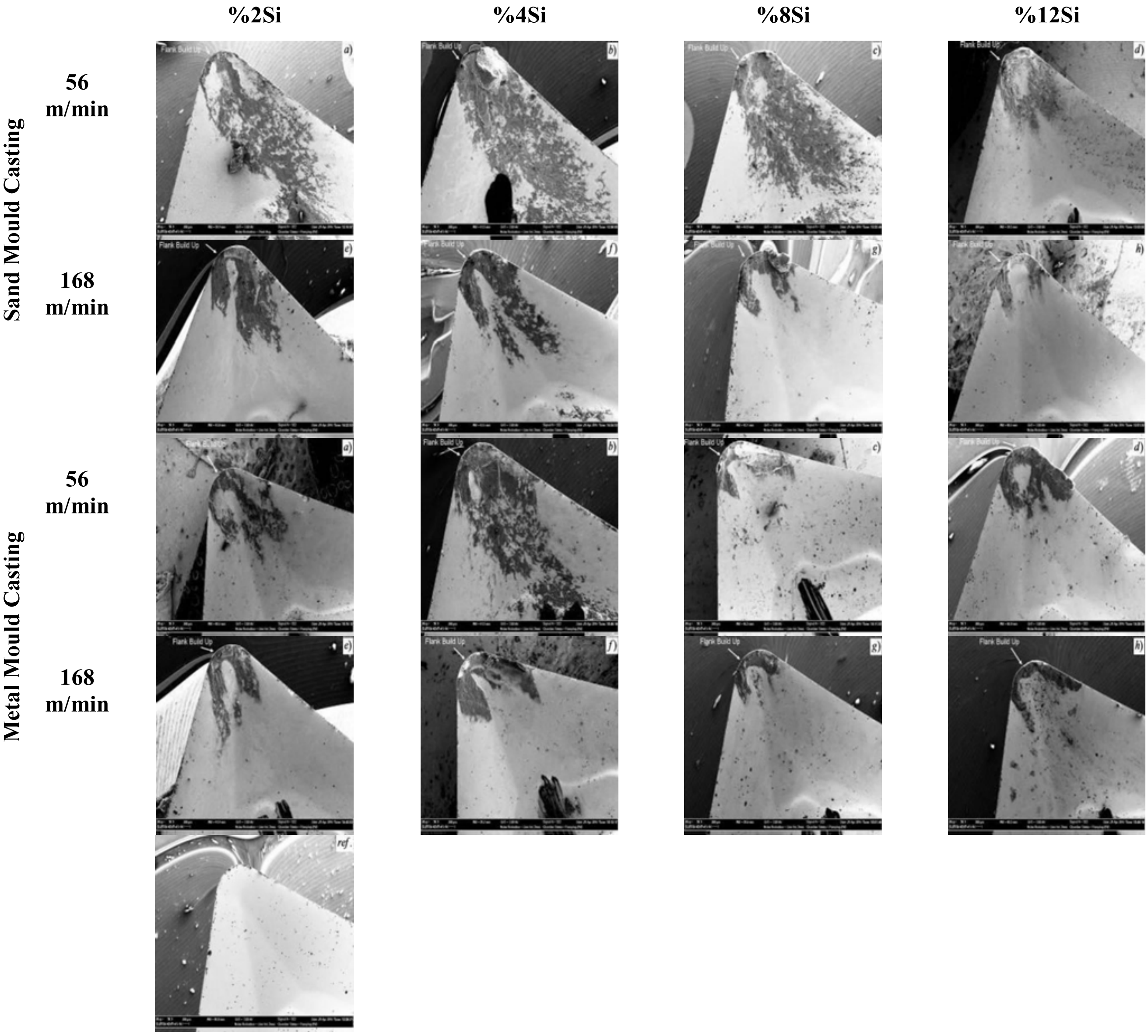


Fig.8 (a-h) SEM image of cutting tool tip used for machining of Al-Si alloys *(V_c:56-168m/min, DoC:0.5 mm, f:0.10 mm/rev)*

In the experimental study, mechanical properties and machinability of Al-Si alloys were observed to improve due to increases in the %Si content and cooling rate in Al-Si alloys (Fig.4-6) Thanks to the rise in %Si in alloy, it was established that chip breaks were facilitated and that this manifested an impact in the form of decreasing cutting forces. The fact that lower cutting forces occurring especially in Al-Si alloy containing 12%Si shows that Si in the structure have a positive impact on machinability. Lower cutting forces in samples removed from metal moulds manifest the effect of cooling rate. It may be noted that cutting forces decrease (machinability increases) due to a rise in cooling rate.

Cutting forces were observed as higher (in both moulds) at lower cutting speeds. It may be argued that the reason for cutting forces being higher at lower cutting speeds as a result of dislocation deposit at lower cutting speeds (deformation hardening/work hardening) [15-17] and that cutting forces rose as a result of chips built-up (FBU) and adherence on cutting edge due to local heating from friction. From this point of view, Si presence in Al-Si alloys (increase in %Si amount) had an impact in the form of dropping cutting forces, and as a result, machinability increased. It was observed in the study that increases in cooling rate and in Si content in Al-Si alloys positively affected mechanical properties and machinability properties of the alloy. Data from the previous sections of the study (Fig.2) support the mechanical test results (Fig.3-4) and data obtained from the machinability section (Fig.5-8). Data obtained from the study complies with the literature [1-11].

The below results were acquired from the experimental study;

- In Al-Si alloys, cutting forces (Fc) formed in experiment samples from the metal mould were lower (compared to samples from sand mould). Rise in the cooling was observed to have an impact in the form of lowering the cutting forces. Therefore, machinability of alloys was improved.
- Machinability of alloys increased parallel to the rise in the %Si content in Al-Si alloys (cutting forces decreased). It was observed that the rise in %Si amount in alloy (Si found in microstructure becoming evident/increasing) had an impact in the form of lowering the cutting forces.
- Mechanical properties of alloys (Hardness and UTS) were observed to increase due to the rise in the %Si content in Al-Si alloys. On the other hand, %El decreased. The rise in the %Si content in alloy (Si found in microstructure becoming evident) had an impact in the form of increasing mechanical properties (Hardness and UTS).
- Cutting forces were observed as higher (in both moulds) at lower cutting speeds. A drop was observed in cutting forces due to rising cutting speeds.
- Surface roughness (Ra) values were observed as decreased (finer surfaces) being inversely proportional to the rise in the %Si amount in alloy. Surface roughness values were observed as higher at lower cutting speeds (rougher surfaces were formed). Lowest surface roughness values were obtained from samples from metal moulds.
- Rise in the %Si amount in alloy was observed to have an impact on chip formation. Chips were established to form at shorter lengths due to increases in %Si amount in alloy and in cutting speed. Chips were observed to form at shorter lengths due to the effect of %Si in Al-Si alloy with higher hardness (containing 12%Si). Chips were formed at longer lengths in 2%Si alloy.
- Rises in cooling and %Si content were observed to affect Flank Build-up (FBU) formation on cutting tool edge. It was established that FBU spread on the cutting edge surface, and that the FBU formation was higher in Al-Si alloy containing 2%Si with higher ductility.

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