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Influence of Al content on machinability of AM series magnesium alloys

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Abstract

This study investigates the effects of Al (aluminium) amount in AM series magnesium alloys on mechanical properties and machinability (cutting forces). Changes in microstructure and mechanical properties and their effects on cutting forces were analysed depending on the increase in Al amount. For this reason, AM series magnesium alloys (AM20, AM40, AM60, and AM90) with varying amounts of Al % (from 2 to 9 %) were used in the study. It was observed that in AM series magnesium alloys (containing 0.5 % Mn), intermetallic phases found in microstructure ($Mg_{17}Al_{12}$ and Al_8Mn_5) improved the mechanical properties and lowered machinability by rising the cutting forces (Fc) depending on the increase in Al amount. Also, the surface roughness (*Ra*) of intermetallic phases was observed to have an impact on flank build-up – FBU and chip formation. While AM90 had the highest values in terms of mechanical properties and surface quality, AM20 had the lowest values. On the other hand, AM20 had the highest El% values and machinability properties.

Key words: machinability, cutting force, AM series magnesium alloys, flank build-up (FBU), surface roughness, chip formation

1. Introduction

Today, magnesium and its alloys are predominantly used in automotive, electronics, and aviation sectors along with various other fields. Magnesium alloys have a distinct advantage over other alloys due to their mechanical and lightweight properties [1, 2]. When considered their weight-strength and weight-hardness properties, magnesium alloys are among the most lightweight construction metals of significantly improved mechanical properties [2–4]. Especially in the automotive and aviation fields, they offer more economical fuel consumption and eco-friendly solution, reducing the material weight and SO_x, CO_2, and NO_x emissions [1–6]. Therefore the number of scientific studies, in recent years, on magnesium alloys have been on the increase. Within this scope, the most common magnesium alloys used in today's industries are AZ series, AS series, and AM series magnesium alloys (aluminium (A-Al), zinc (Z-Zn), silicon (S-Si), manganese (M-Mn)) [1, 5, 6]. To this end, various magnesium alloys have been produced and characterized by various techniques. The main subject of studies on magnesium alloys generally consists of the investigation of microstructure and mechanical properties such as hardness, wear, and creep resistance. Also, there have been ongoing researches to improve creep and fatigue strengths of magnesium alloys under high temperatures.

Studies on the machinability of magnesium alloys are focused primarily on cutting tool materials and cutting angles along with flank build-up (FBU) formation, and their relation with combustion [4–10]. However, these kinds of studies are limited and insufficient to expound the machinability of these alloys.

To author's best knowledge, an investigation of the effects of aluminium amount in AM series magnesium alloys on the machinability is nonexistent. Hence, this study presents in-depth aims to determine the effects of alloy components in AM series magnesium alloys containing varying amounts of aluminium added into the alloy on the mechanical properties, machinability (cutting force), the surface roughness (*Ra*), flank build-up and alloy chip morphology.

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Table 1. The chemical composition of the studied AM series magnesium alloys in wt.%

Alloys*	Al	Mn	Zn	Si	Fe	Mg
AM20	1.9	0.4	0.15	0.01	0.01	Rest
AM40	4.3	0.4	0.15	0.01	0.01	Rest
AM60	6.5	0.4	0.15	0.01	0.01	Rest
AM90	9.4	0.4	0.15	0.01	0.01	Rest

*"A" refers to Al content and "M" refers to Mn content in the alloy

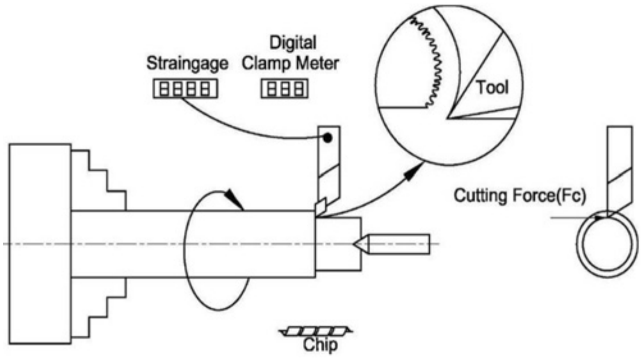

Fig. 1. Schematic representation of experimental set-up with strain.

2. Experimental procedure

AM series magnesium alloys (from 2 to 9 % Al) were used in this study. Magnesium and aluminium bullions at 99 % purity along with AlMn (10 %) master alloy were used in the experimental study. Magnesium and aluminium bullions were purchased from Nova Metal Co., Turkey. Samples used in the experimental study were obtained by melting in an atmosphere-controlled furnace and by casting (at 750 °C) under protective gas (SF_6 gas) into cast iron mould (preheated to 260 °C). The chemical compositions of the alloys used in casting were determined by Spectrolab M8 Optical Emission Spectrometry (Table 1). The dimensions of the cast samples were 22 mm in diameter and 200 mm in length. The cast was carried out to obtain 24 samples from each series. A study by Unal [11] can be referred to the casting methods and process phases of magnesium alloys.

In this study, the surface of the experimental samples (at 16 mm diameter and 10 mm thickness) were cleaned by various sandpapers (emery papers from 200 up to 1200 grits) to observe the microstructure of these alloys. Then, surfaces of these samples were polished by diamond abrasives (6, 3, and 1 μm diamond paste). Surfaces of samples were etched in a solution (100 ml ethanol, 5 ml Acetic acid, 6 g picric acid and 10 ml water) and thus microstructure images were obtained. Microstructures of samples that were subjected to etching process were analysed by an optical microscope (OM; Nikon Eclipse LV150) and scanning electron microscopy (SEM).

Data on the tensile strength of AM series magnesium alloys obtained from tensile tests (Ultimate Tensile Strength (UTS), Yield Strength (YS), and Elongation (El%)) were performed at room temperature according to the ASTM E 8M-99 standard with a crosshead speed of 0.8×10^{-3} mm s^{-1} (Shimadzu Autograph AGS-J 10 kN Universal Tester) on tensile test samples which had a gage diameter and length of 8 and 40 mm, respectively. The averages of minimum six samples were taken into account in the determination of tensile values.

Machining (turning) tests were performed on Alpha300 DMG CNC turning lathe. Machining (turning) procedures were carried out by using Polycrystalline Diamond (PCD) (Taegutec CCGT 120408 FL K10) cutting edge under dry machining conditions. Data on cutting forces in the study were obtained by measuring with specially designed and manufactured strain gage (Fig. 1).

In this study, cutting forces were measured in machinability tests at varying cutting speeds (by maintaining chip section). In the meantime, cutting depth and feed rate were kept at a fixed rate (depth of cut $a = 1$ mm, feed rate $f = 0.10$ mm rev^{-1}).

This study was conducted to determine the machinability of these alloys based on the cutting forces obtained from the experimental study. Data on cutting forces were obtained after surfaces of cast samples were cleaned with 1 mm turning. Cutting force data were obtained by machining (from each sample at a diameter of 20 mm). Surface roughness values of the sample surfaces were measured with Time-TR200 device. Machining parameters used in the experimental study are given in Table 2.

3. Results and discussion

3.1. Microstructural properties

Microstructure images obtained from OM and SEM of AM series magnesium alloys are given in Figs. 2a–d. The microstructure of these alloys is seen to be made up of α-Mg, $Mg_{17}Al_{12}$, and Al_8Mn_5 intermetallic phases as shown in Figs. 2a–d. The intermetallic phase and α-Mg grain (grain size seen on the scale) can easily be distinguished from the matrix under OM and SEM (Figs. 2a–d). The microstructure of these alloys consists of primary α-Mg and intermetallic phases (arranged along the α-Mg matrix grain boundary) which is consistent with the published literature [12–16]. The location and form of intermetallic phases found in microstructure were ob-

T a b l e 2. Machining parameters and conditions used during the test

Operations	Turning
Feed rate f (mm rev^{-1})	0.10 (constant)
The depth of cut a (mm)	1.0
Cutting speed V_c (m min^{-1})	56, 112, 168
Cutting & coolant	Orthogonal, dry cutting
Workpiece materials	AM Series magnesium alloys (from 2 to 9 % Al)
Cutting tool	Taegutec CCGT 120408 FL K10

α	γ	λ	ε	κ	r_ε
7°	5°	0°	80°	50°	0.8 mm

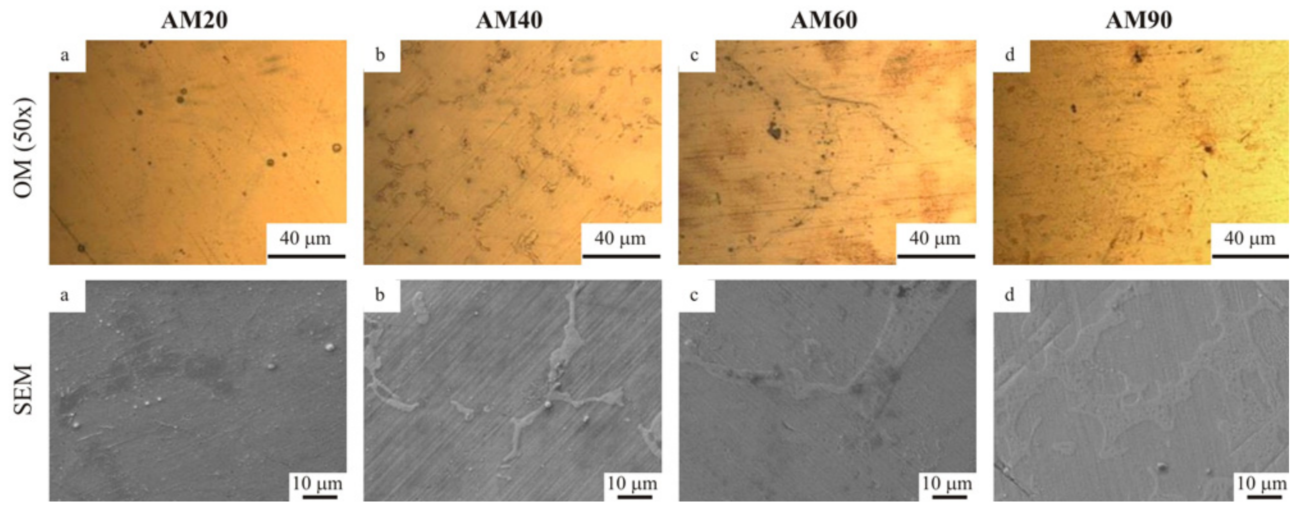

Fig. 2. Optical micrographs of AM series magnesium alloys.

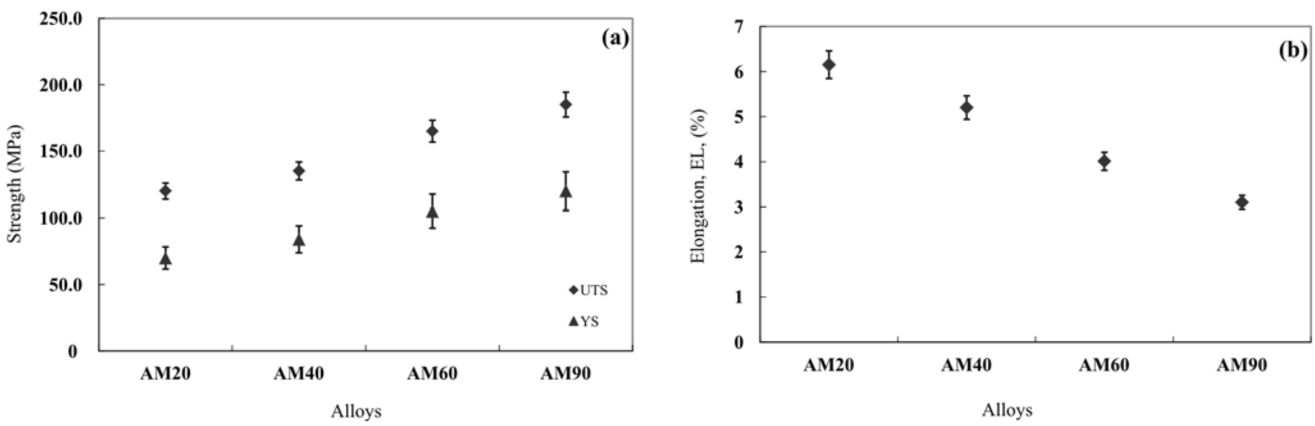

Fig. 3. Tensile tests of AM series magnesium alloys (a) UTS, YS and (b) El%.

served to change depending on the increase in the amount of Al % in the alloy (containing 0.5 % Mn in all alloys) [2–7]. Net-like intermetallic phases had been progressively increased with the increasing Al content (Figs. 2a–d). Microstructure images obtained in this study were in accordance with the literature [12–16].

3.2. Mechanical properties

Tensile tests of AM series magnesium alloys anal-

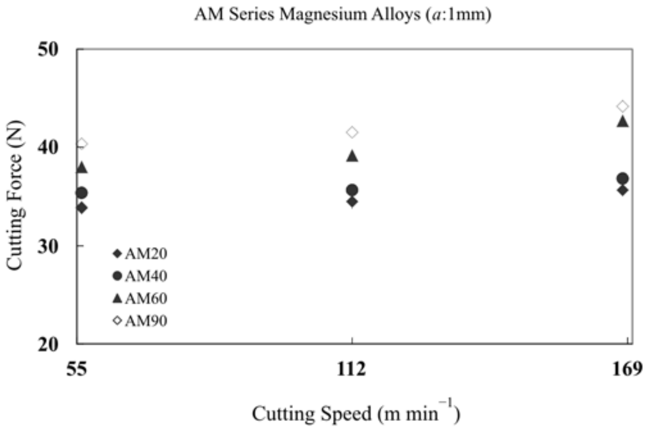

Fig. 4. The relationship between cutting forces and alloy compositions of AM series magnesium alloys; ($a = 1$ mm, $f = 0.10$ mm rev^{-1}).

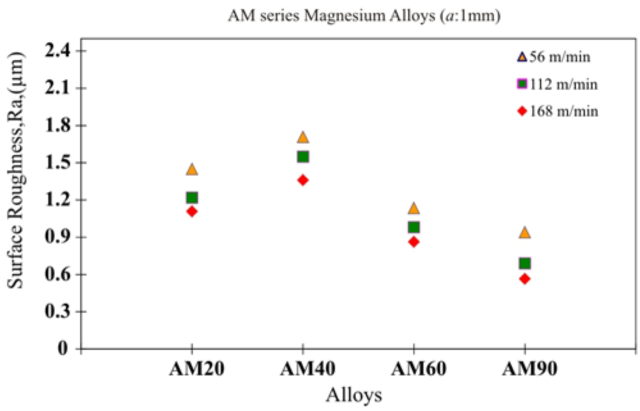

Fig. 5. The relationship between surface roughness and cutting speeds of AM series magnesium alloys ($a = 1$ mm).

ysed in the experimental study were carried out. Data obtained from the study were prepared in the form of graphs (Fig. 3a–b).

The highest UTS and YS values were obtained for AM90 in tensile tests. On the other hand, it was observed that the AM90 alloy had the lowest El% value. When these results were evaluated, it was observed that intermetallic phases ($Mg_{17}Al_{12}$ and Al_8Mn_5) could be very effective in strengthening these magnesium alloys [7–16].

3.3. Machining properties

In the experimental study, data on cutting forces of AM series magnesium alloys were obtained (by keeping chip section fixed) at varying cutting speeds as shown in Fig. 4. An increase was observed in cutting forces depending on the increase of Al amount found in AM series magnesium alloys (Fig. 4).

The increase in cutting forces in AM series magnesium alloys was observed gradually from AM20 (2 % Al) alloy to AM90 (9 % Al) alloy (Fig. 4). There was an increase in cutting forces depending on the rise in cutting speeds (Fig. 4). While the lowest cutting force in all cutting speeds (three cutting speeds) was obtained in AM20 alloy, the highest cutting force (in three cutting speeds) was observed in AM90 alloy. The cutting force value at the lowest cutting speed (56 m min^{-1}) was measured as 33.8 N in AM20 alloy whereas it was measured as 40.3 N in AM90 alloy. When the cutting speed was increased to 168 m min^{-1}, cutting speeds were measured as 35.6 N in AM20 and 44.1 N in AM90. When these results were evaluated, it was observed that an increase in the amount of Al in these alloys (intermetallic phases ($Mg_{17}Al_{12}$ and Al_8Mn_5)) (when 0.5 % Mn was kept fixed) could be effective on cutting force of these magnesium alloys [7–16].

From this point of view, it may be noted that the increase in cutting forces depending on cutting speed could occur due to dislocation build-up with chips in cutting edge [17–23]. The reason for this was the increase in cutting forces with the effect of intermetallic phases ($Mg_{17}Al_{12}$ and Al_8Mn_5) observed in the microstructure. It can also be noted that predominantly in AM90 alloy, the occurrence of the highest cutting force leads to an increase in cutting forces of intermetallic phases in the structure (and thus decreased machinability).

Surface roughness values (*Ra*) occurred by machining AM series magnesium alloys (at fixed chip section) are given in Fig. 5. A decrease was observed in the experiment in surface roughness with an increase in the amount of Al and cutting speeds. It may be noted that intermetallic phases ($Mg_{17}Al_{12}$ and Al_8Mn_5) formed due to Al and Mn effect/presence in these alloys have an impact in the formation of surface roughness values. The lowest surface roughness was observed in AM90 alloy (the highest surface quality) (Fig. 5).

Wear occurred on cutting edge surface due to machining of AM series magnesium alloys is shown in Fig. 6. When the cutting edge surfaces used in the experiment were observed, it may be noted that FBU was formed due to dry adhesion between the workpiece and cutting tool surface during the machining of experimental samples [8, 9, 15] and that the cutting edges were worn. The deepest wear in this study was seen in the cutting edge of AM90 alloy (Fig. 6h). Intermetallic phases occurred/found in the alloy ($Mg_{17}Al_{12}$ and Al_8Mn_5) were effective in the increase of the cutting forces, and thus, the surface of AM90 was worn more. FBU formation increased on the cutting tool due to the effect of intermetallic phases between the cutting edge and sample surface contact point and also this caused an increase in the cutting forces (Fig. 4) [17–23]. It can also be said that FBU formation in-

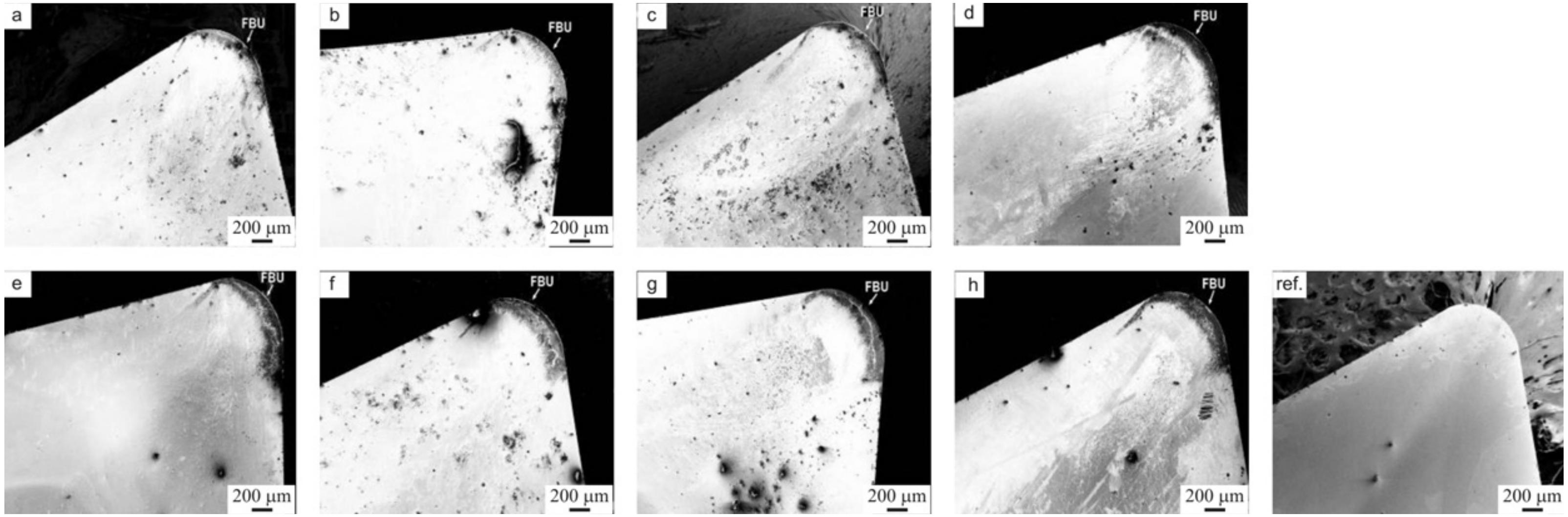

Fig. 6. SEM image of cutting tool tip used for machining of AM series magnesium alloys: (a) AM20, $V_c = 56$ m min^{-1}, (b) AM40, $V_c = 56$ m min^{-1}, (c) AM60, $V_c = 56$ m min^{-1}, (d) AM90, $V_c = 56$ m min^{-1}, (e) AM20, $V_c = 168$ m min^{-1}, (f) AM40, $V_c = 168$ m min^{-1}, (g) AM60, $V_c = 168$ m min^{-1}, and (h) AM90, $V_c = 168$ m min^{-1}; ($a = 1$ mm, $f = 0.10$ mm rev^{-1}).

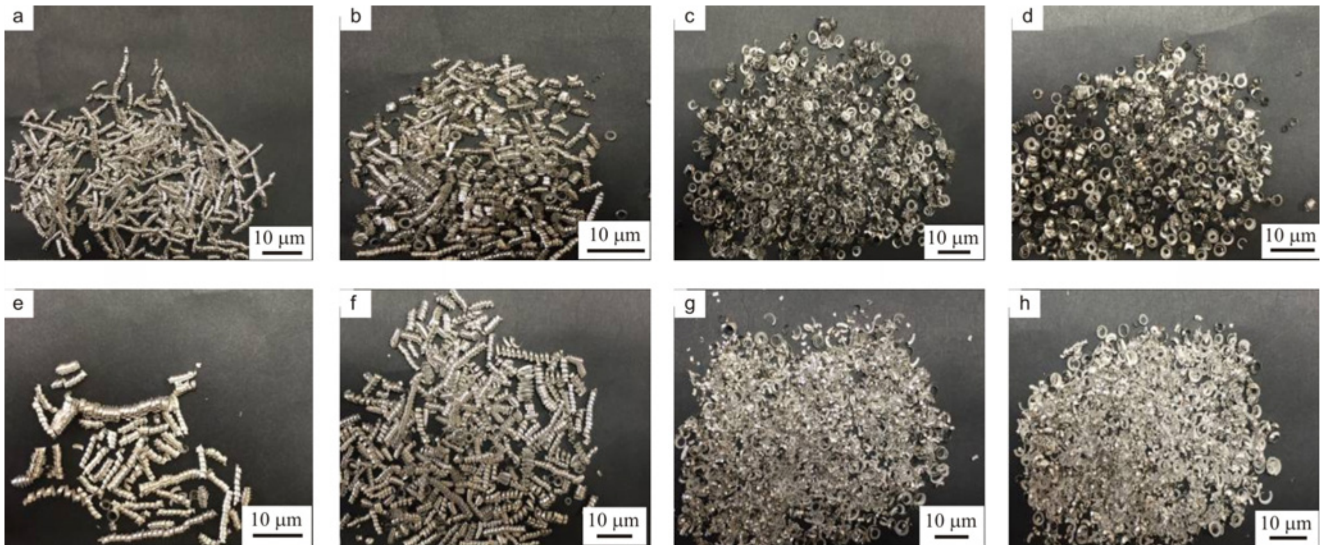

Fig. 7. Chip formation of AM series magnesium alloys: (a) AM20, $V_c = 56$ m min^{-1}, (b) AM40, $V_c = 56$ m min^{-1}, (c) AM60, $V_c = 56$ m min^{-1}, (d) AM90, $V_c = 56$ m min^{-1}, (e) AM20, $V_c = 168$ m min^{-1}, (f) AM40, $V_c = 168$ m min^{-1}, (g) AM60, $V_c = 168$ m min^{-1}, and (h) AM90, $V_c = 168$ m min^{-1}; ($a = 1$ mm, $f = 0.10$ mm rev^{-1}).

creased with friction and temperature rise on the cutter surface due to an increase in cutting speed, and as a result of this, cutting forces also rose. With regard to this, it can also be noted that intermetallic phases formed by the impact/presence of Al and Mn in AM90 were observed to be more significantly effective [8, 9, 12–16] and caused more wear on the cutting tool when compared to AM20.

When checking the formation of chips obtained from the samples in the study (Fig. 6), it was observed that intermetallic phases occurred due to the increase of Al amount (with the effect of Al and Mn) in the alloy had an impact on chip formation (chip morphology) (Fig. 6). During the analysis of chip images formed in these alloys, it was observed that AM90 had more curled and shorter chips when compared to chips of other alloys. The reason for this can be attributed to the harder and more brittle characteristics of intermetallic phases ($Mg_{17}Al_{12}$ and Al_8Mn_5) [9, 13, 17] (Fig. 7).

Data obtained from this section, microstructure examinations conducted in previous sections (Fig. 2a–d), and tensile test results (Fig. 3) support each other.

4. Conclusions

The results below were obtained from this experimental study:

– The microstructural analysis revealed that a network of the intermetallic phase around the grain boundaries had been formed and the amount of intermetallic phase increased with an increase of aluminium content in the magnesium alloys.

– It was also observed that in AM series magnesium alloys (containing 0.5 % Mn), intermetallic phases found in microstructure ($Mg_{17}Al_{12}$ and Al_8Mn_5) improved the mechanical properties (strength) and lowered machinability by rising the cutting forces (Fc) depending on the increase in Al amount.

– Tensile strengths (UTS and YS) increased with the addition of Al to AM series magnesium alloys. Strengths of these alloys (from AM20 to AM90) increased gradually. The highest UTS and YS, and the lowest El% were observed in the AM90 alloy. The reason for this could be attributed to the existence of intermetallic phases in this alloy.

– The surface roughness of alloys decreased due to an increase in the amount of Al, and the lowest surface roughness was obtained for AM90 (in all cutting speeds). Also, it was observed that intermetallic phases had an impact on FBU and chip formation.

– Cutting forces increased linearly as the cutting speed increased for all studied alloys which were attributed to FBU at the tip of the cutting tool during machining. Cutting force of these alloys (from AM20 to AM90) increased and machinability decreased gradually.

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