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A study on wear and machinability of AZ series (AZ01-AZ91) cast magnesium alloys

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Abstract

This study investigated the effect of aluminum (Al%) amount found in AZ series magnesium alloys on hardness, wear resistance, and machinability. The amount of zinc (1 % Zn) used in the experiment was kept fixed, and changes on hardness, wear resistance, and machinability were analyzed depending on the increase in the amount of Al%. To this end, AZ series magnesium alloys (AZ01, AZ21, AZ41, AZ61 and AZ91) (that include aluminum at rates ranging from 0 up to 9 %) were used in the study. It was observed in AZ series magnesium alloys that intermetallic phase in microstructure (β-$Mg_{17}Al_{12}$) affected hardness, wear resistance, and machinability of the alloy depending on the increase in Al amount. It was established that $Mg_{17}Al_{12}$ intermetallic phase in the microstructure of AZ91 alloy increased the machinability of the alloy.

Key words: machinability, cutting force, wear resistance, AZ series magnesium alloys, flank build-up

1. Introduction

Magnesium and its alloys have numerous areas of use due to their mechanical, physical, and chemical properties. In addition to possessing especially low density, high strength, and wear properties, such characteristics of these alloys as being among the lightest construction metals, and also weight-strength and weight-hardness properties enabled use of these alloys in many areas, predominantly in logistics, automotive, and aviation [1–3]. For this reason, recent years saw an increase in the number of studies on the preparation of magnesium alloys with varying alloy properties and on the development of such characteristics as mechanical properties, hardness, and wear [4, 5].

It is of importance for magnesium alloys to be used predominantly in automotive, aviation and logistics sectors in terms of reducing weight, efficient use of energy resources, and decreasing environmentally harmful emissions (SO_X, CO_2, and NO_X emissions).Within this scope, among the most commonly used magnesium alloys in today's industries are AZ series magnesium alloys (aluminum (Al), zinc (Zn)) [6–8]. Studies conducted on magnesium alloys are observed to generally focus on such subjects as microstructure and mechanical properties analyses, hardness, and creep properties. To this end, different alloys are being obtained for the reason of improving the said properties, and tests are carried out on these alloys. However, studies conducted on the machinability of magnesium alloys are quite scarce and insufficient. Studies on the machinability of magnesium alloys generally concentrated on chip formation, cutting material, and especially Flank Build-up (FBU) formation and the relation of burning [9–11].

Our literature review concluded that a study that investigated the effect of Al% amount in AZ series magnesium alloys on wear resistance and machinability was non-existent. This study examined the effect of alloy components in AZ series magnesium alloys containing Al% at different rates (ranging from 0 up to 9 %) on wear resistance and machinability. Changes in hardness, wear resistance, and machinability depending on the increase in Al% amount were investigated keeping the zinc amount (1 % Zn – zinc) fixed in alloys used in the experiment. By investigating microstructure characteristics of these alloys named the AZ series magnesium alloys (AZ01 – AZ91), the effect of inter-

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Table 1. Chemical composition of the studied AZ series magnesium alloys in wt.%

Alloys*	Al	Zn	Mn	Si	Fe	Mg
AZ01	0.4	1.2	0.12	0.13	0.02	rest
AZ21	1.9	1.2	0.13	0.08	0.02	rest
AZ41	4.3	1.2	0.11	0.09	0.02	rest
AZ61	6.5	1.2	0.15	0.11	0.02	rest
AZ91	9.5	1.2	0.11	0.12	0.02	rest

* "A" refers to Al content and "Z" refers to Zn content in the alloy

metallic phases on mechanical properties, wear, and machinability was analyzed. Within this scope, this study is important.

2. Experimental procedure

2.1. Microstructural, XRD and mechanical properties

AZ series magnesium alloys (AZ01 – AZ91) were used in the experimental study. Mg, Al, and Zn bullions at 99 % purity used in the experimental study were purchased from Bilginoglu Metal Co. These alloys were obtained by casting method and melted in a specially designed atmosphere-controlled furnace (750 ℃). A graphite crucible with 5 kg magnesium melting capacity was used to melt magnesium alloys. Protective argon gas was released in the furnace during the whole melting process in an aim to prevent the contact of the molten metal with atmosphere inhibiting ignition. After the alloy reached casting temperature, molten liquid metal was casted into a mold from below the melting furnace (by using SF_6 protective gas). Zn addition was carried out 3 min before the casting to avoid loss of Zn due to vaporization. Protective gas (CO_2 + SF_6 gas) was released in the mold to prevent ignition during casting. Cylindrical samples used in the experiment were formed as a result of casting into metal molds. Samples were prepared by casting in metal mold preheated to 250 ℃ under protective SF_6 gas. Samples obtained by casting were 24 mm in diameter and 200 mm in length. The chemical compositions of the alloys used in casting were determined by Spectrolab M8 Optical Emission Spectrometry (OES). A study by Unal [12] can be referred to for detailed information on casting methods of magnesium alloys. Components of alloys used in the study are given in Table 1. Microstructure analysis, hardness, wear, and machinability tests were carried out on these samples that were obtained by casting method.

Of the samples used in microstructure analyses and hardness tests of alloys, 5 of each (15 mm in diameter and 12 mm in length) were prepared. Surfaces of these samples were cleaned by sanding (using emery papers from 200 up to 12 grits). Then, the surfaces of these samples were polished by diamond paste (6, 3 and 1 μm, respectively). Following polishing process, surfaces of samples were etched in a specially prepared solution (contents: 100 ml ethanol, 5 ml acetic acid, 6 g picric acid, and 10 ml water). Microstructures of etched samples were then analyzed (Nikon Eclipse LV150). X-ray diffraction (XRD) analyses (Panalytical-Empyrean) were carried out under Cu Kα radiation with an incidence beam angle of 2°. Later on, hardness tests were conducted. Test data on mean hardness values of alloys used in the study were obtained (Shimadzu HMV-2). Hardness tests were conducted by applying two different loads (0.5 and 10 N) on surface of test samples for 20 s. Each measurement was repeated at least 10 times. Then, hardness values of alloys were determined by averaging the values applied on sample surfaces at different loads.

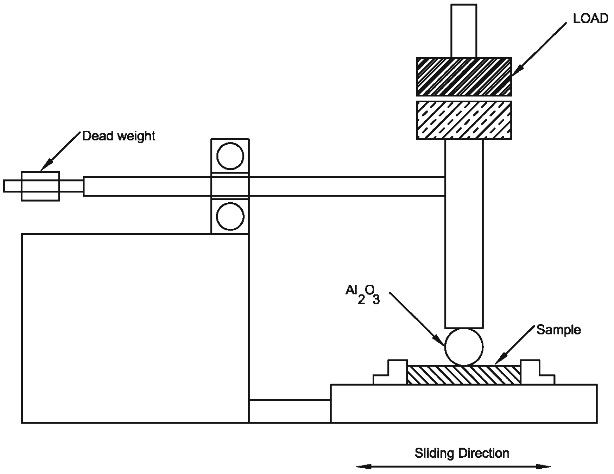

Fig. 1. Schematic view of the reciprocating wear tester utilized in this study.

Wear tests of AZ series magnesium alloy experimental samples (15 mm in diameter and 12 mm in length) were carried out on a pin-on disk test device (Tribotester TM, Clichy) (Fig. 1). At the end of wear test, sizes of marks left on sample surfaces were measured and thus wear resistances of samples were estimated. Wear tests were performed on a reciprocating wear tester under a load of 4 N. Al_2O_3 balls having a 6 mm diameter rub on the surfaces of the samples with a sliding speed of 5 mm s^{-1}. The stroke of the Al_2O_3 balls was 5 mm for the total sliding distance of 25 m. Wear test samples had 15 mm diameter and 10 mm length. The coefficient of friction and frictional force were continuously recorded throughout the wear tests. Contact sur-

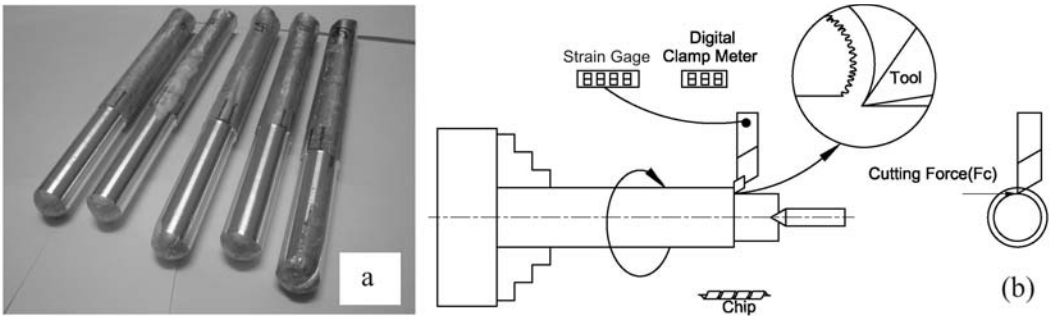

Fig. 2. Test samples of AZ series Mg alloys (a), schematic representation of experimental set-up with strain gage (b).

Table 2. Machining parameters and conditions used during the test

Parameters and conditions						
Operations	Turning					
Feed rate (*f*)	0.10 mm rev^{-1}					
Depth of cut (DoC)	0.5 mm					
Cutting speed (V_c)	56, 112, 168 m min^{-1}					
Lubricant &	Dry cutting / Orthogonal					
Coolant/Cutting	AZ series Mg alloys (AZ01–AZ91)					
Workpiece materials	Taegutec CCGT 120408 FL K10					
Cutting tool	α	γ	λ	ε	κ	r_ε
	7°	5°	0°	80°	50°	0.8 mm

faces of the samples were examined using a surface profilometer (Dektak TM6M). Wear test conducted in the experimental study is given schematically in Fig. 1.

2.2. Machining properties

In this study, data on cutting speeds were obtained by keeping the chip section fixed in various cutting speeds on AZ series magnesium alloys prepared by casting method (Fig. 2a). Machinability of alloys was investigated by the obtained cutting forces. Cylindrical samples with 20 mm diameter and 190 mm length were used in experiments. Samples were processed in the lathe machine by binding between the chuck and tailstock. DMG CTX Alpha 300 CNC lathe machine was used in machining tests. Data on cutting forces were obtained by conducting cylindrical turning process under dry machining conditions and vertical processing method on samples. Polycrystalline Diamond (PCD) (CCGT 120408 FL K10) was used as the cutting edge. Data on cutting forces were obtained from specially designed strain gage (Fig. 2b). Surface roughness values of sample surfaces were measured by Time-TR200. Machining parameters used in the study are given in Table 2.

3. Experimental results and discussion

3.1. Microstructural, XRD and mechanical properties

Microstructure photographs and XRD patterns of AZ series magnesium alloys used in the study are given in Figs. 3a–d and 4, respectively. Microstructure of magnesium alloys analyzed in the study was generally observed to be made up of α-Mg matrix and $Mg_{17}Al_{12}$intermetallic phase along with $\alpha+\beta$ eutectic phase. Among the studied alloys, AZ91 alloy was significantly observed to have intermetallic phase (β-$Mg_{17}Al_{12}$) (Fig. 3d). It was established that location and form of intermetallic phases found in the microstructure changed depending on the Al% amount in alloys (Fig. 3a–d). In AZ series magnesium alloys, the fact that intermetallic phase (β-$Mg_{17}Al_{12}$) within the microstructure occurred in the form of a network around α-Mg matrix was reported in studies [6, 13, 14]. It was noted in literature that intermetallic phase form and formation within the microstructure in AZ series alloys (β-$Mg_{17}Al_{12}$) were related with the presence of Zn and Al% amount. It is known that β intermetallic phase started to become evident thanks to Al amount within the alloy increasing above 3 % and microstructure shifted due to changes in the solidific-

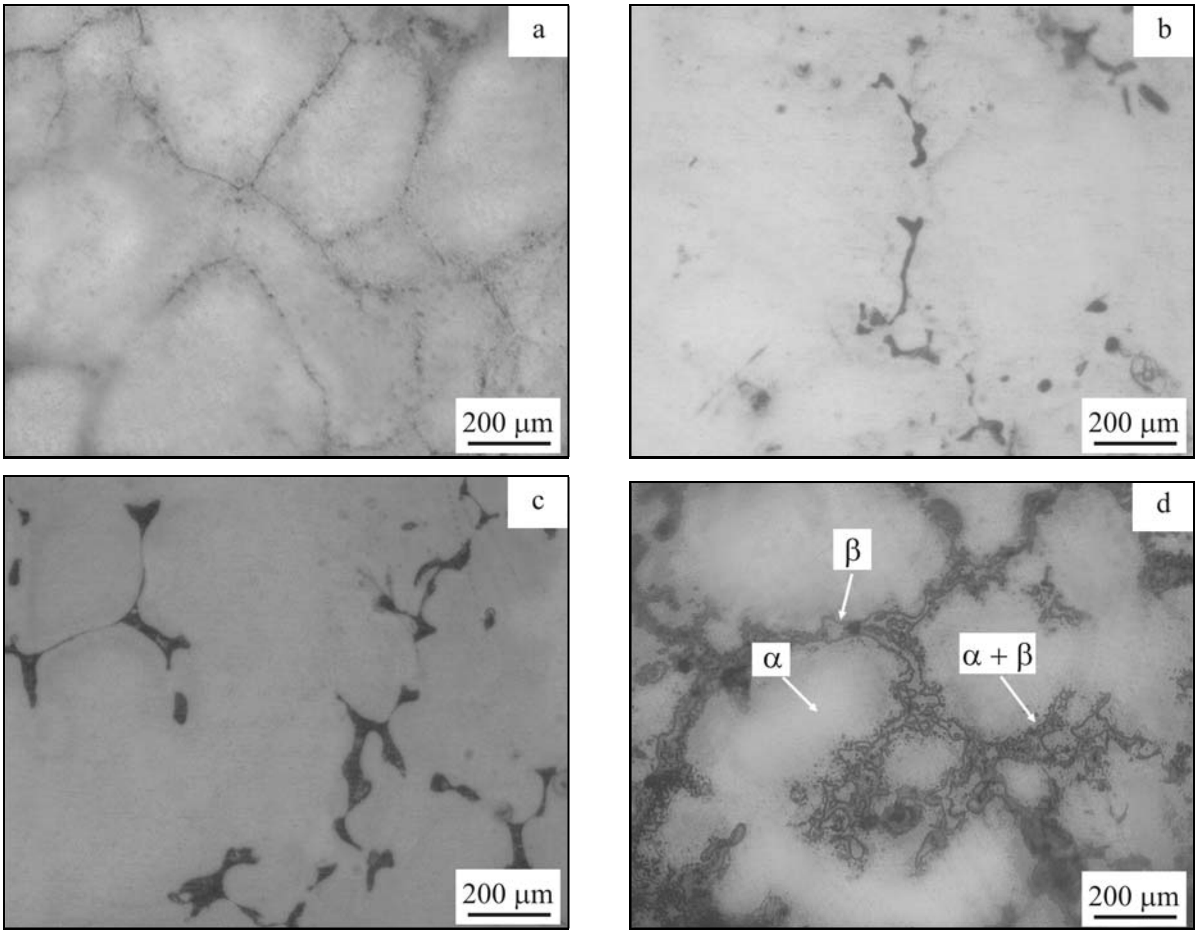

Fig. 3. Optical micrographs of AZ21 (a), AZ41 (b), AZ61 (c), and AZ91 (d) Mg alloys.

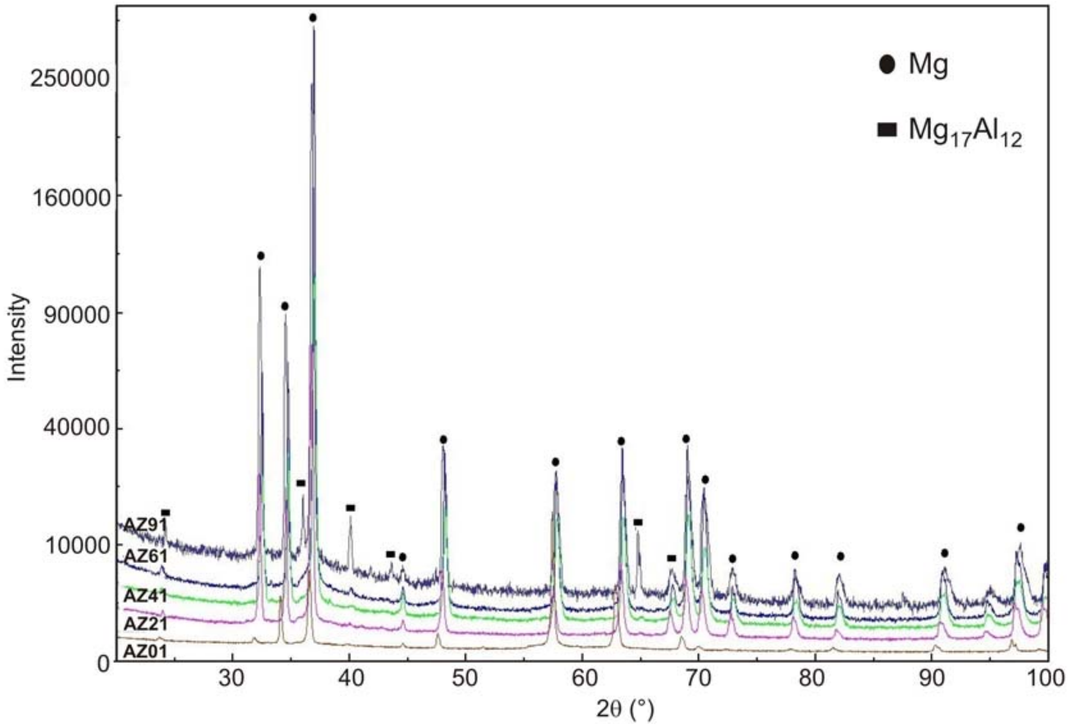

Fig. 4. XRD patterns of AZ series Mg alloys.

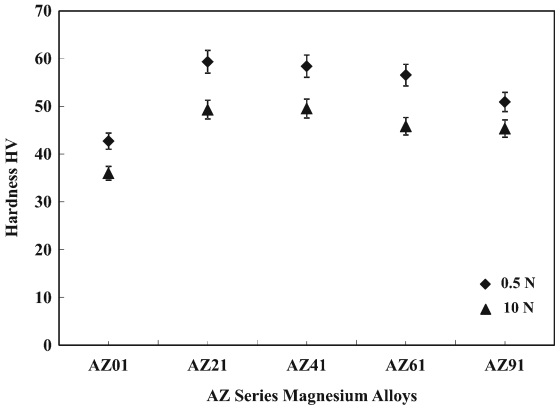

Fig. 5. Hardness (HV) of AZ series Mg alloys.

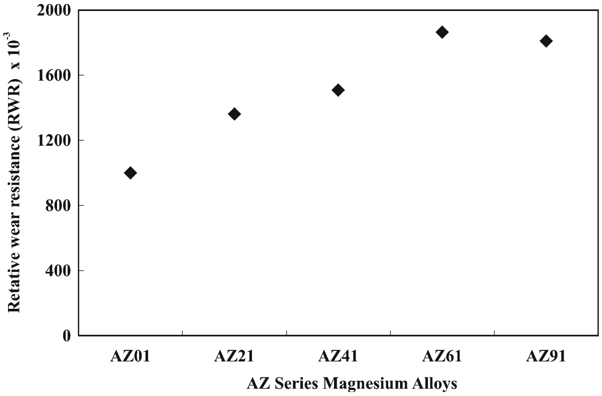

Fig. 6. Relative wear resistance of AZ series Mg alloys.

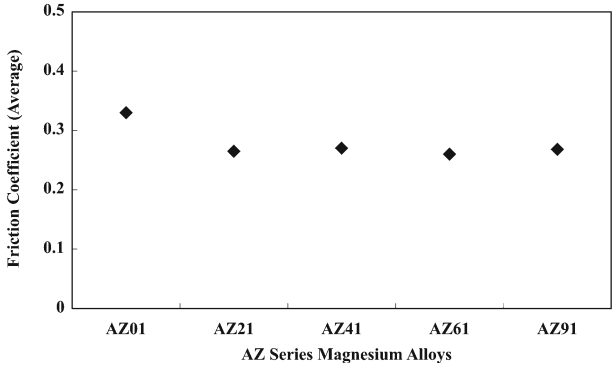

Fig. 7. Friction coefficient (average) of AZ series Mg alloys.

ation behavior [6, 9, 13–17]. Microstructure images of magnesium alloys obtained in this study (Fig. 3a–d) and XRD pattern (Fig. 4) data are in accordance with literature.

Data on hardness and wear values of AZ series alloys are given in Figs. 5–7. When checked the mean hardness values of alloys used in the study (Fig. 5), AZ21 was observed to have the highest hardness. From AZ21, a downward decrease was observed in hardness values of alloys. While the hardness of AZ21 was estimated as 50.2HV_{10}, AZ91 was measured as 45.3HV_{10}. The order of alloy hardness ranged from the highest to lowest as AZ21, AZ41 AZ61 and AZ91, respectively.

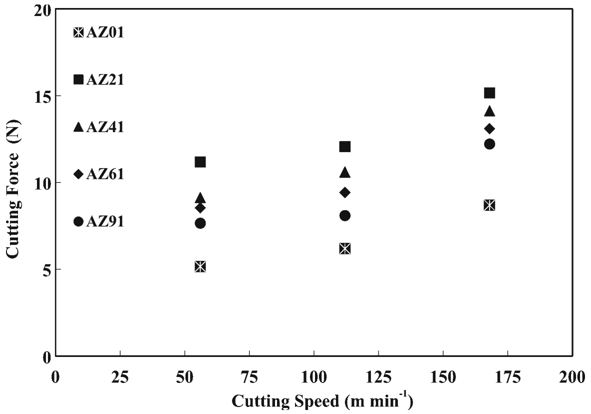

Fig. 8. Relationship between cutting forces and alloy compositions of AZ series Mg alloys (DoC = 0.5 mm, f = 0.10 mm rev^{-1}).

Data obtained from the wear experiments are given in Figs. 6, 7. The highest wear resistances were measured in AZ61 and AZ91 alloys. Based on wear experiment data, wear resistances of AZ series magnesium alloys demonstrated an increase in an order from AZ01 up to AZ91 (Fig. 6). Wear resistance of alloys rose in proportion to the increase in Al% amount within the series. AZ91 alloys showed a wear resistance 80.9 % higher compared to AZ01 alloy and 32.8 % higher compared to AZ21 alloy (Fig. 6). The reason for AZ91 alloy to demonstrate a higher wear resistance compared to AZ21 alloy was due to the intermetallic phase (β-$Mg_{17}Al_{12}$) found in the microstructure of AZ91. It was observed that intermetallic phase (β-$Mg_{17}Al_{12}$) formed due to the effect/presence of Zn in AZ series magnesium alloys and due to increase in Al% amount rose wear resistance. A significant difference was not found between the friction coefficients of alloys used in the experiment (Fig. 7).

3.2. Machining properties

Data on cutting forces of alloys were obtained by keeping the chip section fixed at various cutting speeds in the experimental study (Fig. 8). The highest of the cutting forces in three separate cutting speeds selected in the experiment was obtained from AZ21 alloy. In all alloys, an increase was observed in cutting forces due to increases in cutting speeds (with chip section fixed) (Fig. 8). All cutting forces were ordered from the highest down as AZ21, AZ41, AZ61 and AZ91,

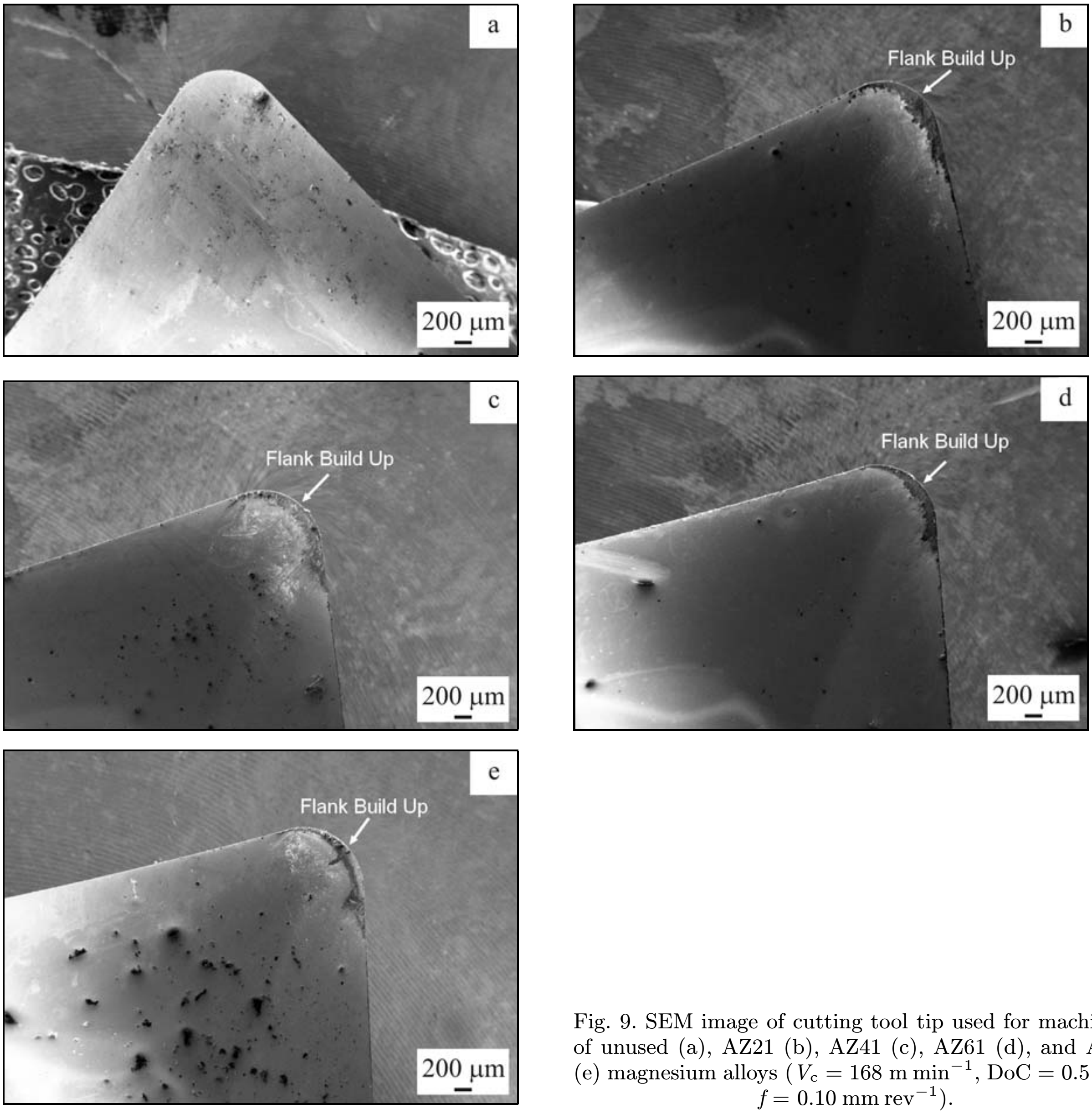

Fig. 9. SEM image of cutting tool tip used for machining of unused (a), AZ21 (b), AZ41 (c), AZ61 (d), and AZ91 (e) magnesium alloys ($V_c = 168$ m min^{-1}, DoC = 0.5 mm, $f = 0.10$ mm rev^{-1}).

respectively. It was observed in AZ series magnesium alloys that cutting forces increased in line with cutting speed rise (Fig. 8).While the highest cutting force value among alloys was 15.2 N at $V_c = 168$ m min^{-1} cutting speed in AZ alloy, it was measured as 12.2 N in AZ91 alloy. The lowest cutting force was obtained as 11.1 N in AZ21 and 7.6 N in AZ91 alloy at 56 m min^{-1} cutting speed.

Depending on the increase in Al% amount in AZ series alloys, intermetallic phase (β-Mg$_{17}$Al$_{12}$) found in microstructure was observed to have an effect on cutting forces. Among the studied alloys, the fact that intermetallic phase (β-Mg$_{17}$Al$_{12}$) with harder and more fragile properties within the microstructure [9] found in AZ91 alloy at a higher rate/more significantly had an impact in the manner of reducing cutting forces. For this reason, cutting forces turned out to be lower in AZ91. Decrease in cutting forces also boosted the machinability of the said alloy. The fact that intermetallic phase (β-Mg$_{17}$Al$_{12}$) with hard and fragile property within the structure of AZ21 alloy did not form enough/was not observed in grain boundaries might be the reason for increases in cutting forces. In AZ21 alloy, it is believed to result from high cutting forces, solid solution strengthening [6, 9], and dislocation build-up. Depending on cutting speed, it may be noted that the increase in cutting forces occurred due to dislocation build-up with chips in cutting edge. Such a build-up occurring more in AZ21 alloy causes an increase in cutting forces. A decrease occurs in cutting forces as a result of brittle breaks in chips due to the fact that intermetallic phase (β-Mg$_{17}$Al$_{12}$) in AZ91 alloy having hard and fragile properties. Data obtained in this section and microstructure analyses,

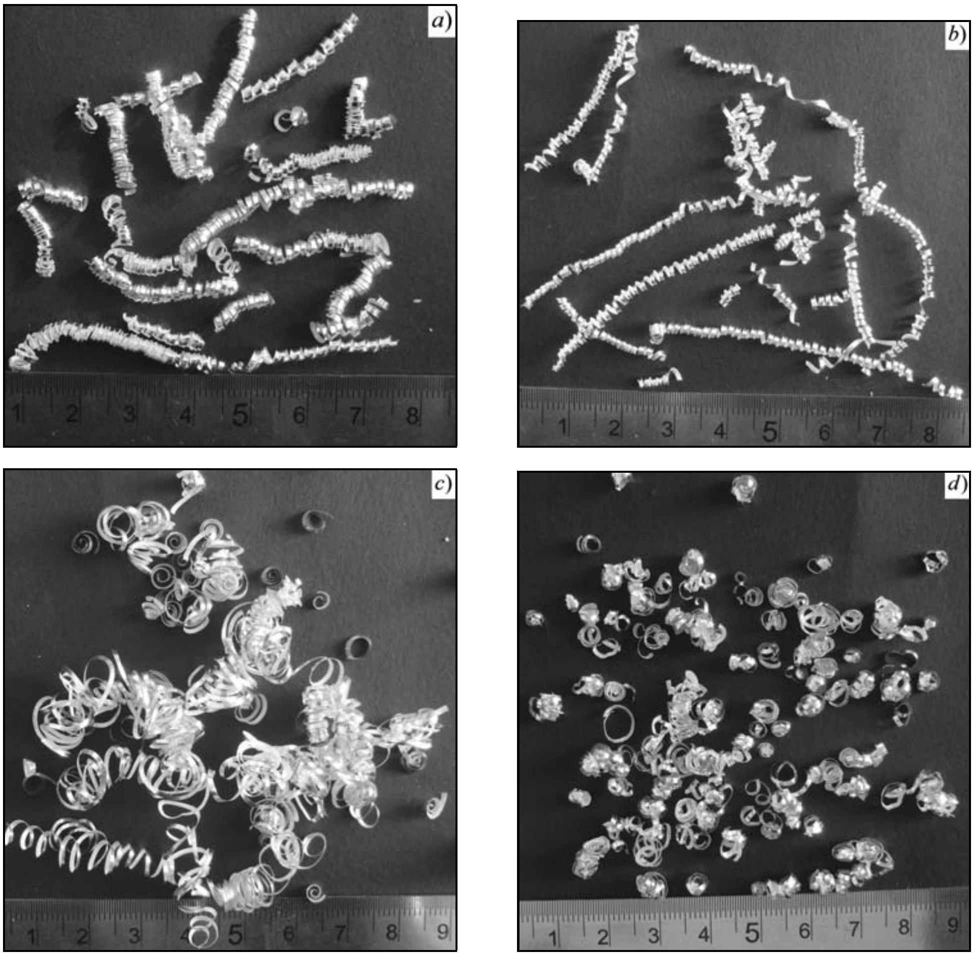

Fig. 10. Chip formation of AZ series Mg alloys ($V_c = 168\ \mathrm{m\ min^{-1}}$, DoC = 0.5 mm, $f = 0.10\ \mathrm{mm\ rev^{-1}}$).

hardness and wear test results in previous sections support each other. Results obtained from the study are in concordance with literature [6, 13].

Images of cutting edges with which alloys used in the experiment were machined are given in Fig. 9. It was observed that Flank Build-up (FBU) occurred due to dry friction between the work piece and cutting edge surface during the machining of alloys and that cutting edge was worn. The wear was established as deeper on the cutting edge with which AZ91 alloy was machined (Fig. 9e). It was reported in previous studies that Flank Build-up increased thanks to the effect of friction and heat occurred there [3, 9, 11, 18]. However, on the cutting edge with which AZ21 alloy was machined, chips were observed to advance along chip angle on the surface and that wear occurred on a wider surface (Fig. 9b).

Flank Build-up (FBU) formation increases along with Al% amount in alloy. It was reported that intermetallic phase (β-$\mathrm{Mg_{17}Al_{12}}$) was formed in AZ91 alloy and that it affected the FBU formation [6, 9]. It is known that β intermetallic phase is related with Al amount within the construction and also β intermetallic phase increases in parallel with Al% amount. It is also common that this raises FBU formation depending on the increase in wear resistance of alloy and is effective in tool wear.

Chip images obtained from the machining of samples (with fixed chip section) are given in Fig. 10. Chips obtained from AZ21 alloy were observed to be longer and in helical form compared chips from AZ91. Chips from AZ21 were firmer and in an overlapping form. Chips from AZ91 alloy were formed as smaller in length and intermittent (discontinuous). In AZ91 alloy, it may be noted that chips were smaller in size due to brittle breaks thanks to the effect of the intermetallic phase (β-$\mathrm{Mg_{17}Al_{12}}$), and in AZ21 alloy, chips were longer due to ductile breaks (Fig. 10). From this viewpoint, intermetallic phase ($\mathrm{Mg_{17}Al_{12}}$) was observed to have an effect on chip formation in AZ series magnesium alloys [6, 19]. It may be noted that chips obtained from AZ91 alloy were harder and more fragile compared to AZ21.

In the conducted experimental study, intermetallic phase (β-$\mathrm{Mg_{17}Al_{12}}$) occurred/found in the microstructure of AZ series magnesium alloys was observed to have an effect on cutting forces. This study established that the machinability of alloys increased due to the rise in Al% amount. Due to the fact that intermetallic phases demonstrated hard and fragile properties within the structure [6], a decrease was also observed in cutting forces. For this reason, machinability increased. Intermetallic phases were found to have an effect on Flank Build-up (FBU) formation between the cutting edge and sample surface contact point [11, 19].

4. Conclusions

– In addition to having an impact on formation, type, and form of intermetallic phases (β-$Mg_{17}Al_{12}$) also had an effect on the hardness, wear resistance, and machinability of the alloy.

– Wear resistance of alloys was observed to rise depending on the Al% amount in AZ series magnesium alloys.

– The alloy with the highest wear resistance among AZ series magnesium alloys is AZ91 alloy. This alloy is also the easiest to machine. The highest hardness values and cutting forces were obtained for AZ21. It had the lowest machinability within the series.

– Intermetallic phase ($Mg_{17}Al_{12}$) observed in the microstructure of AZ series magnesium alloys was found to have an effect on cutting forces and the machinability changed accordingly. It was established that the machinability of alloys increased depending on the rise in Al% amount in alloys.

– Intermetallic phases were observed to have an effect in the formation and breaking of chips. Chips were noted to have a brittle break and shorter lengths thanks to the impact of intermetallic phase in AZ91 alloy. Intermetallic phases were found to increase Flank Build-up formation in cutting tool edge.

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