Machinability of Az21, As21 and Am20 Magnesium Alloys

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Abstract: This study investigates the effect of Zinc (Zn), Silicon (Si) and Mangan (Mn) in (AZ91: 2% Al, 1% Zn, AS21: 2% Al, 1% Si, and AM20: 2% Al, 0.5% Mn) magnesium alloys on mechanical properties, wear resistance and machinability. In magnesium alloys, the effect of mechanical properties, wear resistance and machinability was investigated by establishing the impact of 1% zinc (in AZ21), 1% silicon (in AS21), and 0.5%Mn (in AM20) within the microstructure in these alloys with aluminium amount less than 3%. It was found that the intermetallic phases found in the microstructure within the alloy had an effect on mechanical properties (ultimate tensile strength, yield strength, elongation, hardness), wear resistance and machinability.

Keywords: *Machinability, Cutting Force, Mechanical Properties, Hardness, Magnesium Alloys*

1.INTRODUCTION

Magnesium and its alloys have many areas of use thanks to their mechanical, physical and chemical properties. Especially due to the fact that being among the lightest structure metals in addition to their low density and high resistance characteristics, magnesium alloys find many areas of use predominantly in logistics, automotive, and aviation sectors[1,2,3]. For this reason, magnesium alloys with various alloy properties are prepared and studies are being carried out on improving such characteristics of these alloys as mechanical properties, hardness, and wear[4,5].

Another significant property of magnesium alloys is that it is among construction metals with ease of machinability[6,7,8]. However, the most important risk in machining magnesium alloys is the presence of combustion and burning potential at higher cutting speeds. It may be noted that such possibility may increase especially in finishing operation and high cutting speeds. Risk of combustion rises in the event of magnesium alloys reaching 600°C which is the melting point of fine chips[6]. Especially in certain magnesium alloys, Flank Build-up (FBU) formation on the cutting surface during machining with cemented carbide tools was reported at higher cutting speeds, under dry machining conditions[6,8,9]. FBU formation was also reported to facilitate the occurrence of combustion/burning[6,10]. The reason why FBU is formed in certain alloys has not yet been completely clarified with systematic investigations. FBU formation is believed to correlate with components of alloys. However, a systematic study is not present on the issue. Our study on the machinability of AZ21, AS21 and AM20 series magnesium alloys might be a resource[11].

Studies conducted on alloy properties affecting the improvement of mechanical properties and wear characteristics of magnesium alloys and their correlation with machinability are quite low in number and insufficient. The use of magnesium alloys in engine, piston, and cylinders especially in automotive sector is in the process of development depending on investigating such characteristics as hardness, wear resistance, and machinability. It is known that wear resistance is closely related with tensile properties of the material. Wear can be defined as resistance of metal against friction in its most basic sense. Today, the most commonly used Mg-Al (magnesium-aluminium) alloys are AZ21, AS21 and AM20 alloys. The most significant properties of these alloys are their well castability and improvable mechanical properties.

This study investigates the effect of Zn (Zinc) (in AZ21), Si (Silicon) (in AS21) and Mn (Mangan) (in AM20) magnesium alloys on wear resistance and machinability, and also the effects on mechanical properties (UTS, YS, El, HV), wear resistance and machinability depending on microstructure in AZ21, AS21, and AM20 (containing 1% Zn, 1% Si, and 0.5Mn). Also investigated were the effects of alloy components in magnesium alloys on microstructure and FBU formation and the resulting effect of all this on machinability.

2.MATERIALS AND METHODS

Mechanical and Microstructural Properties

The most common magnesium alloys AZ21, AS21 and AM20 were used in this study. These alloys were obtained by melting in specially designed atmosphere-controlled melting furnace (750°C) by method of casting into metal moulds (preheated to 270°C). As the protective gas, protective SF_6 was used during casting. Extruded samples were 22mm in diameter and 200mm in length. The chemical compositions of the extruded alloys were determined by a Spectrolab M8 Optical Emission Spectrometry (OES). Detailed information on casting methods of magnesium alloys were provided in a study by Ünal (2008)[12]. Components of alloys used in the study are given in Table 1. Later on, microstructure examination, hardness, and wear tests were carried out on samples obtained by casting method.

The sample surfaces prepared (in 15mm diameter and 12mm thickness) and used in microstructure examinations of alloys were cleaned by sanding (emery papers from 200 up to 1200 grits were used). Then, surfaces of samples were polished by diamond paste of 6µm, 3µm, and 1µm, respectively. Following polishing process, surfaces of samples were etched in a specially prepared solution (contents: 100ml ethanol, 5ml Acetic acid, 6g picric acid, and 10ml water) and thus, microstructure images were obtained (Nikon Eclipse LV150).

Table. 1. Chemical composition of the studied AZ21,AS21 and AM20 alloys

(wt %, "A" refers Al content and "Z" refers to Zn, "S" refers to Si, "M" refers to Mn content of the alloy).

Alloys	Al%	Mn%	Zn%	Si%	Fe%	Mg%
AZ21	2.0	0.13	**1.2**	0.08	0.02	Rest
AS21	2.1	0.2	0.2	**1.2**	0.02	Rest
AM20	2.1	**0.5**	0.15	0.01	0.01	Rest

The hardness values of the samples were determined using the Vickers hardness test (HV) with a load of 10N on the microhardness tester (Shimadzu HMV-2). At least ten hardness measurements were determined for each sample. Wear tests of experimental samples (15mm in diameter and 12mm in thickness) were carried out on pin-on disk test device (Tribotester TM, Clichy) (Fig.1.) At the end of wear experiment, 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 4N. Al_2O_3 balls having a 6mm diameter rubbed on the surfaces of the samples with a sliding speed of 5mm/s. The stroke of the Al_2O_3 balls was 5mm for a total sliding distance of 25m.

Tensile tests were carried out. Data on the tensile strengths of alloys (Ultimate Tensile Strength-UTS, Yield Strength-YS) 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 6 samples. The strain rate used for tensile testing was 0.8×10^{-3} s^{-1}.

Machining Properties

This study investigated the machinability of alloys by obtaining data on cutting forces by keeping the chip section fixed at various cutting forces on AZ21, AS21 and AM20 magnesium alloys acquired through casting method. Data on cutting forces were obtained under dry machining conditions and vertical processing method. Machining tests were carried out by turning process in DMG CTX Alpha 300 CNC lathe machine. Polycrystalline Diamond (PCD) tool (CCGT 120408 FL K10) was used as the cutting edge. Data on cutting forces were obtained from specially-designed strain gauge. Surface roughness values of sample surfaces were measured with Time-TR200. Machining parameters used in the study are given in Table 2.

Table.2. Machining Parameters and Conditions used during the test.

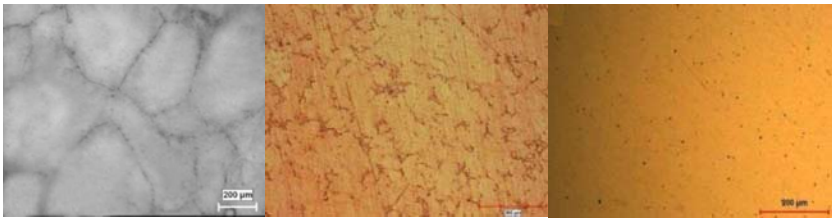
Parameters and Conditions	
Operations	Turning
Feedrate (*f, mm/rev*)	0.10 (Constantly)
Depth of Cut (*DoC, mm*)	1.0
Cutting Speed (*V_c , m/min*)	56, 112, 168
Cutting Conditions & Lubricant-Coolant	Orthogonal and Dry Cutting,
Workpiece Materials	AZ21, AS21 and AM20 Magnesium Alloy
	CCGT 120408 FL K10
Cutting Tool Properties	

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

3.RESULTS AND DISCUSSION

Microstructural, Mechanical and Microstructural Properties

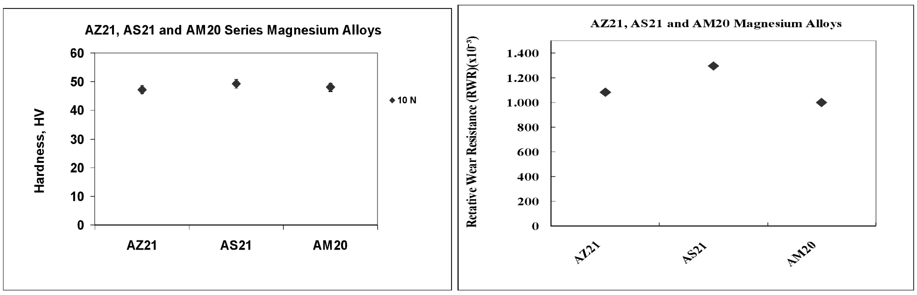
Microstructure photographs of AZ21, AS21 and AM20 magnesium alloys used in the study are given in Fig.1. Microstructure of magnesium alloys analysed in the study was generally observed to be made up of α-Mg matrix and intermetallic phases ($Mg_{17}Al_{12}$ and Mg_2Si, Al_8Mn_5). In AZ series magnesium alloys, the fact that β intermetallic phase within the microstructure ($Mg_{17}Al_{12}$) occurred in the form of network within the scope of α-Mg matrix was reported in studies[11,13,14-26]. In AS21 magnesium alloys, the fact that Mg_2Si intermetallic phase was observed in the form of Chinese script form within the microstructure was already known through the literature[14-17,24]. It was reported in literature that the formation of β intermetallic phases within the microstructure ($Mg_{17}Al_{12}$ and Mg_2Si) was correlated with the Al% amount in the alloy. β intermetallic phases were reported to become clear along with the increase in Al amount to above 3% in alloy[6,11]. It was reported in previous studies that the formation, appearance and shape of intermetallic phases in magnesium alloys shifted depending on changes in the alloy components and in the solidification behaviour [5,14-24]. It can be found in Fig. 1 that β intermetallic phases in microstructure of AZ21, AS21 and AM20 alloys were not observed and did not occur in a completely apparent manner. Microstructure images obtained in this study are in concordance with the literature.



a)AZ21 **b)AS21** **b)AM20**

Fig.1. Optical Micrographs of a) AZ21, b) AS21 and c)AM20 magnesium alloys.

Hardness and wear values of the analysed AZ21, AS21 and AM20 alloys are given in Fig.2. When checked the mean hardness values of alloys, these were estimated to be 47.2 HV_{10} in AZ21 alloy, 49.3 HV_{10} in AS21 alloy, and 48.1 HV_{10} in AM20 alloy. It was observed from the hardness tests that AS21 and AM20 alloy demonstrated a higher hardness property compared to AZ21 alloy. The fact that AS21 and AM20 demonstrated a higher hardness property resulted from the intermetallic phase (Mg_2Si, Al_8Mn_5) found in the microstructure [14-17,24].

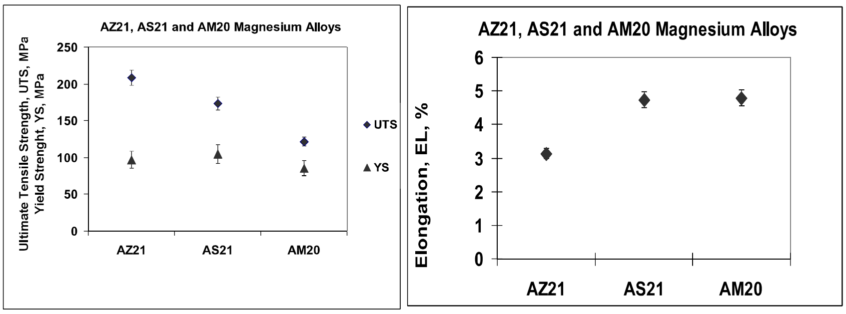


a) **b)**

Fig.2. Hardness (HV) of AZ21, AS21 and AM20 Magnesium Alloys

Based on the data obtained from wear tests, presence of intermetallic phase (Mg_2Si) in AS21 alloy microstructure provided the demonstration of a higher wear resistance at a rate of ~29% compared to AM20 alloy. According to this, it was observed that the Mg_2Si intermetallic phase that occurred thanks to the effect/presence of Si in AS21 alloy increased wear resistance compared to $Mg_{17}Al_{12}$ intermetallic phase formed due to the effect/presence of Zn in AZ21 alloy or Mn in AM20 (Al_8Mn_5).

Tensile tests (UTS, YS and EL%) of alloys analysed in the experimental study were carried out. Data obtained from the study were prepared in the form of graphs (Fig.3.). The highest UTS and YS values were produced by AZ21 in tensile tests. On the other hand, AZ21 alloy had the lowest El% value. Evaluation of results indicated that intermetallic phases ($Mg_{17}Al_{12}$, Mg_2Si and Al_8Mn_5) could be very effective at strengthening magnesium alloys [7-16].



(a) (b)

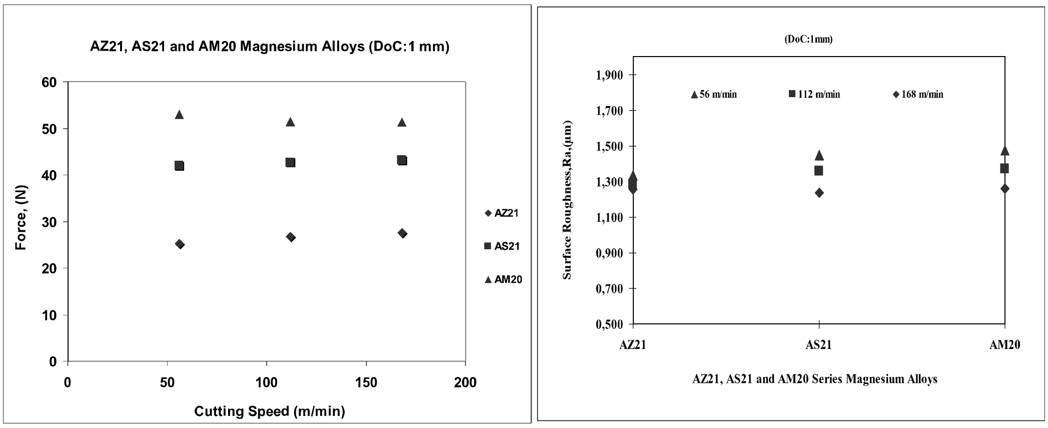
Fig.3. Tensile tests of AZ21, AS21 and AM20 magnesium alloys (a)UTS, YS and (b) EL%

It was reported in previous studies that hardness and strength of alloy increased parallel to the rise in Al% amount in magnesium alloy. Microstructure images of intermetallic phases causing the increase in hardness and strength of alloys are given in Fig.3. Massive β intermetallic phases were reported in previous studies to appear along with the increase in Al amount to above 3% in alloy[11]. It was observed in studies that these intermetallic phases within microstructure affected the mechanical properties of the alloy.

Machining Properties

In the turning processes of the samples used in the experimental study, data obtained (cutting force and surface roughness) are given in Fig.4. Figure 4a-b shows the effect of cutting speed variations on the cutting force for the machined samples as a function of alloy composition. When compared the cutting forces formed during the machining of these alloys, the highest cutting force value was obtained from AM20 alloy (Fig.4). The lowest cutting force in all cutting speeds (three cutting speeds) was obtained in AZ21 alloy. While the cutting force value at the lowest cutting speed (56m/min) was measured in AZ21 alloy as 25.3N, in AS21 alloy 41.9N, and it was measured as 52.8N in AM20 alloy. When the cutting speed was raised to 168m/min, cutting speeds were measured as 27.6N in AZ21, 43.1N in AS21, and 51.3N in AM20 alloy. 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. The surface roughness (*Ra*) of the samples given in Fig.4b revealed that surface roughness for all the alloys decreased as the cutting speed increased. This shows that the alloy content had considerably affected the *Ra*.

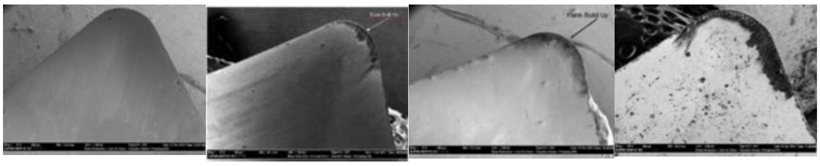
It was observed that that the (in AM20 alloy;Al_8Mn_5, in AS21 alloy; Mg_2Si) intermetallic phase found in the microstructure of these alloys compared to $Mg_{17}Al_{12}$ intermetallic phase (in AZ21 alloy) was more effective, and that it caused cutting forces to increase during machining along with rising the hardness and wear resistance of the alloy.



(a) (b)

Fig.4. Relationship between cutting forces and alloy compositions (a) and surface roughness of AZ21, AS21 and AM20 magnesium alloys (DoC: 1 mm, f: 0.102 mm/rev).

Wear occurring on the cutting edge surface due to machining the alloys are shown in Fig.5 When analysing the cutting edge surfaces used in the experiment, it was observed that Flank Build-up (FBU) occurred due to dry friction between the work piece and cutter surface during the machining of the samples [4,6-8,14], and that the cutting edges were worn. This wear was found to be deeper on the cutting edge belonging to AM20 alloy. It is shown in Fig.5 that the (Mg_2Si and Al_8Mn_5) intermetallic phases that occurred in the alloys were effective in the increase of the cutting forces, and thus, the surfaces of the AS21 and AM20 were more worn.



a) Unused **b)AZ21** **c)AS21** **d)AM20**

Fig.5. SEM image of cutting tool tip used for machining of (a) Unused, (b)AZ21, (c)AS21, (d)AM20 magnesium alloys (*V_c:168 m/min, DoC:1mm, f:0.10 mm/rev*).

Flank Build-up (FBU) formation increases depending on the cutting speed. That $Mg_{17}Al_{12}$ β intermetallic phase was formed in AZ21 alloy and that affected FBU formation were reported[11]. It is known that β intermetallic phase within the structure is correlated with Al amount and that β intermetallic phase increases along with the rise in Al% amount. Also known is that this increased FBU formation and has an impact on the rise in surface roughness and tool wear.

Chips Images obtained (with fixed chip section) from machining AZ21, AS21 and AM20 magnesium alloys are given in Fig.6. When analysed the chip images, it was observed that chips formed from AZ21 alloy were longer compared to chips from AS21 and AM20. Chips from AS21 were found to be firmer and in an overlapping helical form[6,18]. It may be noted that chips from AM20 alloy were smaller in length and occurred as a result of brittle breaks due to the effect of Al_8Mn_5 intermetallic phase, and in AZ21 alloy, chips were longer and formed as a result of ductile breaks due to the effect of intermetallic phase ($Mg_{17}Al_{12}$, Mg_2Si, Al_8Mn_5)(Fig.6.). In these alloys, chip formations were observed to occur due to intermetallic phases thanks to Zn, Si and Mn effect/presence ($Mg_{17}Al_{12}$, Mg_2Si and Al_8Mn_5) found in the alloy[6]. It may be mentioned that chips obtained from AM20 alloy were harder and more fragile compared to AZ21 and AS21.

a)AZ21 **b)AS21** **c)AM20**

Fig.6. Chip Formation of a) AZ21, AS21 and c) AM20 Magnesium Alloys (*V_c:168 m/min,* DoC:1mm, f:0.10 mm/rev).

Moving from the experimental study, ($Mg_{17}Al_{12}$, Mg_2Si and Al_8Mn_5) intermetallic phases occurred/found in the microstructure of AZ21, AS21 and AM20 alloys were observed to have an effect on cutting forces and mechanical properties.

Since the Mg_2Si and Al_8Mn_5 intermetallic phase formed due to the effect/presence of Si and Mn in AS21 and AM20, respectively, demonstrated a higher increasing effect on hardness and wear resistance of alloys compared to $Mg_{17}Al_{12}$ intermetallic phase formed due to the effect/presence of Zn in AZ21. It may be noted that this increased cutting forces and caused wear in cutting surfaces[7,18]. Flank Build-up(FBU) increase in the cutting surface between the cutting edge and sample surface due to intermetallic phases also causes a rise in cutting forces (Fig.4). Flank Build-up(FBU) formation increases with friction and temperature rise occurring on the cutter surface due to an increase in cutting speed and this may be noted to raise cutting forces[7,18,27-30]. Increase in cutting forces reduces the machinability of materials.

Zn, Si and Mn found in the alloys that were investigated in this study were effective on the hardness, wear resistance and machinability of alloy in addition to having an impact on formation and type of intermetallic phases ($Mg_{17}Al_{12}$,Mg_2Si and Al_8Mn_5) formed in the microstructure. It was observed that intermetallic phases had an increasing effect on hardness and wear resistance of the alloys.

It was found that the Mg_2Si and Al_8Mn_5 intermetallic phase that occurred thanks to the effect/presence of Si in AS21 and Mn in AM20 alloy increased wear resistance and hardness compared to $Mg_{17}Al_{12}$ intermetallic phase formed due to the effect/presence of Zn in AZ21 alloy.

It was observed that the Mg_2Si and Al_8Mn_5 intermetallic phase found in the microstructure of AS21 and AM20 alloy compared to $Mg_{17}Al_{12}$ intermetallic phase in AZ21 alloy was more effective, and that it caused cutting forces to increase during machining along with rising the hardness and wear resistance of the alloy. This, as a result, reduces the machinability of alloy.

Both alloys were observed to have an increase in surface roughness as the cutting speed rises. It was observed that the surface roughness values obtained from AM20 alloy were higher compared to surface roughness values from AZ21 and AS21 alloy.

The mechanical properties of AZ21 alloy was higher compared to AM20 alloy. Its machinability was higher (lower cutting force) compared to AS21 and AM20.

It was observed that chips formed from AM20 alloy were longer compared to chips from AZ21 and AS21. Chips obtained from AM20 alloy were established as harder and more fragile compared to AZ21, AS21. Intermetallic phases ($Mg_{17}Al_{12}$, Mg_2Si and Al_8Mn_5) were found to have an effect on chip formation.

Intermetallic phases within the microstructure have an impact on cutting forces, FBU formation, chips form and machinability. Cutting speed influences cutting forces reaching the cutting tool, surface roughness and chip form.

Hardness of AZ21 alloy was found to be higher compared to AS21 and AM20 alloy. However, machinability of AZ21 was higher compared to AS21 and AM20.

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