Effects of Si and Mn on machinability and wear resistance of AS91 and AM90 magnesium alloys

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Abstract— **Abstract-This study investigates the effect of Silicon (Si) and Manganese (Mn) in AS91 (9% Al, 1% Si) and AM90 (9% Al, 0.5% Mn) magnesium alloys that are among important magnesium alloys wear resistance and machinability. Hardness of intermetallic phases found in the microstructure of magnesium alloys was observed to affect wear resistance and machinability. Mg_2Si found in the microstructure of AS91 alloy was established to reduce machinability while intermetallic phase increased hardness and wear resistance. It was found that intermetallic phases ($Mg_{17}Al_{12}$, Mg_2Si and Al_8Mn_5) of AS91 and AM90 magnesium alloys had an impact on cutting forces and machinability and mechanical properties.**

Keywords— Machinability, cutting force, surface roughness, wear, AS91, AM90 series magnesium alloys

I. INTRODUCTION

Today, there are numerous areas of use for magnesium and its alloys due to their characteristics, and these areas of use grow in number every day. Especially due to being among the lightest structure metals for their low density and high resistance characteristics, magnesium alloys gain importance in many fields, predominantly in logistics, automotive, and aviation sectors [1,2,3]. Their use in vaster fields continues depending on improving certain characteristics. Some of such characteristics to be improved are their mechanical features, hardness, wear, and machinability. A large number of studies carried out on magnesium alloys were about obtaining different alloys and investigating the mechanical characteristics of such alloys [4,5]. Studies conducted on alloy properties affecting the improvement of wear characteristics of magnesium alloys and their correlation with machinability are quite low in number and insufficient. It is quite important to investigate the use of magnesium alloys in engine, piston, and cylinders especially in automotive sector and also 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 AZ91, AM20, AM60, AS21, AS41, AJ62 etc. The most significant properties of these alloys are their well castability and improvable tensile properties.

This study investigates the effect of Si (Silicon) and Mn (Manganese) on wear resistance and machinability, and also the effects on hardness, wear resistance, strength, and machinability depending on microstructure of AS91 and AM90 containing 1% Si and 0.5% Mn.

II. EXPERIMENTAL PROCEDURE

The magnesium alloy used AS91(containing 9%Al, 1%Si) and AM90 (containing 9% Al, 0.5% Mn) in the experimental study were prepared by melting pure magnesium (Mg) and Aluminium (Al), Al-Si and Al-Mn master alloys in a graphite crucible under Argon gas (Ar) atmosphere at 750°C. Mg, Al, and Zn bullions (with a minimum purity of 99.90%) used in the casting and aluminium silicon (Al-Si 50%) and aluminium manganese (Al-Mn 10%) master alloys bullions were supplied from Bilginoglu Co. AS91 and AM90 magnesium alloys used in this experimental study were obtained by cast into a cast iron mould (preheated to 270°C) under protective SF_6 gas. Detailed information on the production methods of the magnesium alloys can be found in the work of Unal [6]. The produced magnesium alloys samples were 22 mm in diameter and 200 mm in length. The chemical compositions of the alloys were determined by a Spectrolab M8 Optical Emission Spectrometry (OES). After the casting process characterization of the alloys were made by microscopic examinations and tensile tests. Alloy compositions are listed in Table I.

TABLE I
CHEMICAL COMPOSITION OF THE STUDIED AS91 AND AM90 ALLOYS

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

Alloys	Al%	Mn%	Zn%	Si%	Fe%	Mg%
AS91	9.3	0.1	0.2	1.2	0.02	Rest
AM90	9.41	0.5	0.26	0.1	0.02	Rest

Microstructural surveys were conducted on the metallographic samples by optical microscopy (LV150 Nikon Eclipse). The samples prepared 12 mm in diameter and 15 mm in length were machined, ground with grit emery papers (200, 400 600, 800 1000, and 1200 grits, respectively), and then polished with 6µm, 3µm and 1µm diamond paste using pure water. Lastly, the samples were etched in a solution of

100ml ethanol, 5ml Acetic acid, 6g picric acid and 10ml water for use in microstructural evaluations. X-ray diffraction (XRD) analyses (Panalytical-Empyrean) were carried out under Cu Kα radiation with an incidence beam angle of 2°. The tensile tests (ASTM E 8 M-99 standards) were performed at a crosshead speed of 0.8 mm/min^{-1} and at room temperature (Shimadzu Autograph AGS-J 10 kN Universal Tester). 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.

Wear tests of experimental samples were carried out on pin-on disk test device (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 (Tribotester TM, Clichy) under a load of 4 N. 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. Wear test samples were 15mm in diameter and 10mm in length. The coefficient of friction and frictional force were continuously recorded throughout the wear tests. Contact surfaces of the samples were examined using a surface profilometer (Dektak TM 6 M).

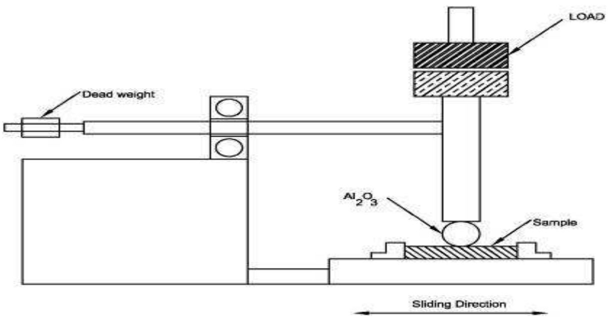


Fig.1 Schematic view of the reciprocating wear tester utilized in this study.

Machining tests were conducted to determine the cutting forces using a DMG CTX Alpha 300 CNC lathe machine. In the turning operations under dry cutting conditions, Polycrystalline Diamond (PCD) (CCGT 120408 FL K10) was used as cutting tool. The turning tests were used for orthogonal cutting process. Cutting force curves were obtained by creating a mechanism with the help of strain gage as shown in Fig.2. Surface roughness tests were carried out by Time-TR200 test instrument.

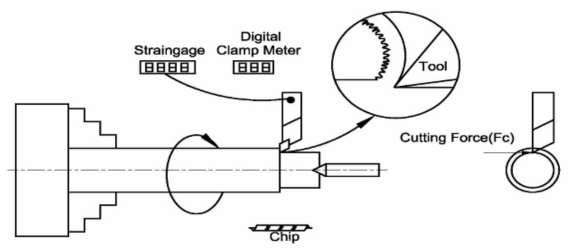


Fig.2 Schematic representation of experimental set-up with strain

Cutting forces were implemented to evaluate the usage of two experimental methodologies. The feed rate (*f*) and depth of cut (DoC) were held constant to maintain the cross-sectional area of the chips in millimetres per revolution (*mm/rev*). The feed (f:*mm* min^{-1}) was held constant for various revolutions. The machining parameters and conditions of the experimental studies are given in Table II. The cast magnesium alloy samples were subjected to a pre-cleaning operation (i.e. diameter reduced from 22 to 20mm) before the experiments.

TABLE II
MACHINING PARAMETERS AND CONDITIONS USED DURING THE TEST

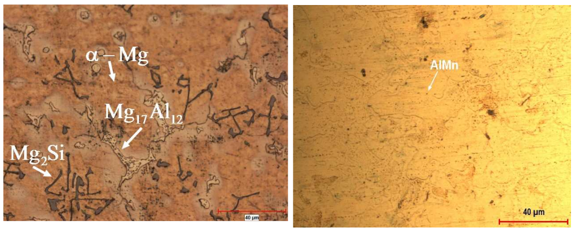
Parameters and Conditions	
Operations	: Turning
Feedrate (*f, mm/rev*)	: 0.10 (Constantly)
Depth of Cut (*DoC, mm*)	: 1.0
Cutting Speed (V_c, *m/min*)	: 56, 112, 168
Cutting Conditions & Lubricant-Coolant	: Orthogonal and Dry Cutting,
Workpiece Materials	: AS91 and AM90
Cutting Tool Properties	α: 7^o, γ: 5^o, λ: 0^o, ε: 80^o, κ: 50^o, r_ε: 0.8

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. *Microstructure and Mechanical Properties*

Microstructure photographs and XRD patterns of AS91 and AM90 magnesium alloys used in the study are given in Fig.3 and Fig.4, respectively. Microstructure of magnesium alloys analysed in the study was generally observed to be made up of α-Mg matrix and intermetallic phases. It was observed that network formation of $Mg_{17}Al_{12}$ intermetallic phase in AS91 Mg alloys tended to surround α-Mg grains throughout the matrix[7]. The intermetallic phase could easily be distinguished from the matrix under the optical light microscopy (Fig.3a).

In AS91 alloy, Mg_2Si intermetallic phase was present along with $Mg_{17}Al_{12}$ intermetallic phase [8]. Previous studies reported the presence of $Mg_{17}Al_{12}$ intermetallic phase in AZ91 alloy [9,10]. The formation of $Mg_{17}Al_{12}$ phase was repeatedly reported due to changes of the solidification behaviours of the melt caused by Zn addition [9,10]. In AS91 magnesium alloy, the constitution of the matrix is α-Mg phase, $Mg_{17}Al_{12}$, and Mg_2Si phases as shown in Fig.3. The formation of Mg_2Si phases in AS91 alloy appeared as Chinese script form in accord with the published literature [5,8-13]. In AM90 magnesium alloy, the constitution of the matrix is α-Mg phase and Al_8Mn_5 intermetallic phases as shown in Fig.3.



a)AS91 **b)AM90**

Fig.3 Optical Micrographs of magnesium alloys (50x).

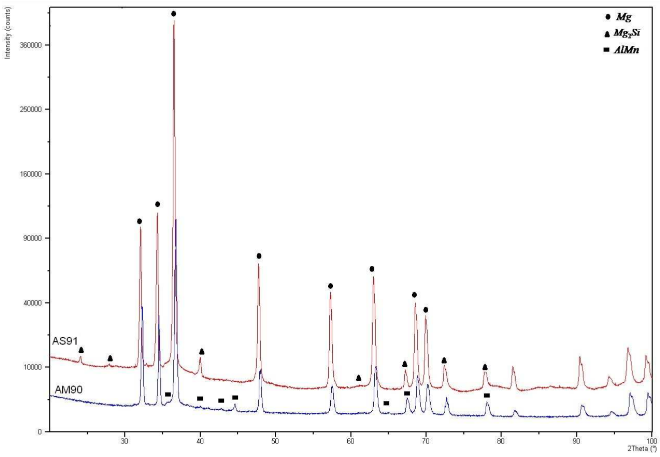


Fig.4 XRD patterns of AS91 and AM90 magnesium alloys.

B. *Mechanical Properties*

Hardness and wear values of the analysed alloys are given in Table III. When checked the mean hardness values of alloys, these were estimated to be 61.45 HV_{10} in AS91 alloy and 88.5 HV_{10} in AM90 alloy. The fact that AM90 demonstrated a higher hardness property resulted from the Al_8Mn_5 phase found in the microstructure.

Based on the data obtained from wear tests, presence of Al_8Mn_5 intermetallic phase in AM90 alloy microstructure provided the demonstration of a higher wear resistance at a rate of 22% compared to AS91 alloy. According to this, it was observed that the Al_8Mn_5 intermetallic phase that occurred thanks to the effect/presence of Mn in AM90 alloy increased wear resistance compared to (Mg_2Si,$Mg_{17}Al_{12}$) intermetallic phase formed due to the effect/presence of Si in AS91 alloy. A significant difference was not found between the friction coefficients of these two alloys. The reason for AM90 alloy to demonstrate a higher hardness and wear resistance compared to AS91 alloy was due to Al_8Mn_5 intermetallic phase found in the microstructure. When analysed the correlation between wear resistance and hardness in the experimental study, wear resistance was observed to increase depending on hardness (Table III). From this point of view, Al_8Mn_5 intermetallic phase found in AM90 alloy was observed to have an impact on hardness and wear properties. Experimental test results obtained from AS91 and AM90 series magnesium alloys are given in Table III.

TABLE III
EXPERIMENTAL TEST RESULTS

	AS91	AM90
Hardness Test Results		
Hardness (HV_{10})	61.45	88.5
Tensile Test Results		
Ultimate tensile strength (UTS)	189.65	145.60
Yield strength (YS)	118.7	89.7
Elongation (%El)	2.99	2.67
Wear Test Results		
Relative Wear Resistance (RWR)	1.00	1.22
Friction Coefficient (Average)	0.26	0.28

Table III show the dependence of the ultimate tensile strength (UTS), yield strength (YS) and elongation (EL) of the alloys studied on their Si and Mn content. The results obtained for UTS, YS and EL values could entirely be attributed to the the presence of intermetallic phases ($Mg_{17}Al_{12}$, Mg_2Si and Al_8Mn_5) occurred in the structure. The various morphologies of the intermetallics indicate that particles were formed under various conditions [6,9-19]. Deviations from the reported results [12,16,19] are caused probably because of the production conditions such as casting temperature, solidification condition and impurity of the alloy.

C. *Machining Properties*

In the turning processes of AS91 and AM90 experiment samples used in the experimental study, data obtained as a result of applications conducted by keeping chip sections fixed are given in Fig.5. The highest cutting force in AM90 alloy was obtained as 55.7N at a cutting speed of V_c:168m/min, and as 49.8N in AS91 alloy; the lowest cutting force value was 43.12N in AS91 and 48.8N in AM90 at a cutting speed of 56m/min. It was observed at three different cutting speed selected in the experiment that cutting forces occurred during machining AM90 alloy was higher compared to cutting forces occurred during machining AS91 alloy. An increase was observed in cutting forces (with chip section fixed) due to a rise in cutting speed in machining AS91 and AM90 alloys (Fig.5). When compared the cutting forces, the highest cutting force value was obtained from AM90 alloy (Fig.5). 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.

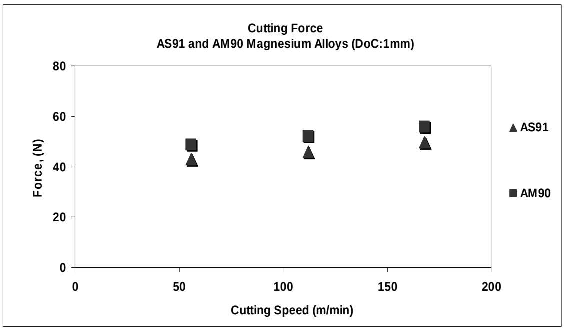


Fig.5 Relationship between cutting forces and alloy compositions of magnesium alloys (*DoC:1 mm, f:0.10 mm/rev*).

Values of surface roughness that occur by machining AS91 and AM90 magnesium alloys are given in Fig.6. 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 AS91 alloy were higher compared to surface roughness values from AM90 alloy. It may be noted that intermetallic phases that occurred due to Si effect/presence (Mg_2Si, $Mg_{17}Al_{12}$) in the alloy had an impact on the formation of surface roughness values.

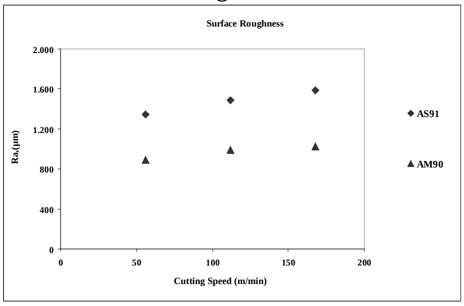
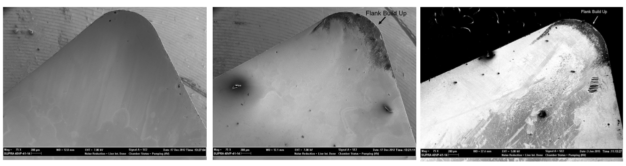


Fig.6 Relationship between surface roughness (Ra) and cutting speeds of AS91 and AM90 series magnesium

Wears occurring due to machining AS91 and AM90 alloys on the surface of cutting edge surface are observed in Fig.7. When analysed cutting edge surfaces used in the experiment, it was established that Flank Build-up (FBU) occurred due to dry friction [13-16] between the work piece and cutting tool surface during the machining of AS91 and AM90 alloys and that cutting edges were worn. The said wear was found to be deeper in the cutting edge from AM90 alloy; and when analysed the cutting tool surface with which AS91 alloy was machined, chips were observed to advance along chip angle on a vaster surface (Fig.7c). Intermetallic phases (Mg_2Si, $Mg_{17}Al_{12}$ and Al_8Mn_5) that occurred/found in alloy were effective in the increase of the cutting forces. From this point of view, it was observed that Al_8Mn_5 intermetallic phase formed due the effect/presence of Mn in AM90 alloy had a harder structure compared to Mg_2Si, $Mg_{17}Al_{12}$ intermetallic phase formed due to the effect/presence of Si in AS91 and that this wore the cutting tool much more [17-19].

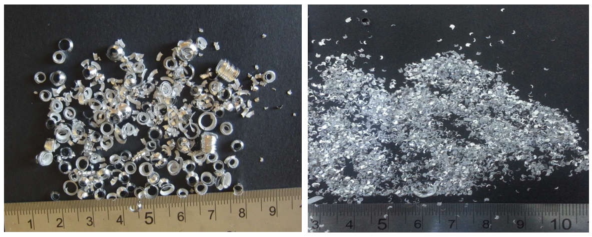
Flank Build-up (FBU) increase in the cutting surface between the cutting edge and sample surface due to intermetallic phases also causes a rise in cutting forces (Fig. 5) Flank Build-up (FBU) formation increases with friction and temperature rise occurring on the cutting tool surface due to an increase in cutting speed [14], and this may be noted to raise cutting forces (Fig.5)



a) Unused **b)AS91** **c)AM90**

Fig.7 SEM image of cutting tool tip used for machining of magnesium alloys (a)Unused, (b)AS91 and (c) AM90 series magnesium alloys (*V_c:168 m/min, DoC:1mm, f:0.10 mm/rev*).

Images of chips obtained from machining AS91 and AM90 magnesium alloys are given in Fig.8. When analysed the chip images, it was observed that while chips formed from AM90 alloy were smaller in length and more plaited, chips from AS91 alloy were longer and helical [13,17]. When compared chips from AS91 with chips from AM90, it was found that chip lengths reduced and had more brittle breaks, and that chips were in the form of sawtooth. It may be noted that chips from AM90 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 AS91 alloy, chips were longer and formed as a result of ductile breaks due to the effect of Mg_2Si and $Mg_{17}Al_{12}$ intermetallic phase (Fig.7). In both alloys, chip formations may be noted to occur due to intermetallic phases thanks to Si and Mn effect/presence (Mg_2Si, $Mg_{17}Al_{12}$ and Al_8Mn_5) found in the alloy [13]. It was observed that chips obtained from AM90 alloy were harder and fragile compared to AS91.



a)AS91 b)AM90

Fig.8 Chip Formation of Magnesium Alloys (*V_c:168 m/min*, DoC:1mm, f:0.10 mm/rev).

IV. CONCLUSIONS

The below results were obtained from this experimental study;

- Si and Mn found in the AS91 and AM90 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 formed in the microstructure.
- It was found that intermetallic phases ($Mg_{17}Al_{12}$, Mg_2Si and Al_8Mn_5) of AS91 and AM90 magnesium alloys had an impact on cutting forces and machinability.
- AS91 alloy had lower hardness and wear resistance compared to AM90 alloy. AM90 alloy had higher machinability. While it was observed that chips formed by machining AM90 alloy were smaller in length, chips from AS91 alloy were longer. It was established that intermetallic phases were effective in the formation of chips and cutting force.
- Intermetallic phases were found to be effective on surface roughness. Higher surface roughness were obtained from AS91 magnesium alloy compared to AM90.
- Hardness and wear resistance of AS91 alloy was lower compared to AM90 alloy.
- Wear resistance and hardness (at Al_8Mn_5 intermetallic phase) of AM90 alloy was higher compared to AS91

alloy (in which $Mg_{17}Al_{12}$ and Mg_2Si intermetallic phase occurred).

- Intermetallic phases occurred from AS91 and AM90 magnesium alloys were observed to have an effect on machinability.
- Si and Mn were observed to have an effect on the formation of intermetallic phases in AS91 and AM90 magnesium alloys.

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