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Araştırma Makalesi - Research Article

Thermal Properties of AM Series Magnesium Alloys

AM Serisi Magnezyum Alaşımlarının Termal Özellikleri

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ABSTRACT

This paper presents experimental investigation on thermal properties (thermal diffusivity and thermal conductivity) of AM series cast magnesium alloys. The effects of the changing in Al content (from 2 to 9 Al and constantly 0.5 Mn, wt. %) in the alloys on thermal properties, density and hardness were comparatively analyzed. It was observed that intermetallic phases ($Mg_{17}Al_{12}$ ve Al_8Mn_5) found in the microstructure of the alloys have an effect on thermal diffusivity, thermal conductivity, density and also hardness. The thermal properties of the alloys were decrease with increasing Al content in the alloy. The thermal properties of the alloys were increase with increasing temperature (the temperature range from 25°C to 400°C). The highest thermal diffusivity was measured on AM20 alloy and the lowest thermal diffusivity were observed on AM90 alloy**.**

Keywords- Thermal Diffusivity, Thermal Conductivity, Density, Magnesium Alloys, Hardness

ÖZ

Bu makale, AM serisi döküm magnezyum alaşımlarının termal özellikleri (termal yayılma ve termal iletkenlik) üzerine deneysel araştırmalar sunmaktadır. Alaşımlardaki Al içeriğindeki değişimin (2'den 9 Al'e ve sabit 0.5 Mn, ağırlıkça %) ısıl özellikler, yoğunluk ve sertlik üzerindeki etkileri karşılaştırmalı olarak analiz edilmiştir. Alaşımların mikroyapısında bulunan intermetalik fazların **(**$Mg_{17}Al_{12}$ ve Al_8Mn_5**)** ısıl yayınım, ısıl iletkenlik, yoğunluk ve ayrıca sertlik üzerine etkisi olduğu görülmüştür. Alaşımın ısıl özellikleri, alaşımdaki Al içeriği arttıkça azalmıştır. Alaşımların termal özellikleri artan sıcaklıkla artmıştır (sıcaklık 25 °C'den- 400 °C'e kadar). En yüksek termal difüzivite AM20 alaşımında ve en düşük termal difüzivite ise AM90 alaşımında gözlenmiştir.

Anahtar Kelimeler- Thermal Difüzivite, Termal İletkenlik, Yoğunluk, Magnezyum Alaşımları, Sertlik

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I. INTRODUCTION

Today's magnesium alloys, owing to their high specific strength and low density, weight-resistance and weight-hardness characteristics, excellent casting properties and mechanical properties, biodegradable properties, are usually used as lightweight structural materials in various applications, such as automobile and aerospace parts, electrical, telecommunication and microelectronics appliances, materials-handling and medical implants (i.e. stents, orthopedic, spinal and dental implants) [1-10]. Notably, in automotive and aerospace industry (i.e. AM40, AM60, AZ91, AS21, AS41, AJ51), the using of magnesium alloys are important goal to decrease fuel consumption and so, air pollutants such as SOx, CO_2, and NOx emissions [1-8].

In the literature, the largely used Mg alloys are classified as AZ, AS, AM and AJ series Mg alloys [7-26]. Among many magnesium alloys developed, i.e. AM50, AM60, AS21, AS41, AZ31, AJ62 and AZ91 are the most widely used commercial alloys because of their microstructure, mechanical, wear and castability properties [5-15]. Magnesium products/parts are generally produced by machining (turning, milling etc.) after the casting process [3,6]. It is realizable a high speed machining for magnesium alloys; but, there are refer that with an increase in cutting speed, there may be critical flank build-up (FBU) due to adhesion between the cutting tool surface and the workpiece as well as chip ignition and tool wear [3,6-17]. There are studies in the literature discussing chip ignition and burning issues, which arise during machining of magnesium alloys. These studies examine the effects of processing parameters on chip ignition and burning [3,6-17]. In the literature, there are some studies on FBU and chip formation (chip morphology) on cutting tool surfaces depending on characteristics and processing parameters of magnesium alloys [3,6-17]. In previous works of the author, it was reported that FBU increases due to the friction on cutting tool surface during machining, and it was emphasized that the cutting forces increase and also chip formation and surface roughness change [6-8]. Cutting tool and workpiece surface temperature, exposure time to heat, dislocation density, and thermal properties of magnesium play a crucial role on chip ignition, chip formation, and the oxidation mechanism [17].

In the literature, there are limited studies on thermal properties/behaviors of magnesium alloys. We found the study of Lee et al. [18] and Rudajevová and Lukáč [19] who studied AZ31, AZ61 and AM20, AS21 magnesium alloys as a function of Al content by comparing thermal properties/behaviors of these alloys. On the other hand, the comparison may be arguable since AZ, AS and AM alloys have different microstructures and alloy compositions. Therefore, we investigated effect of Al alloying additions systematically (from 2 to 9 Al and 0.5 Mn constantly, wt. %) to AM series cast magnesium alloys on its thermal properties/behaviors (thermal diffusivity, thermal conductivity, density and also hardness). For this reason, this study is important and distinctive for literature.

II. MATERIALS AND METHOD

AM series magnesium alloys used in this study were obtained by casting into metal molds after being melted in atmosphere controlled melting furnaces (under CO_2+SF_6 shielding gas medium). Casting or manufacturing of magnesium alloys was detailed by Akyüz [7,8] and Ünal [5] in their previous studies. Furthermore, details of preparation and processing stages of tests performed in this study, details of sample standards and test procedures (i.e. microstructure samples polishing, etching process and etching solutions) were explained in previous studies of the author [7,8]. Microstructure and XRD analyses were performed on each sample. X-ray diffraction (XRD) analyses (Panalytical-Empyrean) were carried out under Cu Kα radiation with an incidence beam angle of 2°. Hardness tests (Shimadzu HMV-2) were carried out (on each sample at ten measurements). The alloy compositions of test samples of AM series cast magnesium alloys (Spectrolab M8 Optical Emission Spectrometry) are presented in Table 1.

Table 1. Alloy composition of the samples (wt. %)

Alloys	Al	Mn	Zn	Si	Fe	Mg
AM20	2.04	0.5	0.1	0.01	0.01	Rest
AM40	4.18	0.5	0.1	0.01	0.01	Rest
AM60	6.22	0.5	0.1	0.01	0.01	Rest
AM90	9.24	0.5	0.1	0.01	0.01	Rest

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

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The density of the alloys was measured (at least ten measurements) by the Archimedes method (He gas atmosphere, under 22 psi/1.5 pressure, in 10 cm^3 specimen container, AccuPycII 1340 Pycnometer, Micromeritics Instrument Corp. U.S.A.). Density of these alloys was determined by averaging ten measurement values. The thermal diffusivity of AS series cast magnesium alloys was measured. The thermal diffusivity measurement was carried out the temperature range from 25°C to 400°C (with a NETZSCH model LFA 457 Laser Flash Device, and Atmosphere N_2, gas flow 100.00 ml/min, under isothermal conditions more than 10 min.). Chunming et al (2013) explained a comprehensive description the test sample standards and test procedures or process of the magnesium alloys [26]. The following equation was used in calculating the thermal conductivity [18]:

$$\lambda=\alpha\ \rho\ c_p \quad (1)$$

Where λ is the thermal conductivity (λ: W m^{-1} K^{-1}), α is the thermal diffusivity (α:m^2s^{-1}), ρ is the density (ρ: g cm^{-3}) and c_p is the specific heat capacity (c_p: J g^{-1} K^{-1} accepted as fixed).

Lee et al. 2013 [18] reported that there is no significant difference in the specific heat capacities of AZ31 and AZ61 as the aluminum quantities are quite similar. In their study, the specific heat capacity of magnesium (1.0241 J $g^{-1}K^{-1}$) and aluminum (0.9025 J $g^{-1}K^{-1}$) showed very little difference at room temperature [18]. Therefore, changes in the specific heat capacities of magnesium alloys caused by addition of aluminum in differing proportions are not significant. In this study, the specific heat capacity (c_p) is accepted as fixed.

III. RESULTS AND DISCUSSION

A. Microstructure, XRD pattern and Hardness

The microstructure images (optical light microscopy-OM) and XRD patterns of the alloys are seen on Figure 1 and Figure 2, respectively. The microstructure of these alloys is made up of α-Mg matrix and intermetallic phases ($Mg_{17}Al_{12}$ and Al_8Mn_5) (Figure 2). It is seen that the Al_8Mn_5 intermetallic phase in the microstructure is in the form of points and $Mg_{17}Al_{12}$ intermetallic phase ranges roughly along the grain boundaries (network formation). The morphologic structure of these alloys are consistent with the literature [7,8,19-24]. In the literature, it was indicated that the formation and location of intermetallic phases were due to changes in the solidification behavior of the melt by alloy addition (i.e. Zn, Si, Mn, Sr etc.) [7,8,19-24]. When the microstructure images of the AM90 alloy (seen in Figure 1e.) were examined, it was observed that the intermetallic phases in the alloy ($Mg_{17}Al_{12}$ and Al_8Mn_5) were more evident and distributed within the structure depending on the variation of alloy components (9 Al, wt.%).

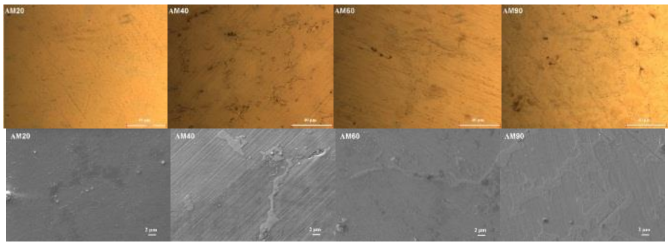

Figure 1. Microstructure of the alloys

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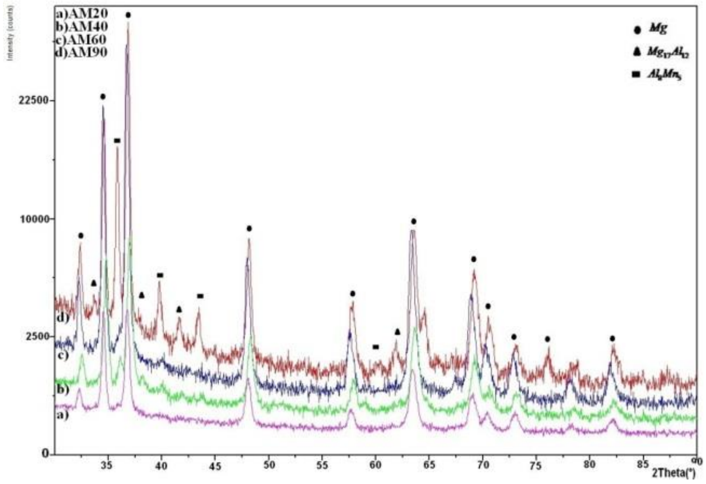

Figure 2. XRD patterns of the alloys.

The hardness tests results obtained from the alloys are given in Figure 3. The mean hardness values of alloys were estimated as 38.8 HV_{10} in the AM20 alloy, 51.18 HV_{10} in the AM40, 64.85 HV_{10} in the AM60 alloy and 86.75 HV_{10} in the AM90 alloy, respectively. The highest hardness was obtained from the AM90 alloy.

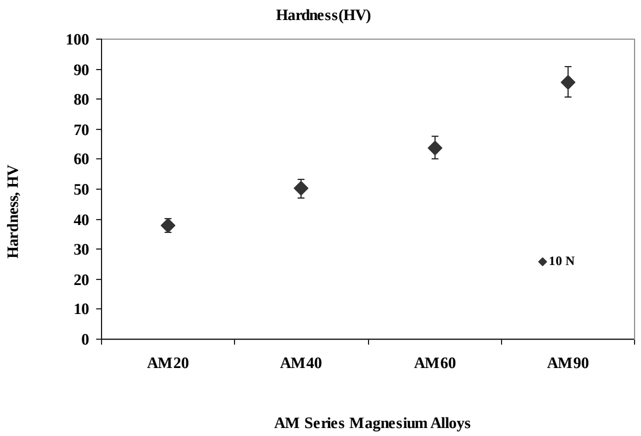

Figure 3. Hardness of the Alloys

B. Density and Thermal Properties

The densities (seen in Figure 4) and thermal properties (thermal diffusivity and thermal conductivity-seen in Figure 5a-b) of the alloys varied according to the Al content. The densities of the alloys increased with increasing the Al content in the alloy (seen in Figure 4). The highest density was acquired from the AM90 alloy while the lowest density was detected in the AM20. The densities of these alloys are 1.75 g cm^{-3} in the AM20 alloy and 1.84 g cm^{-3} in the AM90 alloy, which increase starting from AM20 up to AM90 (Figure 4).

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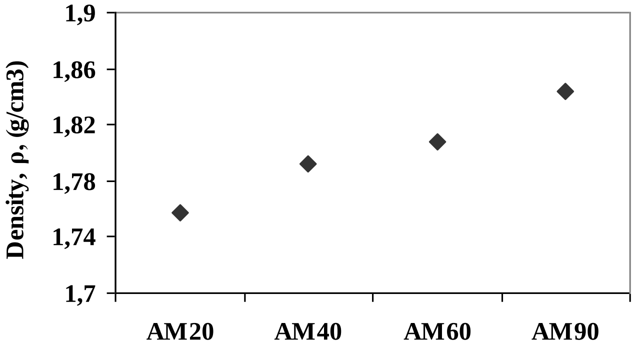

Figure 4. Density of the alloys

Figure 5(a-b) shows the effect of microstructure variations on the thermal properties of the alloys as a function of the alloy content. Thermal diffusivity and thermal conductivity of the Mg alloys used in the test were observed to decrease as the Al content (wt.%) in the alloy increased. Thermal properties of these alloys increased with increasing temperature. As is known from the literature, thermal properties of pure metals are higher than those of alloys [25]. Depending on the temperature increase (from 25°C to 400°C) in these alloys, thermal diffusivity and thermal conductivity were observed to increase (Figure 5a-b). While the highest thermal diffusivity and thermal conductivity (at all temperatures) occurred in the AM20 alloy, the lowest thermal properties (at all temperatures) were observed in the AM90 alloy (seen in Figure 5a-b). Considering the thermal diffusivity data of the alloys (from AM20 to AM90) at 25 °C, the thermal diffusivity values of these alloys were 36.65$m^2 s^{-1}$, 24.96 $m^2 s^{-1}$, 29.56 $m^2 s^{-1}$ and 22.52 $m^2 s^{-1}$, respectively (seen in Figure 5a).When the temperature was increased to 400 °C, thermal diffusivity values were measured as 47.25 m^2s^{-1}, 34.82 $m^2 s^{-1}$, 40.23 $m^2 s^{-1}$ and 29.34 $m^2 s^{-1}$, respectively (seen in Figure 6a). The thermal conductivity values of these alloys were 64.82W $m^{-1} K^{-1}$, 53.15 $Wm^{-1} K^{-1}$, 44.9 $Wm^{-1} K^{-1}$, and 39.85 $Wm^{-1} K^{-1}$ at 25 °C, respectively (seen in Figure 5b).When the temperature was increased to 400 °C, thermal conductivity values were measured as 83.28$Wm^{-1} K^{-1}$, 72.46 $Wm^{-1} K^{-1}$, 61.30$Wm^{-1} K^{-1}$ and 52.9 $Wm^{-1} K^{-1}$, respectively (seen in Figure 5b). The thermal properties of AM series cast magnesium alloys increased depending on the temperature (from 25°C to 400°C) (seen in Figure 5). On the other hand, thermal diffusivity and thermal conductivity decreased with increasing Al content (seen in Figure 5).

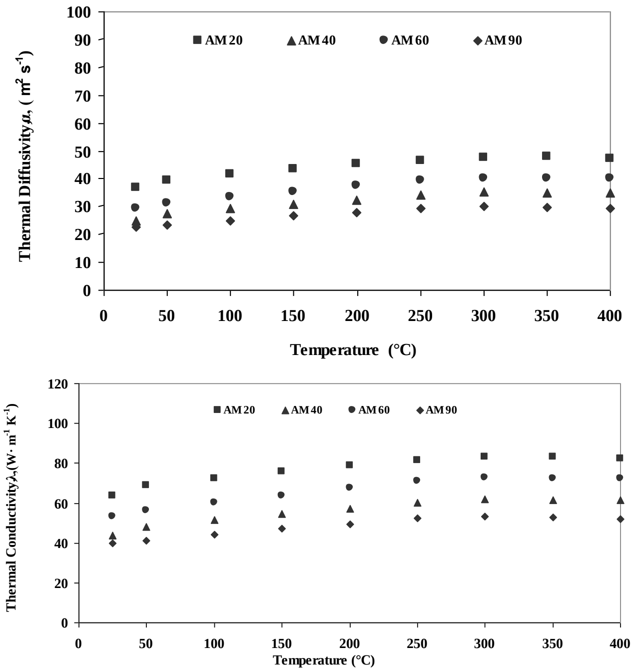

Figure 5. (a) Thermal diffusivity and (b) thermal conductivity of the alloys

This experimental study results show that the intermetallic phases found ($Mg_{17}Al_{12}$ and Al_8Mn_5) in microstructure of AM series magnesium alloys could be very effective on density, thermal properties (thermal diffusivity and thermal conductivity) and hardness as well. Results obtained from the study are in agreement with the literature [7-9,19-30].

IV. CONCLUSION

The following results were obtained as a result of this experimental study:

1. The alloy composition (from 2 to 9 Al and 0.5 Mn, wt.%) has an effect on the place and shape of intermetallic phases ($Mg_{17}Al_{12}$ and Al_8Mn_5) in the microstructure of AM series cast Mg alloys. The intermetallic phases in the alloys are effective on density and thermal properties/behaviors.

2. The densities and thermal properties of the alloys vary according to the Al content (and constant Mn). The densities of the alloys increase with increasing Al content. While the highest density was observed in the AM90 alloy (1.84 g cm^{-3}), the lowest density was in the AM20 (1.75 gcm^{-3}).

3. Thermal properties/behaviors of the alloys were observed to decrease with increasing Al content (wt.%) in the alloy. Depending on the increase in temperature in the alloys (from 25°C to 400°C), thermal diffusivity and thermal conductivity were observed to increase (except for AM20). While the highest thermal properties (at all temperatures) occurred in the AM20 alloy, the lowest thermal properties (at all temperatures) were observed in the AM90 alloy (Figure 6a-b).

4. We may conclude that the Mg alloy components affect the alloy microstructure (Al_8Mn_5 and $Mg_{17}Al_{12}$ intermetallic phases) and thermal properties, they also have an effect on temperature increase at the cutting tool tip, FBU occurs/accelerates at the cutting tool tip, wear occurs at the cutting tip and chip lengths vary, thereby facilitating ignition and burning.

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