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Effects of Al_2O_3 nanoparticle on the compression flow curve of AZ11 magnesium alloy

Hamid Batmani *, Saeed Tanomand, Hamed Babri

Sama Technical and Vocational Training College, Islamic Azad University, Islamabad Gharb, Iran

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ABSTRACT

Compression testing on an AZ11 magnesium alloy performed with and without alumina nano particles as an additive. The nanoparticles were tested at various sizes (30, 80, and 150 nm) and different percentages by weight (1%, 2% and 4% particle load) at room temperature. Samples were prepared by casting in low-carbon steel molds and turned to have appropriate size and surface quality. Due to the small radius of the barreling in samples, was ignored. The presence of nano-Al_2O_3 particulates with a size of 30 nm and 2% volume significantly improved (by 13.44%) the compressive yield strength of AZ11 magnesium alloy. An attempt is made to correlate the effect of the amount and size of Al_2O_3 nanoparticulates on the properties of AZ11 magnesium alloy.

1. Introduction

Magnesium (Mg), with a density of 1.74 g/cm^3, is one of the lightest engineering materials available on the earth and about 35% and 78% lighter than aluminum-based (~2.70 g/cm^3) and iron-based (~7.87 g/cm^3) materials, respectively (Davis, 1993). Magnesium alloys containing aluminum (Al) and zinc (Zn) are known as AZ alloys (Wu et al., 2005; Jing et al., 2006). Among different Mg alloys, the AZ series is the most important; accordingly, many studies have been carried out to study the mechanical behavior of this series (Fereshteh-Saniee et al., 2012). These alloys are easily available, reasonably priced, and used in many engineering applications. However, reinforcement of these allows can further improve their properties (Alam et al., 2011; Lloyd, 1994).

Due to their low density and superior mechanical properties, magnesium-based nano-composites are potential candidates for applications in the aerospace, automobile, transportation, and consumer industries where keeping weight low is of great importance (Goh et al., 2005; Morisada et al., 2006; Gehrmann et al., 2005). In addition, the low density and considerable high-yield strength of magnesium alloys are favorable properties in designing various utilities (like casings for electronic devices) (Yin et al., 2005; Cao et al., 2006). Enhancement of the tensile properties of Mg and Mg alloys has been attempted by reinforcing them with nano particulates such as Al_2O_3, Y_2O_3, ZrO_2, Cu, and carbon nano-tubes (Goh et al., 2005; Hassan and Gupta, 2006). Despite these advantages, they have moderate strength and poor formability at room temperature due to their hexagonal close-packed (hcp) structure and limited slip systems. Various solutions, such as microstructural refinement (Masoudpanah and Mahmudi, 2009; Torbati-Sarraf and Mahmudi, 2010), use of alloying elements, (Nayyeri et al., 2010), and composite reinforcements, (Habibnejad-Korayem et al., 2009), have been proposed to improve the mechanical properties of Mg alloys.

Recent studies, (Francis et al., 2011; Habibnejad-Korayem et al., 2009, 2013; Alam et al., 2013; Sankaranarayanan et al., 2013; paramsothy et al., 2012), have focused on the application of alumina nanoparticles (or "nano-alumina") (Al_2O_3) to magnesium and its alloys. Francis et al. (2011), in order to acquire ultra-high-strength composite magnesium, investigated the amount of alumina that would improve mechanical properties such as hardness and flexural strength when used to reinforce ceramic. These researchers applied different amounts of nano-alumina additives with volume percentages of 3.5%, 7%, and 14%using a powder metallurgy combination method. Mechanical thermal analysis revealed that the coefficient of thermal expansion was significantly reduced after the addition of the alumina nanoparticles to ceramic magnesium. Investigation of the mechanical properties also showed increases in the hardness and flexural strengths of the material at all three volume percentages. The compound with a nano-alumina volume percentage of 7% had the best mechanical properties; conversely, the resistance and toughness of the 14% volume nano-alumina decreased. Habibnejad-Korayem et al. (2009, 2013),

* Corresponding Author.
Address: Sama Technical and Vocational Training College, Islamic Azad University, Islamabad Gharb, Iran

studied the properties of nano-alumina additives with weight percentages of 0.5%, 1%, and 2% in pure magnesium and AZ31alloy through a corrosion casting method. In these studies, a decrease in the thermal expansion coefficient and a considerable increase in the yield stress and tensile strength were observed. From an investigation performed on fracture surfaces, the nature of the fractures was clearly different, with the soft failure of the relatively uniform matter (that is, without the presence of nano-alumina) becoming brittle and fracturing with the change in the material due to the addition of alumina nano particles. With an increase in the amount of the alumina nano particles, the work hardening rate increases. Alam et al. (2013), studied the effect of the simultaneous addition of alumina nano particles and calcium additives in the AZ41 and AZ51 alloys and determined that compressive and tensile strengths were increased for both alloys. Sankaranarayanan et al. (2013), investigated the effect of alumina nanoparticles as an additive and the effect of heat treatment on the MG-(5.6Ti+3Al) composite. Some of this study's main findings included the improvement of the compressive and tensile strengths of the resulting nano-ceramic. Nguyen et al. (2009), investigated the effect of alumina nanoparticles and copper additives and the effect of a heat treatment on the stretching response of AZ61 magnesium alloy. The result of this research was a 54% increase in the tensile strength, flexibility, and failure in the AZ61-1.5Al_2O_3-1Cu sample. paramsothy and Gupta (2013), examined the addition of alumina nano-particles and copper to reinforce the AZ91/ZK60A combination magnesium alloy. In this study, the addition of alumina nano particles and copper to the combined alloy of AZ91/ZK60A magnesium led to strength being increased by 12% and flexibility reduced by 10% on the tensile test; on the compression test, the strength was increased by 12% and the plasticity was reduced by approximately 12%.

Paramsothy et al. (2012), investigated the effect of alumina nanoparticles on the flexibility of the AZ81magnesium alloy. The results of this research showed an increase in the flexibility of the AZ81 alloy in the tensile and compression tests after addition of the alumina nanoparticles.

The aim of the current study is to examine the effects of Al_2O_3 nanoparticles on the compression flow curve of AZ11 magnesium alloy at room temperature.

2. Experimental procedure

Cast AZ11 magnesium alloy with and without nano-Al_2O_3 particulateswasused for preparation of the test samples. The compositions of this alloy (AZ11) are summarized in Table 1. The percentages of alloy elements in this Mg alloy are within the limits suggested by the American Society for Testing and Materials (ASTM).

For the compression tests, cylindrical samples (9.0 mm and 6.0 mm in height and diameter, respectively) were prepared through a machine operation depicted in Fig. 1.

Table 1: Composition of AZ11 magnesium alloy

Al	Zn	Mg	Si
1 %	0.7 %	Balance	0.1 %

Fig. 1: Sample of compression test (before the test).

The conventional compression test should theoretically be carried out under zero friction conditions; however, it is impossible to create these conditions. For this reason, the compression tests were performed under dry conditions. Due to the small radius of the barreling in samples, was ignored. To determine the ceramic compound with alumina nanoparticles that provided the best mechanical properties, several different sizes (30, 80, and 150 nm) and volume percentages (1%, 2%, or 4%) were tested for the compounds. Compression tests were conducted at a strain rate of 0.001 s^{-1}.

For this test, the amounts of energy and the height will be measured. This allows the counting of the flow stress for each amount of strain. The test chosen for the study is easy to perform step-by-step at room temperature, and all steps of the test for every distinctive strain rate would be finished with just one sample. As with the conditions in the tensile test, the following relations for the same pressure test are to be considered (Eqs. 1 and 2).

$$\bar{\varepsilon} = \ln \frac{h_o}{h} = \ln \frac{A}{A_o} \quad (1)$$

$$\bar{\sigma} = \frac{P}{A} \quad (2)$$

In the equations above, A and A_o are based on momentary and primary levels, h and h_o based on momentary and primary height of the sample, $\bar{\varepsilon}$ and $\bar{\sigma}$ are based on effective strain and stress, respectively, and P is also the incoming energy on this sample.

After placing the sample in the center of the jaw of the compression test machine, the sample was compressed until failure (fracture/breaking). During the test, the force–height values (and, therefore, the force–displacement values) were measured. Figure 2 shows one of the broken samples.

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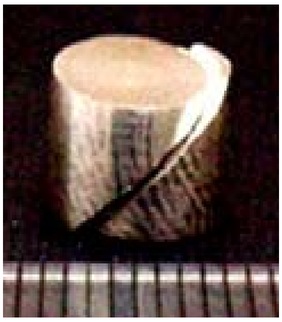

Fig. 2: Sample of the compression test (after the test).

3. Results and discussion

Based on force–displacement values, the obtained experimental flow stresses in Figs. 3- 7.

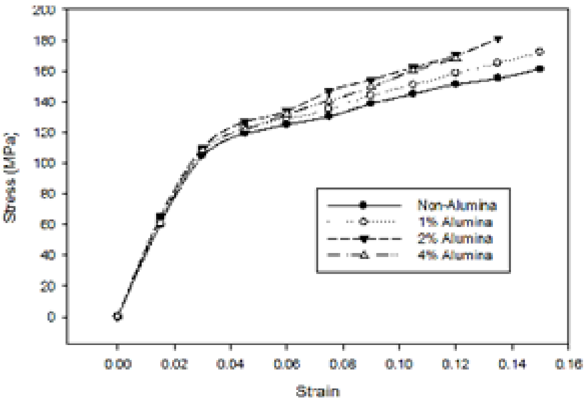

Fig. 3: Experimental flow stresses of AZ11 alloy with different weight percentages of 150(nm)nano-Al_2O_3 during the compression test.

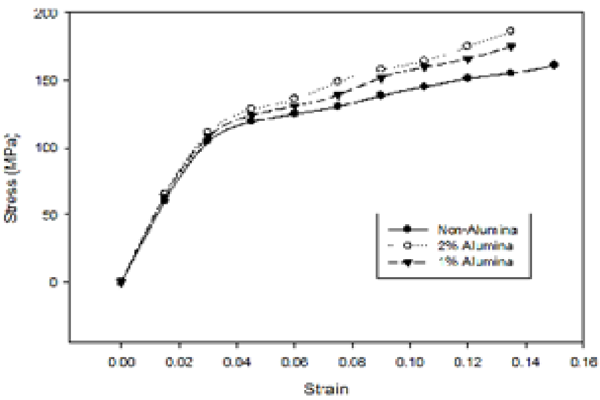

Fig. 4: Experimental flow stresses of AZ11 alloy with different weight percentages of 80(nm)nano-Al_2O_3 during the compression test.

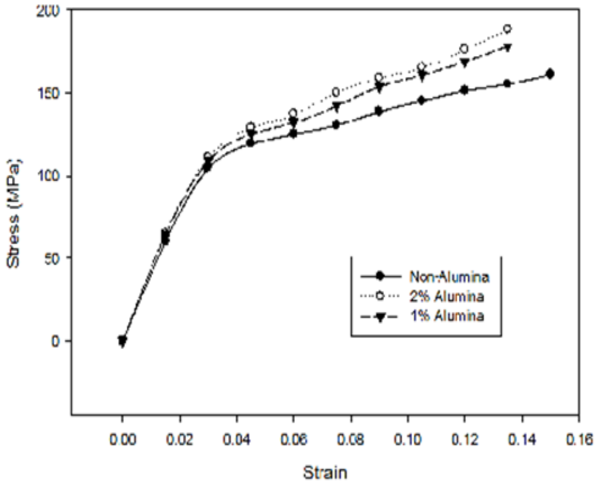

Fig. 5: Experimental flow stresses of AZ11 alloy with different weight percentages of 30(mm) nano-Al_2O_3during the compression test.

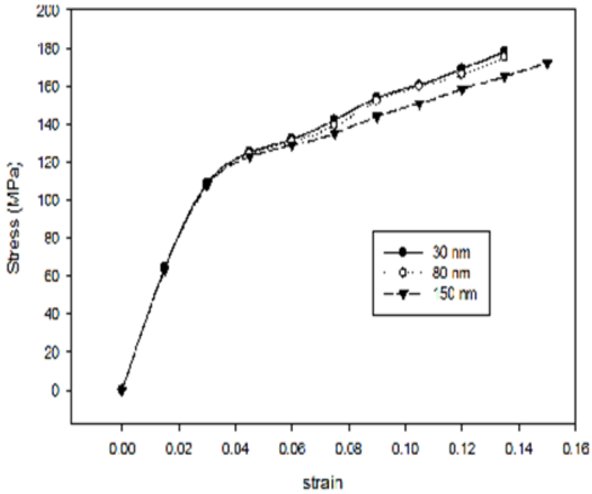

Fig. 6: Experimental flow stresses of AZ11 alloy with different sizes of vol. 1% nano-Al_2O_3 during the compression test.

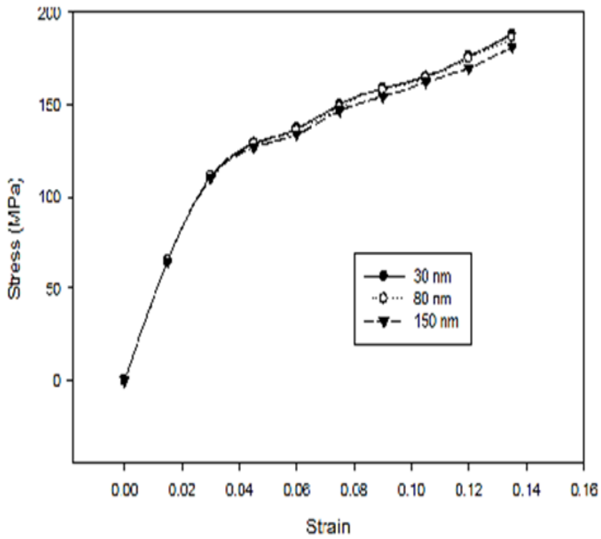

Fig. 7: Experimental flow stresses of AZ11 alloy with different sizes of vol. 2%nano-Al_2O_3 during the compression test.

The fracture of a sample of AZ11, a Magnesium Alloy, occurs at the point σ=166.34 [MPa] and ε=0.163 by means of a compression test. In the cases of addition of 1% of nano-alumina with 150, 80, and 30 nanometers in diameter to the Magnesium Alloy AZ11 the fracture occurs at the points σ=173.05 [MPa] and ε=0.152, σ=177.64 [MPa] and ε=0.146, and σ=182.32 [MPa] and ε=0.142, respectively. Also adding 2% of nano-alumina with 150, 80, 30 nanometers in diameter to the Magnesium Alloy AZ11, will cause the fracture to occur at the points σ=184.27 [MPa] and ε=0.1392, σ=188.16 [MPa] and ε=0.1375, and σ=188.69 [MPa] and ε=0.1356 respectively. And finally in the case of addition of 4% of nano alumina with 150, 80, and 30 nanometers in diameter to the Magnesium Alloy AZ11 the fracture occurs at the point σ=169.30 [MPa] and ε=0.122.

To calculate the variation percentage of compressive strength and ductility (softness) we use the Eqs. 3 and 4 respectively:

$$\frac{\sigma - \sigma_0}{\sigma_0} \times 100\ \% \qquad (3)$$

$$\frac{\varepsilon - \varepsilon_0}{\varepsilon_0} \times 100\ \% \qquad (4)$$

Where σ_0 and σ are the initial and secondary stresses and ε_0 and ε are the initial and secondary strains.

The results obtained by equations (3, 4) are summarized in Table 2.

Table 2: Compressive strength and ductility variations of the alloy AZ11 in combination with different sizes and volume fractions of nano-Al_2O_3 additives in comparison with the alloy AZ11 itself

Percent of Nano-Al_2O_3	1 Vol.% Nano-Al_2O_3			2 Vol.% Nano-Al_2O_3			4 Vol.% Nano-Al_2O_3
Size of Nano-Al_2O_3 (nm)	150	80	30	150	80	30	150
Percent of Compressive Strength	4.03%	6.79%	9.61%	10.78%	13.12%	13.44%	1.78%
Percent of Ductility	-6.75%	-10.43%	-12.88%	-14.60%	-15.64%	-16.81%	-25.15%

Table 2 obviously states that the increase in percentage of volume fraction of nano-alumina additives up to 2% will cause the compressive strength increase in value too; however, there is a major reduction in the value of compressive strength in volume fraction of 4%. As the particles of nano-alumina additives become finer, the value of compressive strength increases. Thus, the optimal case occurs when the additive is of 2% weight fraction of alumina with a diameter of 30 nanometers (AZ11 + 2 Vol. % Nano-Al_2O_3). In concern with the ductility variations we can conclude that increase in weight fraction and decrease in nano-alumina particles size will lead into a descending decrease in ductility.

Maximum stresses of each sample are presented in Table 3 which is obtained from the experimental data.

Table 3: Maximum stress applied to the alloy AZ11 combined with the different sizes and volume fractions of nano-Al_2O_3 additives.

Percent of Nano-Al_2O_3	Non Nano-Al_2O_3	1 Vol.% Nano-Al_2O_3			2 Vol.% Nano-Al_2O_3			4 Vol.% Nano-Al_2O_3
Size of Nano-Al_2O_3 (nm)	–	150	80	30	150	80	30	150
Pick Stress (MPa)	161.17	172.12	175.23	178.12	181.8	186.3	188.21	168.23

As Table 2 represents, it can be seen that the optimal case in which the alloy would withstand the maximum stress is when the 2Vol. % of Nano-Al_2O_3 additives with 30(nm) in diameter are combined with alloy AZ11.

To calculate the variation percentage of maximum stress Eq. 5 will be used.

$$\frac{\sigma - \sigma_{p_0}}{\sigma_{p_0}} \times 100\ \% \qquad (5)$$

Where σ_{p_0} and σ_p are the initial and secondary maximum stresses.

The results of Eq. 5 are summarized in Table 4.

Table 4: Variation of maximum stressapplied to the alloy AZ11 combined with the different sizes and volume fractions of nano-Al_2O_3 additives in comparison with the alloy AZ11 itself.

Percent of Nano-Al_2O_3	1 Vol.% Nano-Al_2O_3			2 Vol.% Nano-Al_2O_3			4 Vol.% Nano-Al_2O_3
Size of Nano-Al_2O_3 (nm)	150	80	30	150	80	30	150
Percent of Pick Stress (MPa)	6.79%	8.72%	10.52%	12.80%	15.59%	16.78%	4.38%

It can be seen from Table 4 that the optimal case concerned with increase in maximum stress to the value of 16/78% is when 2% of nano-alumina with the diameter of 30nanometers are added to the magnesium alloy.

4. Conclusions

According to the experiment of pressure effect on AZ11 magnesium alloy and addition of alumina nanoparticles 1%, 2% and 4%, with 30, 80 and 150 nm diameters, the results are listed as follow:

- Addition of alumina nanoparticles (up to 2%) to AZ11 magnesium alloy increases the compressive strength.
- Decreasing the size of alumina nanoparticles raises the compressive strength.
- The plasticity is reduced by increasing the number of alumina nanoparticles.
- Addition of 4% of nano alumina to AZ11 magnesium alloy has negative effects and reduces the compressive strength. It also increases the cost of method.
- The highest compressive strength is achieved when 2% of alumina nanoparticles with 30 nm diameter are added to AZ11 magnesium alloy. Therefore, the best condition is the addition of alumina nanoparticles (2%) with diameter of 30 nm.
- Using alumina nanoparticles in AZ11 magnesium alloy is a convenient method when the high compressive strength is a significant issue rather than plasticity.
- Addition of alumina nanoparticles demonstrates the excellent potential as a regenerator agent in the magnesium matrix.
- Increasing the amount of alumina nanoparticles makes an unstable situation after a while and has not a specific effect.
- The results obtained from this research have a good conformity with authoritative articles.

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