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Effect of steel ball diameter in the surface mechanical attrition treatment (SMAT) on microstructure, roughness, hardness and wear behavior of AZ31 magnesium alloy

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ABSTRACT

Surface Mechanical Attrition Treatment (SMAT) is recognized as an effective technology for enhancing hardness and surface abrasion resistance. This study examined the influence of SMAT on the microstructure, surface roughness, hardness, and wear behavior of the AZ31 magnesium alloy. For the experiments, steel balls of different diameters – 3.2mm, 4mm, and 5.6mm – were used to perform the SMAT process, which was consistently timed at 8.5 minutes. Detailed analyses of the resultant microstructures were then conducted using tools such as a scanning electron microscope and X-ray diffraction. The hardness and wear were measured using the Vickers and the disk pin methods, respectively. It was observed that the SMAT process significantly reduced the grain size on the sample surfaces. For example, when a steel ball with a diameter of 5.6mm was utilized, the grain size was reduced from 225nm to just 96nm. The process also led to a substantial increase in hardness, with measurements rising from 65 HV to 190 HV, once again when a steel ball of 5.6mm diameter was utilized. Furthermore, the SMAT process, when executed with a tool diameter of 5.6mm, eliminated weight loss in the wear test, which had been previously recorded at 0.26mg, indicating an increase in surface abrasion resistance. An observed correlation suggested that as the tool diameters increased, the abrasion resistance of the surface improved. Abrasion was adhesive on untreated samples; on treated samples, it was ridged and scratched. However, as the tool diameter—and consequently, the surface hardness—increased, the scratches were seen to reduce gradually.

Keywords: *AZ31 Magnesium Alloy, Surface Mechanical Attrition Treatment (SMAT), Microstructure, Wear Resistance, Hardness.*

1. Introduction

Due to their ultralight properties, Magnesium alloys are frequently utilized in engineering applications. These alloys exhibit only one-fourth the density of steel and two-thirds that of aluminum, coupled with high weight resistance, which accounts for their categorization as ultralight alloys. Their significant weight resistance makes them particularly useful in various fields, including the automotive and aerospace industries [1-3].

However, despite these advantages, magnesium alloys are known to have subpar wear and corrosion resistance, which limits their applicability [4-7]. High sensitivity in the structure and surface of the material can result in numerous defects, including fatigue failure, wear, corrosion, and abrasion. It has been suggested that these issues can be mitigated by refining grains and nanocrystals [8].

Thus, the optimization of the microstructure and surface properties of these materials could provide a viable means to enhance their performance and longevity. It has been established that the alteration of surface microstructures using various plastic deformation methods can effectively improve material surfaces [9-11].

Several techniques have been developed for severe plastic deformation (SPD), aiming to reduce surface grains and augment the physical and chemical properties of metals and alloys. Examples include constrained groove pressing (CGP) [12, 13], non-equal channel angular pressing (NeECAP) [14], cyclic close die forging (CEC)‌ [15-17], equal channel angular rolling (ECAR) [18], and surface mechanical attrition treatment (SMAT) [19].

In recent years, the SMAT process has been proposed as the most efficient technology for surface nanocrystallization [20, 21]. SMAT can refine surface grains down to the nanometer scale, with grain size increasing progressively from the surface toward the core of the sample [22, 23]. Generally, it is recognized that nanostructured distinctions can enhance the mechanical properties of alloys.

The strength composition of materials can be significantly improved, albeit with a trade-off of reduced ductile properties [24, 25]. Among various techniques, Surface Mechanical Attrition Treatment (SMAT) has been identified as an effective method for creating surface nanocrystals, capable of refining material surface grains to the nanometer scale without altering their chemical composition [26].

The successful creation of nanocrystals on the surface of a TiNi alloy was attributed by Hu et al. to the application of the SMAT process [27]. A notable improvement in mechanical properties was observed following this process. For instance, the tensile strength of the AZ31 magnesium alloy was effectively enhanced through SMAT, although this was accompanied by a decrease in fracture length [28].

In a separate study, Sun et al. [29] analyzed the tribological behavior of surface nanocrystals on AZ91 magnesium alloy produced by SMAT. The findings suggested that the presence of nanograins in the surface layers reduced the coefficient of friction due to the surface's fine-grain strengthening. This process also resulted in nanostructured layers exhibiting a lower wear rate compared to coarse-grained layers.

SMAT has been successfully applied to a range of metallic materials, including stainless steel [30-32]. For example, Sun [33] focused on the abrasion resistance of AISI 304 stainless steel, reporting an increase in wear resistance resulting from the formation of microcracks and creating a hard surface layer via SMAT. Furthermore, Wang et al. [34] studied grain refinement at the nanometer scale in copper alloys induced by plastic strain. Ahu et al. [35] examined the nanostructure formation mechanism in titanium using the SMAT process.

This study investigated the impacts of SMAT on the microstructure, hardness, and wear behavior of the AZ31 magnesium alloy using varying parameters, such as the diameter of steel balls and a fixed frequency of 20kHz. The Vickers microhardness test, SEM, and XRD were utilized for analysis, while samples were subjected to a pin-on-disk wear test.

2. Experimental details

In this study, an AZ31 magnesium alloy sheet was utilized, the chemical composition of which was determined through quantometry analysis, as illustrated in Table 1. The schematic of the Surface Mechanical Attrition Treatment (SMAT) process is depicted in Figure 1.

Samples extracted using a wire cut machine were prepared with diameters and thicknesses of 20mm and 5mm, respectively. The SMAT process was conducted at room temperature, using steel ball tools with diameters of 3.2mm, 4mm, and 5.6mm. Each sample was treated for a constant duration of 8.5 minutes at a frequency of 20KHz per tool size.

To investigate the structural alterations, X-ray diffraction (XRD) was performed at a 2θ angle, spanning from 10 to 80 degrees. A grazing test was also conducted to measure surface grains alongside metallographic procedures employed to study the

Table 1- The chemical of composition of AZ31 magnesium alloy (wt %)

Al	Zn	Mn	Cu	Mg
2.89	0.85	0.32	0.002	Bal.

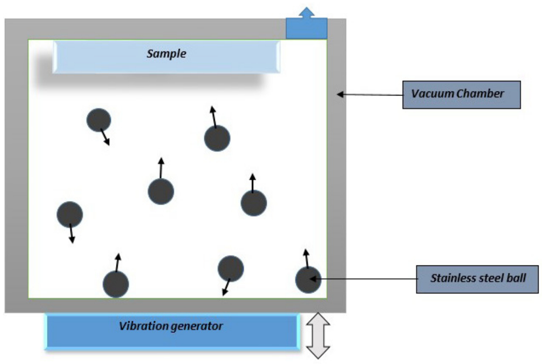

Fig. 1- Schematic of mechanical surface modification device (SMAT).

surface structure. The etching solution comprised a mixture of 4.5 grams of picric acid, 10 ml of acetic acid, 10 ml of water, and 70 ml of ethanol. SEM analysis was performed using Philips equipment.

The hardness of the samples was gauged using the USA Buehler microhardness test, with measurements taken at 50 μm intervals, an applied force of 100 grams, and a dwell time of 15 seconds. Surface roughness was also assessed at intervals of 5.6 mm.

The wear mechanism was evaluated using the pin-on-disc method, with an applied force of 230 grams, and wear was measured over a distance of 900 meters at a speed of 0.1 m/s under ambient conditions. SEM was employed to identify the wear mechanism and inspect the sample surfaces.

3. Result and discussion

3.1. Microstructure Investigation

The XRD results for both the untreated sample and those subjected to SMAT are depicted in Figure 2.

As evident from Figure 2, the peaks have broadened, and their intensity has decreased due to the SMAT process and the formation of fine grains and microstrains on the surface. Crystal size calculations, derived from the XRD data, revealed a reduction from 225.21 nm in the untreated sample to 94.6 nm when a 5.6 mm ball was employed in the SMAT process. The shrinking crystal size was attributed to cold mechanical work.

For instance, a study conducted by Haghighi et al. [36] on the AZ31 magnesium alloy reported a similar broadening of peaks and reduction in crystal size, outcomes of the shot pinning operation. They also mentioned grain crushing and the formation of surface microstrains as consequential effects.

This research presents comparative images of fine surface grains post-SMAT treatment and untreated coarse grains in Figure 3. It was observed that with an increase in the diameter of the steel balls used in the cold mechanical work of SMAT, the thickness of the deformed layer also escalated.

Consistent with other research findings, it was noted that an increased diameter of steel balls in SMAT led to finer surface grains and an increased thickness of nanocrystal layers, while the grain size beyond this layer remained relatively constant [1].

3.2. Examination of the hardness of the specimens

The hardness test results for the untreated sample and the SMAT-treated samples are depicted in Figure 4. Following Surface Mechanical Attrition Treatment (SMAT), the samples displayed an increased hardness of 175%, 184%, and 198% for ball diameters of 3.2mm, 4mm, and 5.6mm, respectively, in comparison to the untreated sample. The increase in hardness is attributed to the creation of fine grains, nanocrystals, and microstrains on the surface due to the SMAT process.

Examination of the images revealed that a layer approximately 200 μm thick was formed due to the cold mechanical work, beyond which the hardness of the sample surface decreased. These results agree with other researchers' findings [1, 36, 37]. For instance, a study on the AZ91D magnesium alloy treated with SMAT showed that an increase in the diameter of the steel balls led to increased hardness in the samples, which gradually decreased as it approached the core or base of the alloy [1].

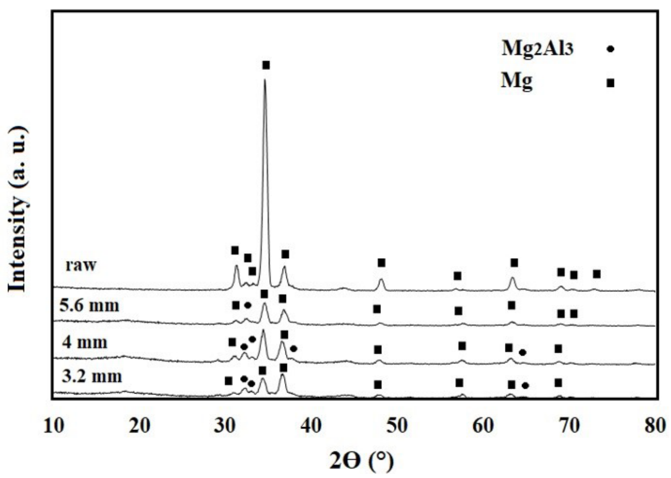

Fig. 2- XRD analysis of AZ31 magnesium alloy for untreated and SMAT-treated samples.

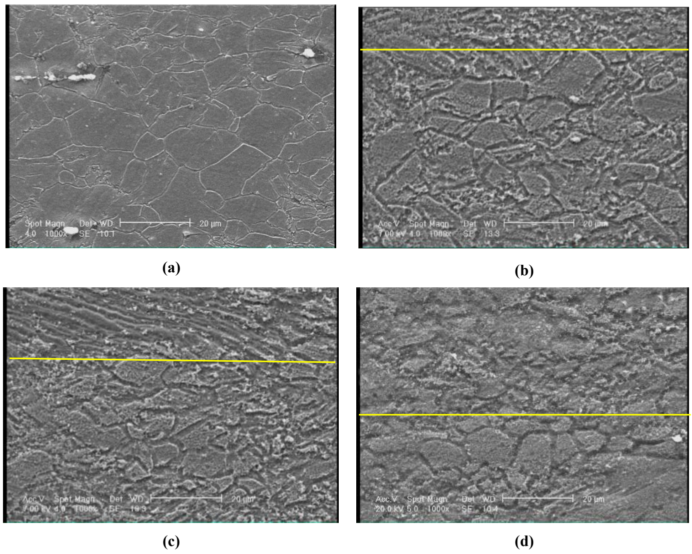

Fig. 3- Microstructure of samples: (a) untreated sample, (b) processed with a tool diameter of 3.2 mm, (c) processed with a tool diameter of 4 mm, (d) processed with a tool diameter of 5.6 mm.

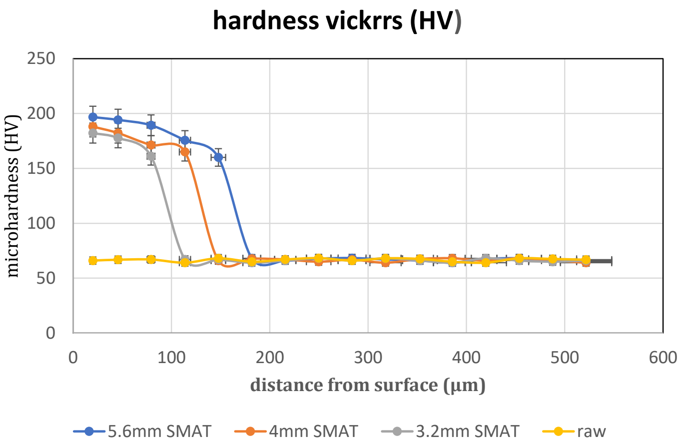

Fig. 4- Microhardness changes from the surface to the depth of untreated and SMAT-treated samples with different ball diameters.

Consequently, it was noted that the hardness of the samples increased due to the SMAT process, depending on the diameter of the steel balls, with the smallest and largest being 3.2mm and 5.6mm, respectively.

3.3. Investigation of the wear testing

The wear test results, depicted in Figure 5 and based on weight loss per unit distance traveled, indicate that wear resistance increases with the diameter of the steel balls. In the untreated sample, the weight loss was 0.26 mg, while for the sample treated with a 5.6 mm diameter ball, the weight loss was reduced to zero due to the SMAT process. This phenomenon can be attributed to the formation of fine grains and microstrains, which increase the hardness of the alloy's surface through mechanical treatment. As the balls' diameter increased, the nano-crystalline layers' thickness on the surface increased due to the SMAT process, subsequently enhancing hardness. These wear test results align well with the findings of other researchers [1]. For instance, HU et al. reported an increase in the wear resistance of TiNi alloy samples treated with SMAT compared to untreated samples [27].

3.4. Wear mechanism

The wear mechanism was investigated using

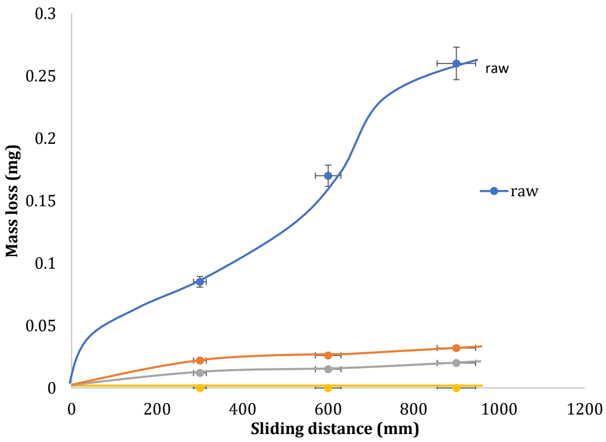

Fig. 5- Different weight loss in the traveled distance for different samples.

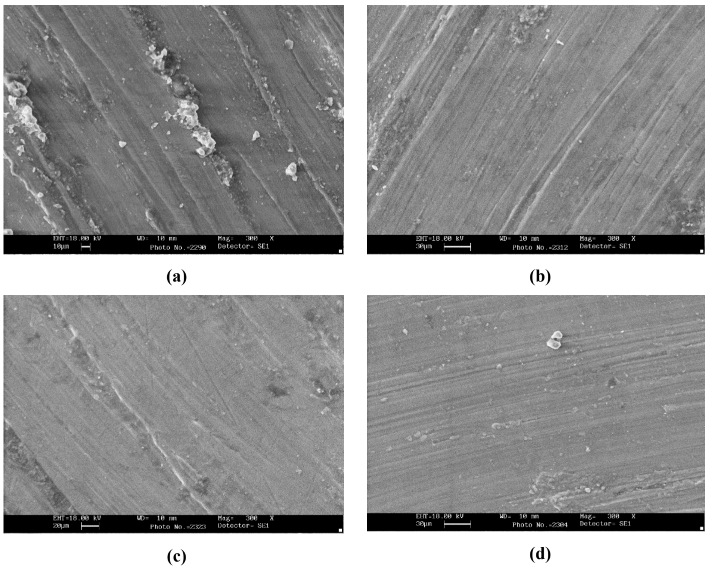

Fig. 6- SEM images of sample wear: (a) Untreated sample, (b) Treated sample with a tool diameter of 3.2 mm, (c) Treated sample with a tool diameter of 4 mm, (d) Treated sample with a tool diameter of 5.6 mm.

a Scanning Electron Microscope (SEM), with the results shown in Figure 6. Adhesive wear, evident in the form of layers across a portion of the surface, was found to be the predominant wear mechanism in the untreated sample. This change in comparison to the treated samples can be attributed to the increase in the diameter of the steel balls and, consequently, the increase in surface hardness of the SMAT-treated samples. A review of the images indicates that as the diameter of the balls increases, the depth of the wear grooves decreases, and as hardness increases, the severity of the scratches also decreases. This correlation between increased hardness and wear resistance aligns with findings from research conducted by Haghighi et al. on the AZ31 magnesium alloy [36].

3.5. Investigation of surface roughness

As evidenced in Figure 7, an increase in the diameter of the steel balls used in the SMAT process resulted in an increase in surface roughness. This observation is further illustrated in Figure 8, which displays SEM images of the untreated and SMAT-treated samples. The increase in surface roughness is attributable to the random impacts of the steel balls on the sample surface, which induce depressions. As the diameter of the steel balls is increased to 5.6 mm, a corresponding increase in surface roughness is noted. These findings are consistent with those reported by other researchers [1, 36, 38].

4. Summary

In this study, the impact of Surface Mechanical

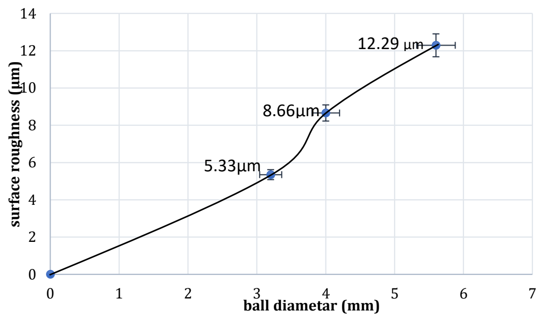

Fig. 7- Surface roughness diagram of samples after SMAT.

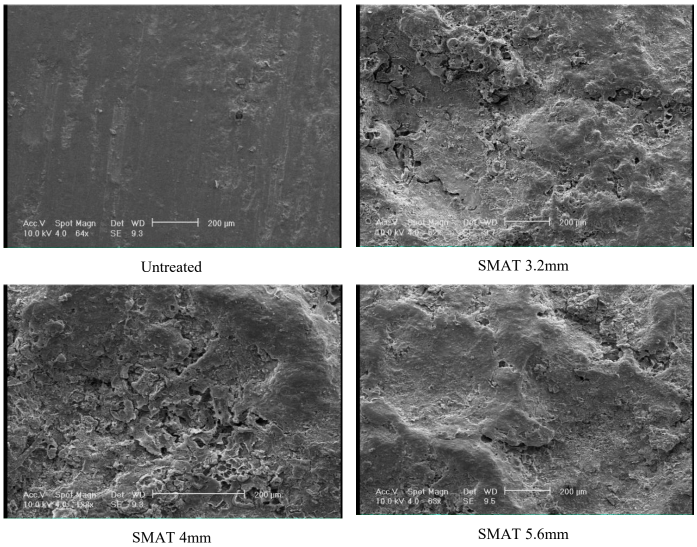

Fig. 8- Scanning electron microscope (SEM) images of surface roughness of untreated and SMAT-treated samples.

Attrition Treatment (SMAT) and variations in the tool ball diameter on the microstructure, hardness, and wear behavior of AZ31 magnesium alloy was examined. The results demonstrated that SMAT induces the formation of fine grains and nano-crystalline layers on the surface. Furthermore, as the diameter of the balls utilized in the SMAT process increased, the thickness of the mechanically affected area also expanded. Consequently, the SMAT process with ball diameters of 5.6 mm, 4 mm, and 3.2 mm enhanced the surface hardness of the samples by 198%, 184%, and 175%, respectively, relative to the untreated sample. Wear resistance also improved with the increase in ball diameter during the SMAT operation. As such, weight loss was observed to decrease from 0.26 mg in the untreated sample to zero in the sample treated with a 5.6 mm diameter ball. This improvement is attributed to the fine grains and microstrains created on the surface. Examination of the surface wear of the samples revealed a shift in the wear mechanism from the adhesive in the untreated sample to the abrasive in the treated samples. As the ball diameter increased in the SMAT process, the grooves on the surface were reduced, which can be associated with the increased surface hardness achieved by using larger-diameter steel balls in the SMAT process.

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