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Shot Peening Induced Corrosion Resistance of Magnesium Alloy WE43

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Abstract

Mechanical surface treatments like shot peening provide a pathway to stabilize degradation of magnesium alloys without compositional change. The resultant subsurface grain refinement, twin dislocations, and nanoprecipitation improves fatigue life but lowers corrosion resistance of magnesium. The lower corrosion resistance is justified by an increase in surface roughness after shot peening. However, a skewed estimate of surface area is expected to justify the inconsistent corrosion behavior of shot peening magnesium compared to other mechanical surface treatments. The objective of this research was to understand the influence of surface topography due to shot peening on the corrosion kinetics of a magnesium alloy WE43. Results showed that the corrosion resistance increased after shot peening WE43 when using an adjusted surface area that better accounts for the topographical features under exposure to corrosion attack.

Keywords: shot peening; surface topography; magnesium; corrosion

1. Corrosion Kinetics of Magnesium after Shot Peening

Magnesium electrochemically reacts in aqueous environments and forms soluble magnesium hydroxide ($Mg(OH)_2$) and hydrogen gas (H_2). This degradation characteristic alongside high specific strength presents opportunities for magnesium in time-resolved devices, such as degradable orthopedics and dissolvable oil fracking plugs. Industrial implementation of magnesium alloys is deterred by the lack of technical expertise over the control of corrosion kinetics. Alloying and surface treatments were proposed to address unstable corrosion of magnesium [1]. However, high-stakes industries like biomedical device manufacturers are slow to adopt new material compositions due to rigorous testing requirements and associated expenditure. Hence, mechanical treatments on existing magnesium alloys remain the effective way to lower corrosion kinetics of magnesium without altering material composition.

Mechanical surface treatments like shot peening influence mechanical behavior of magnesium without altering material composition. Functional surfaces of devices are bombarded in shot peening with small spherical media that strike the material and create small indentations, *i.e.*, dimples on the surface. As these dimples displace material at moderate strain rates, reasonable compressive residual stresses are introduced near the surface. As several shots are directed at the surface while peening to achieve uniformity, an even layer of compressive residual stress forms due to the overlapping of dimples. Further, shot peening magnesium also results in randomly oriented newly formed fine grains, deformation twins, and nano-precipitates [2]. As a result, shot peening has consistently demonstrated improved fatigue life that can be explained by improvements to the surface integrity [2,3,4]. However, the mechanisms that result in improved mechanical properties are inconsistent in improving corrosion resistance. In both immersion [5] and polarization [2,3,4] studies, shot peening magnesium has consistently demonstrated decreasing corrosion resistance. That is, the surface after shot peening is more prone to corrosion attack even though mechanical behavior is improved. This seems contradictory since stress corrosion behavior suggest the surface integrity should improve the corrosion resistance [6]. Other surface treatments, such as laser peening [7,8] and burnishing [5], have exhibited improved corrosion resistance using both immersion and polarization measurement methods. It is well known that surface topography is an important parameter in considering the degradation behavior of magnesium devices. Shot peening parameters, such as air pressure, impact angle, distance from sample surface, and size of shot affect surface topography, and thus, the corrosion rate. Further, high intensity peening alters the dominant corrosion mechanism from pitting to uniform corrosion and lowers corrosion kinetics [9]. Uniform corrosion refers to an even distribution of bulk material loss across exposed surfaces, and pitting corrosion refers to localized material loss at random sites on exposed surfaces.

One challenge to designing tailored corrosion responses using mechanical surface treatments is isolating how individual contributions from the surface integrity, such as surface topography, residual stress, and microstructure, affect the corrosion behavior. This research attempts to address why experimentally observed corrosion rates after shot peening magnesium exhibits a lower corrosion resistance when analogous surface treatments typically exhibit the opposite behavior. This work demonstrates that inaccurately accounting for surface topography induced by shot peening is the underlying reason corrosion kinetics appear faster. The objective was to measure how the surface topography from shot peening, namely the exposed area rather than the projected area, affects the potentiodynamic polarization behavior of rolled WE43. The results improve our understanding of how mechanical surface treatments produce topographical features that play an influential role on corrosion kinetics.

2. Experimental Procedure

2.1 Materials

As-rolled sheets of WE43 magnesium alloy (4% Y, 2.5% Nd, 0.5% Zr, 1.2% Gd) were bought from China Hunan High Broad New Material Co. Ltd. Samples with dimensions of 80 mm × 10 mm × 1 mm were cut (Fig. 1) and polished with a silicon carbide paper of 800 grit size.

Metallographic etching was used to capture the microstructural features of rolled WE43 that was later shot peened. A representative microstructure is presented in Fig. 2. A solution of 10 mL hydrofluoric acid and 90 mL water was used to etch WE43 as per ASTM E407-07 standard [10]. Etching was performed in a fume hood with a ventilation rate of 80 cfm. Polished and peened samples were immersed and gently agitated in this solution for 25 to 30 seconds. The etched surfaces were then observed under an optical microscope. The grain size ranged from 50 to 150 µm

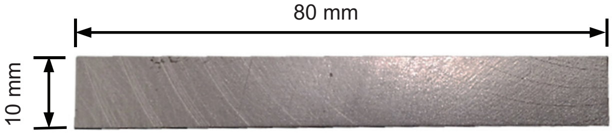

Fig. 1 WE43 sample for surface topography and corrosion measurement.

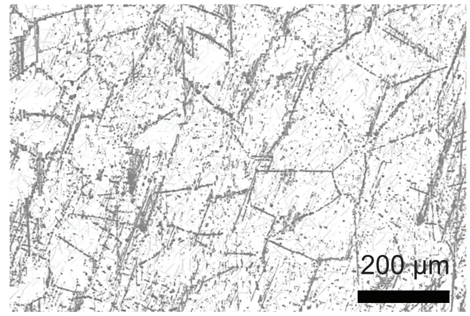

Fig. 2 Microstructure of rolled WE43.

2.2 Shot Peening

The WE43 samples were shot peened in a blast cabinet with a connected compressor air-line. The samples were supported on a wooden block with double-sided tape during peening. The peening gun was kept orthogonal 15-20 cm away from the sample surface while peening. A pressure regulator connected to the air-line was used to set static pressure for peening at 20, 40, 60, and 80 psi. Samples were peened for 20 seconds on each side. Glass beads were used instead of steel beads as shots since magnesium has low strength and hardness compared to other engineering metals. Contamination from steel beads may also affect corrosion by introducing galvanic cells on the peened surfaces. All peened samples were compared to a same sized control samples that were polished with 800 grit size silicon carbide paper.

2.3 Corrosion Rate

Corrosion behavior of magnesium alloys is related to composition, microstructure, and surface chemistry. Therefore, topography analysis is a necessary step to explain corrosion behavior of surface treated magnesium. The corrosion rate of magnesium is higher than other engineering metals as the cathodic reaction is a water reduction (producing H_2). Hence, potentiodynamic polarization (PDP) test are well suited for a comparative corrosion assessment on magnesium alloys.

In this study, PDP test were used to compare the effect of static air pressure during shot peening on the corrosion rate of WE43. A conventional three-electrode cell was used on a Gamry 1100E Potentiostat. The counter electrode was made of graphite and the reference electrode was a saturated calomel electrode (Fig. 3). A 0.5% NaCl solution at 37°C was used as the electrolyte. The PDP scans were performed on polarized shot peened samples at 1 mV/s scan rate from -3 V to 1 V potential range. The pH of the solution was checked after each test and was maintained in the range of 7.0 to 7.8. The solution was discarded if pH shifted beyond these limits. Each polarization test was repeated three times.

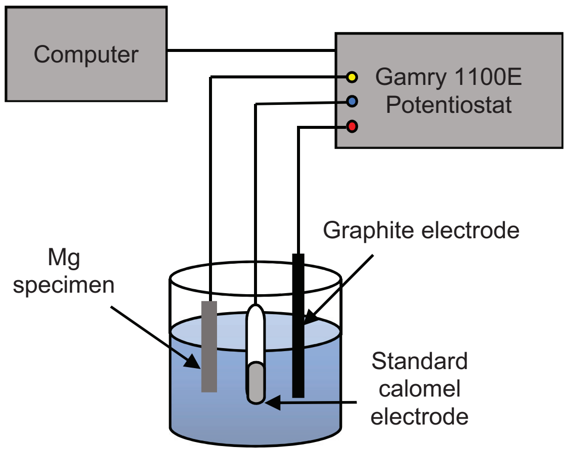

Fig. 3 Schematic of a three-electrode potentiodynamic polarization test.

The current density is the amount of electric current flowing per unit cross-sectional area of a material and is proportional to the corrosion rate. The current density was calculated based on Eqn. 1:

$$i = \frac{I\ (\text{instantaneous current values})}{A\ (\text{surface area exposed to solution})} = \frac{I}{S \times A_0} \qquad (1)$$

where i = current density (A/cm^2), I = instantaneous current density (A/cm^2), A = total surface area exposed to the solution, S = surface area ratio, and A_0 = projected area of sample.

3. Surface Topography Analysis

Three-dimensional surface topography was measured by Keyence Laser Scanning Microscope VK-X200K. The microscope performed non-contact surface profile measurements by scanning approximately 1.5 × 1.5 mm^2 of sample surfaces at 5X magnification. Qualitative analysis of peak and valley roughness from Fig. 3 indicates tall peaks and deep valleys at low peening pressures. The amplitude of peaks and valleys reduced with increasing peening pressures, indicating uniform surface treatment at higher static pressures. Topographical features analyzed by VK Analyzer software also showed increase in arithmetic mean (*Ra*), peak (*Rp*), and valley (*Rv*) roughness at higher peening pressures (Fig. 5). Higher *Ra*, *Rp*, and *Rv* substantiates evidence of uniform surface peening at elevated static pressures.

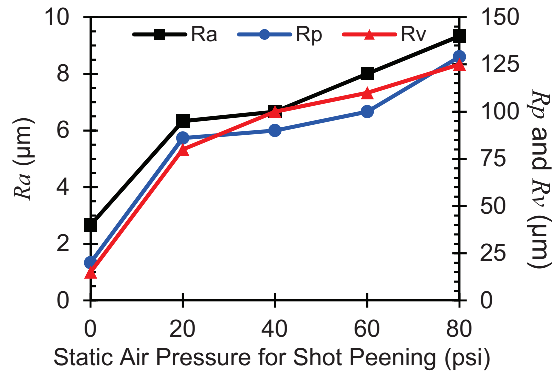

Fig. 5 Impact of static air pressure used for shot peening on surface topography metrics: *Ra*, *Rp*, and *Rv*.

Peening pressure and time govern coverage of a sample surface during shot peening. Coverage is the percentage of surface area impacted by shot peening within a designated time-period [11]. Fig. 6 shows that samples peened at 20 psi and 40 psi pressure did not attain 100% coverage. The surface area for 40 psi peened sample was higher due to deeper dimple formation (Table 1). Shot peened dimples fully covered the sample surface after the static air pressure was increased to 60 psi and 80 psi. The total surface area of all peened samples increased due to the deformation from shot peening. The total surface area exposed to corrosive media affects the current density (*i.e.*, corrosion rate) passing through the sample. Hence, change in surface area after peening was essential information for subsequent corrosion rate calculations. Using the exposed planar area rather than the exposed surface area is possibly one reason previous corrosion rates reported in literature on shot peening of magnesium were higher.

Table 1 Exposed surface area and normalized surface area ratio due to shot peening WE43

Sample	Control	20 psi	40 psi	60 psi	80 psi
Surface Area (mm^2)	5.94	10.15	11.52	20.07	26.01
Surface Area Ratio	1.00	1.71	1.94	3.38	4.38

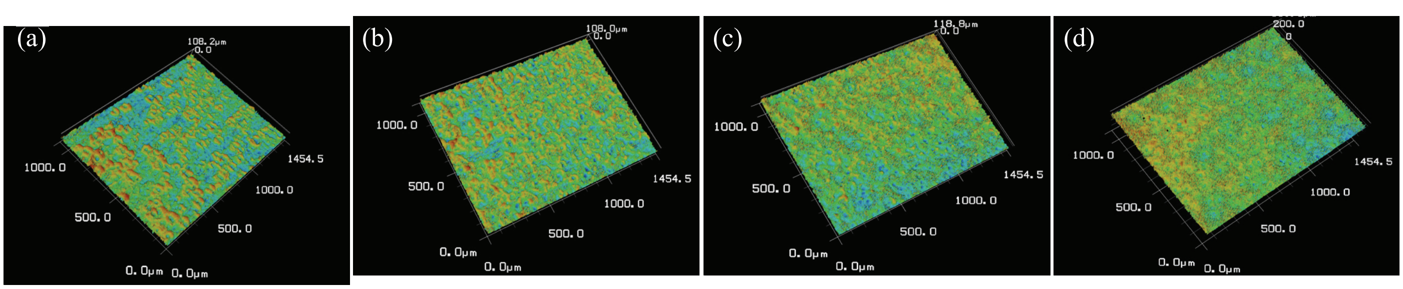

Fig. 4 3D topography profile of samples shot peened at (a) 20 psi, (b) 40 psi, (c) 60 psi, and (d) 80 psi.

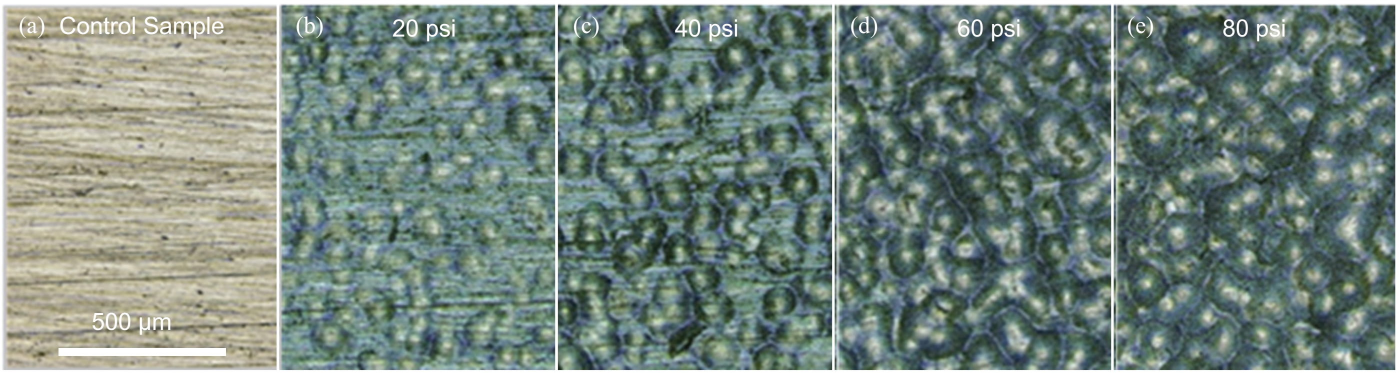

Fig. 6 Surfaces produced after shot peening WE43 with different static air pressures: (a) untreated control, (b) 20 psi; (c) 40 psi, (d) 60 psi, and (e) 80 psi. All images are at the same magnification.

4. Corrosion Resistance After Shot Peening

Surface area ratio of samples required to calculate current density was attained from the surface topology analysis (Table 1). Higher shot peening pressures led to increased sample surface area. Hence, the surface area exposed to corrosive media varied after peening with different intensities. Shot peening WE43 at 80 psi increased surface area of sample by 4.38 times compared to the control samples.

Shot peening increased sample surface area due to which the surface area ratio from Table 1 was incorporated into current density calculations. The potentiodynamic polarization results (also known as a Tafel plot, V *vs.* log i) in Fig. 7 showed a decrease in current density with increasing static air peening pressures due to inverse proportionality with surface area ratio. Tafel extrapolation in Fig. 8 further quantified corrosion potential (E_{corr}) and current density (i_{corr}) for different peening pressures. The corrosion current progressively reduced while corrosion potential increased with peening intensity. Magnesium samples were rendered noble and unwilling to corrode at higher peening pressures.

All intensities of shot peening improved corrosion resistance of magnesium contrary to previous publications [2,3,4,5]. One possible explanation is the different method to account for surface area in Faraday's law. Therefore, accounting for a change in surface area of magnesium from shot peening is critical for accurate estimation of corrosion kinetics.

Also, it is important to address why shot peening consistently shows higher corrosion rates while analogous surface treatments, such as laser peening and burnishing exhibit slower corrosion rates. One likely explanation is that the change in surface roughness in laser peening and burnishing is smaller than for shot peening. The effect on calculated corrosion rates may not be significant for laser peening and burnishing because of the comparatively smoother surface than that from shot peening. The stochastic nature of shot peening implies the surface is not uniformly peened and there will exist substantially higher peak-to-valley distances that increase exposure area.

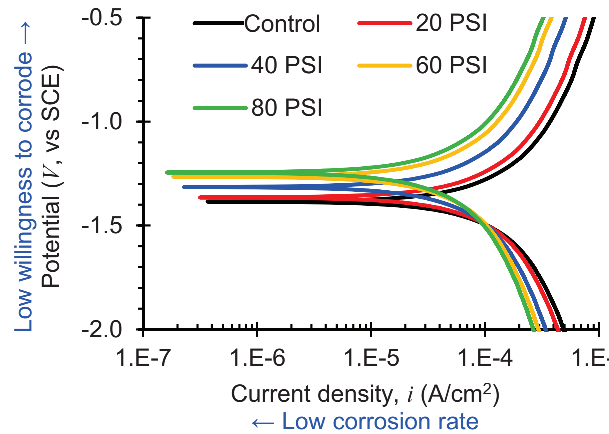

Fig. 7 Potentiodynamic polarization of shot peened WE43 with different static air peening pressures. Determined using actual area rather than projected area.

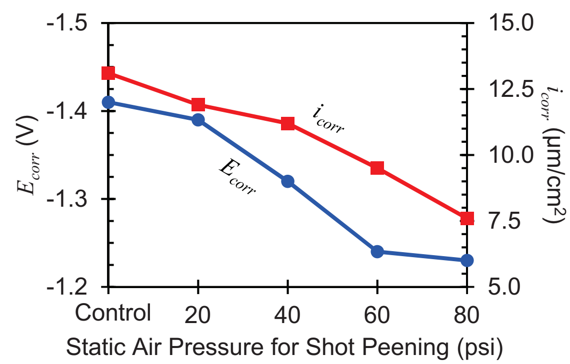

Fig. 8 Improved corrosion resistance from shot peening WE43 by incorporating the surface area ratio.

5. Summary and Conclusions

Magnesium WE43 samples were shot peened with different static air pressures. Shot peening modeified the surface topography. Higher static air pressure resulted in increased surface roughness. While higher surface roughness typically increases corrosion kinetics, increased peening pressures led to higher corrosion resistance. Tafel extrapolation from poteniodynamic tests showed high corrosion potential and low current density for peened samples. Literature typically reports increased corrosion rates after shot peening. We explain the apparent paradox that shot peening decreases corrosion resistance by taking into account the true exposed surface area of the rough peened surface. The planar or projected surface area is inaccurate for calculating the corrosion rate. Instead, the surface area ratio must be accounted for so that the true exposed area is used to determine the corrosion rate. Future work will investigate the influence of surface integrity, such as residual stress, grain refinement, and microhardness, on stress-corrosion behavior on WE43 magnesium alloys.

6. Acknowledgements

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