PLASTICALLY DEFORMED DEPTH IN SHOT PEENED MAGNESIUM ALLOYS

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ABSTRACT

The objective of this task was to measure and evaluate shot peened damage depth in three magnesium alloys, AZ91, EZ33, and ZE41. Four evaluation techniques were employed: acoustic (internal friction), electrical conductivity (eddy current), optical metallography, and x-ray diffraction.

The internal friction techniques employed included ultrasonic longitudinal wave pulse-echo attenuation, ultrasonic velocity, and surface wave attenuation measurements. Of these, surface wave attenuation at 15 MHz proved to correlate best with cold work damage, especially for alloy AZ91A. Damage was estimated to be of order 0.1-1.0 mm. All ultrasonic techniques proved ineffective in separating the damage produced for the three peening conditions: 005A, 010A, and 015A (Almen units).

Electrical conductivity measurements, performed with a commercial eddy current instrument, provided quantitative measure of surface roughness and defined peening damage for the three peening conditions. However, the measurements are indirect and require calibration against a primary signal-damage correlation to give a usable measure of cold work depth.

The optical metallographic measurements gave a direct measure of cold work for alloys EZ33 and ZE41. The etches employed were ineffective for AZ91.

X-ray diffraction measurements gave a direct measure of damage depth for all three alloys. This method involved successive removal of metal layers by chemical etching until well-defined x-ray patterns were obtained.

KEYWORDS

Magnesium alloys; non-destructive evaluation; shot-peen damage depth; internal friction, eddy current measurements; optical metallography; x-ray diffraction.

INTRODUCTION

Magnesium alloys, because of their high stiffness-to-weight ratio, are very attractive for military items and equipment. However, magnesium alloys have limitedly military applications, since they represent as a class, the most corrosive structural metals. Nonetheless, if properly protected against marine, high humidity environmental conditions and if the threat of galvanic effects can be eliminated by proper practices and techniques to isolate the magnesium at junctures with dissimilar metals, then magnesium alloys can be used with reasonable assurance of good service. Even where electrical continuity through the magnesium member is required, proper enveloping of the magnesium part by means of electroplating is feasible.

The degree of fatigue endurance of magnesium alloys utilized for structural applications can be enhanced significantly by compressive stresses imposed by peening the metal surfaces, and is related to the depth, intensity, and distribution of the compressive stresses. Further, the types of shot or peening medium used and the extent of metal degradation attributable to the velocity, impact force, and frequency of the shot will influence required surface processing or the earlier stages of corrosion of the metal.

All these factors are especially apropos to magnesium alloys because of their comparatively high energy absorbability (damping capacity) and their greater reactivity with most environments. Consequently, the control of parameters affecting the peening of magnesium alloys must be assured. Unfortunately, ready information in this area is not accessible either from publications or personal sources. Other than the published reference available (Found, 1951) and the preliminary x-ray information developed in certain recent work (Gallaccio and others, 1977) there is an evident paucity of information on this subject.

Because the peening of magnesium alloy castings is viewed as an important precursor toward achieving optimum fatigue endurance and since its effects might influence the performance of protective systems, meaningful characterization and measurement of the peening depth and intensity in such alloys is of importance, and was the basis of this study. Non-destructive methods which merit evaluation for detecting and measuring changes in microstructures of magnesium alloys wrought by mechanical working, e.g., from peening, were evaluated. These methods included acoustic (internal friction) and electrical conductivity measurements. Direct methods evaluated for destructively determining the damage depth were optical metallography and x-ray diffraction measurements.

EXPERIMENTAL

Materials

Three cast magnesium alloys are included in this study. The composition of each follows:

Alloy	Al	Zn	Mn	Zr	Ce	Mg
AZ91-T6*	8.7	0.8	0.13	--	--	Bal.
EZ33A-T5**	--	2.6	--	0.7	3.1	Bal.
ZE41A-T5**	--	3.7	--	0.9	1.3	Bal.

* Solution heat treated and thermally aged.
**Thermally aged.

Cast panels, as procured, measured 9.8 x 102 x 152 mm (0.385 x 4 x 6 in).

Shot Peening Parameters

Shot peening was accomplished with low alloy, aircraft quality C-1018 steel shot, 3.2 mm (0.125 in) dia. of an average hardness of R_c 64. The intensities of shot peening utilized were Almen intensities of 5A, 10A, and 15A (measured by standard steel strips).

Ultrasonic Surface Wave Studies

Surface waves or Rayleigh waves travel along surfaces of flat or irregular topography in such a manner that about 90% of their acoustic energy is contained within one wavelength of the surface (Kolsky, 1963). Their velocity and attenuation are strong functions of a material's micro- or sub-microstructure; thus they make an ideal tool for monitoring the metallurgical structure of an alloy near its surface.

In these experiments, surface waves pulses of 15 MHz frequency and about 5 μ sec duration were propagated along flat surfaces of plates of the three alloys in the unpeened, 005A, 010A and 015A peened conditions. The waves were propagated from an Automation Industries[1] SFZ transducer (which acted as the transmitter) to an identical receiver transducer one cm away. The transducers were coupled to the sample surfaces with glycerin, and a MATEC[2] ultrasonic system was used to transmit and receive the ultrasonic signal (Fig. 1).

The initial pulse energy was kept constant for all 12 plates, so the received pulse height gave an indication of the attenuation of the wave as it traversed the distance between the two transducers. The surface wave velocity (v_s) in Mg alloys (Kolsky, 1963) is about 3 x 10^6 mm/sec, so at a frequency f of 15 MHz, the Rayleigh wave-length $\lambda = v_s/f$ is of order 10^{-1} mm. This technique is capable of sampling structural changes caused by peening within this thickness of surface layer.

Eddy Current Testing

In eddy current testing, an a.c. signal of high frequency (usually between 1 kHz and 10 MHz) is transmitted to a probe on the sample surface. This signal induces an eddy current near the surface with a depth of penetration inversely proportional to the frequency (McGonnagle, 1961). The sample's electrical resistivity (and for a ferromagnetic material, the magnetic permeability) are strong functions of its micro- and sub-microstructure; thus the amplitude and phase of the induced signal relative to the initial one are very structure-sensitive. The induced signal can be detected by the exciting transducer and used to provide a measure of such parameters as surface micro-roughness, cold work, grain, and precipitate size and alloy composition.

In these tests, an Automation Industries Multitest EM 3300 eddy current test system was used with various probes, ranging from 5 kHz to 2.5 MHz exciting signal, employed. The oscilloscope of the system produced a direct amplitude-phase trace (impedance diagram) of the induced signal. Optimum results were obtained with the 5-50 kHz transducer operated at 10 MHz. At this frequency the eddy currents penetrated one mm beneath the sample surface to give a direct indication of surface structure.

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[1] Automation Industries, Danbury, CT 06810, USA
[2] MATEC Corp., Warwick, RI 02886, USA

Metallography

Optical metallography is an excellent tool, although a destructive one, for the determination of peening depth, because various etchants may be used to reveal near-surface cold work in the cross sections of an alloy. Mg alloys undergo plastic deformation by twinning, so metallographic determination of twin density could be used as an index of damage depth.

The 12 specimens were cut for metallographic observation in the direction perpendicular to the peened surface. They were then cold mounted (Buehler Plastic Powder, Fulton Quickmount, and Castro-Mold), so that the visible face was the one marked by an "X" in Fig. 2e. Since Mg alloys are very soft and easily deformable, the high pressures and temperatures of hot mounting would probably have altered the true microstructure.

After the mounting came a difficult grinding and polishing procedure. Each specimen was ground on belts of 80 and 180 mesh (with water as a coolant) and then on wheels of 240, 320, and finally, 600 grit (with using no coolant at all). A small to moderate amount of pressure was used. Magnesium's extremely high corrosiveness was the reason for not using any coolant during fine grinding. Next, the specimens were rough-polished with 6-micron diamond past on a LECO[3] 800-678 Nylon Cloth. For fine polishing, no suitable abrasive could be found: i.e., dry alumina (0.05 micron), alumina-distilled water slurry (0.05 micron), 1 micron and 1/4 micron diamond paste all had harmful effects on the specimens[4]. So, the alloys were rough polished on the 6 micron diamond paste for an extended time (3-5 minutes) and the fine polishing stage was eliminated.

After the rough polish, the specimens were etched in Acetic-Picral acid of the following composition:

5 ml	acetic acid
6 g	picric acid
10 ml	distilled water
100 ml	ethanol (95%)

The metallographic mounts were submerged specimen face-up in the etchant, and the bath was gently swirled until the specimen face exhibited a brown stain. They were then removed, rinsed with a stream of alcohol and dried in a blast of hot air.

The etched samples were then ready for metallographic observation.

X-Ray Diffraction

A copper emitter, without filter, was used at 40 Kv, 20 ma at 30 mm to determine the depth to which the metal structure was affected by peening. Following each peel or surface removal, conducted over a 45 minute period, approximately 0.5 mm (0.002 in) of metal was removed, using 10% nitric acid, until a clear diffraction pattern was obtained.

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[3] LECO Corp., St. Joseph, MI 49085, USA

[4] Effects of these abrasives ran from severe pitting (by alumina) to excessive scratching (1/4 micron diamond).

RESULTS AND DISCUSSION

Ultrasonic Surface Wave Studies

In the surface ultrasonic technique it was postulated that the weaker the received ultrasonic signal (i.e. the higher the Rayleigh Wave attenuation), the greater the depth of damage. This is because the high dislocation density and deformation twins caused by pinning would absorb and scatter the energy of the acoustic wave (Truell and others, 1969).

Table 1 shows received signal strength (relative units) as a function of peening condition for all three alloys. As expected, signal strength decreased (attenuation increased) as peening intensity increased. The decrease showed a clear quantitative relation to peening intensity only for alloy AZ91, but the qualitative correlation indicates that the surface ultrasonic technique has potential as an indicator of surface peening damage.

TABLE 1 Received Rayleigh Wave Signal Strength at 15 MHz

Peening Condition	Alloy ZA91	Alloy EZ33	Alloy ZE41
Unpeened	6.2	6.4	6.2
5A	3.5	5.1	5.1
10A	3.3	5.9	5.1
15A	1.2	5.2	5.4

Eddy Current Studies

The optimum eddy current signal was obtained at 10 MHz, and Fig. 2 shows oscilloscope amplitude-phase traces for the three alloys in the four processing conditions.

Several conclusions emerge:

1. As peening intensity increased, surface roughness increased. This caused the origin to the traces to be displaced to the left (relative to the unpeened trace) on the x-axis; this x-axis location of the signal gives a direct measure of surface topography.

2. The greater the peening intensity, the higher the displacement of the trace on the y-axis; thus y-axis location is a direct measure of peening damage.

These trends are clear for all 12 samples. A measurable inversion of the 005A and unpeened sample y displacement occurred for alloy EZ33. The reason for this is unclear; however, this minor aberration does not detract from the applicability of this tool for non-destructive determination of peening depth in these alloys.

Optical Metallography

The specimens were examined under a metallograph. Cold working in the form of twins was readily visible in the peened specimens, and the surface was relatively free of scratches from the polishing. The depth of the cold working was then measured with a calibrated eyepiece of the metallograph (where 1 unit on the eyepiece was equivalent to 5.08×10^{-3} mm or 2×10^{-4} inch at 200X), and the results were recorded. (Note: The dark green staining of the AZ91A alloy prevented any detail of cold working to be seen, and so no measurements could be taken.) Photomicrographs were taken of the microstructures so as to show how the depth of the cold working decreased as the severity of the peening decreased. Data taken from the micrographs are summarized in Table 2.

TABLE 2 Optical Metallography Results

Alloy	Severity of Peening	Depth of Cold Work (mm)
ZE41A	15A	0.762
	10A	0.610
	05A	0.508
	unpeened	-----
EZ33A	15A	0.762
	10A	0.508
	05A	0.305
	unpeened	-----

The depth measurements show that the extent of microstructural deformation varies with the severity of shot peening. In fact, there is an approximate linear relationship between the depth of cold working and the intensity of the shot peening for the EZ33A alloy (Fig. 3). These data clearly show that destructive tests provide the most quantitative and reliable measure of plastic deformation depth caused by peening.

X-ray Diffraction

Results from the x-ray peelings have established the depth of penetration of peening stress into the magnesium alloys. As was found earlier (Gallaccio and others, 1977) the copper emitter, operating at 40 KV, 20 ma, at 3 cm, for a period of 45 minutes for each determination, will result in a clear diffraction pattern beyond the region of peening-stressed microstructure. Data acquired from the x-ray examinations for the three alloys, peened with low alloy steel shot, 3.2 mm (0.125 in) dia. follow:

TABLE 3 X-Ray Diffraction Results

Alloy	Almen Peening Intensity	Depth of Peen-Affected Metal Structure
AZ91	5A	0.41 - 0.50 mm (0.0160 - 0.0196 in)
	10A	0.47 - 0.51 mm (0.0187 - 0.0200 in)
	15A	0.58 - 0.62 mm (0.0228 - 0.0246 in)
EZ33	5A	0.53 - 0.66 mm (0.0208 - 0.0260 in)
	10A	0.80 - 0.86 mm (0.0315 - 0.0340 in)
	15A	0.89 - 1.00 mm (0.0350 - 0.0395 in)
ZE41	5A	0.41 - 0.49 mm (0.0162 - 0.0194 in)
	10A	0.59 - 0.71 mm (0.0242 - 0.0279 in)
	15A	0.77 - 1.00 mm (0.0305 - 0.0395 in)

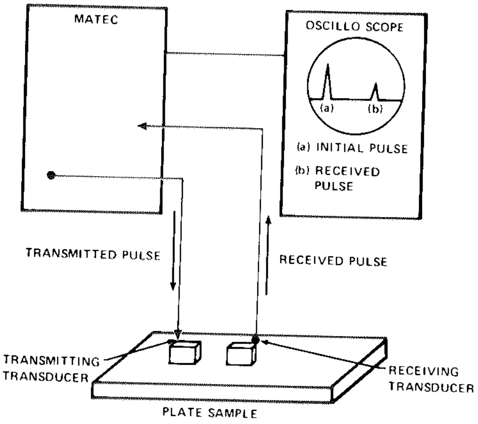

Fig. 1. System for ultrasonic measurements.

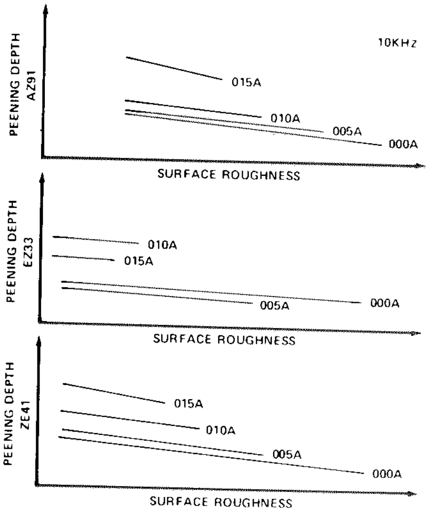

Fig. 2. Traces of 10MHz Eddy-current oscilloscope signals.

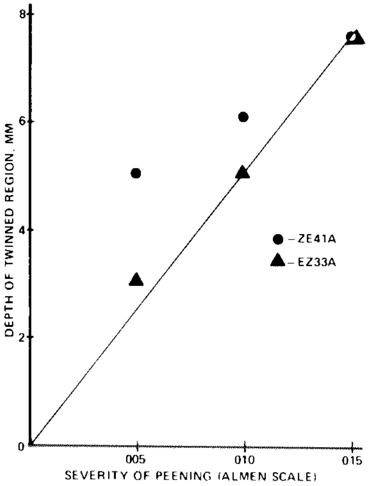

Fig. 3. Relationship of depth of twinned region to severity of peening.

CONCLUSIONS

1. Acoustic surface wave attenuation measurements at 15 MHz give an indirect, qualitative measure of peening damage in alloy AZ91.

2. Electrical conductivity (eddy current) measurements at 10 kHz give an indirect, but qualitative gage of peening damage and surface topology in all three alloys. This technique has high potential for evaluation of damage depth.

3. Optical metallography provides a direct and quantitative indication of peening damage depth in alloy EZ33 and ZE41.

4. X-ray diffraction also provides a direct indication of peening damage depth although the method involves a lengthy incremental surface layer removal procedure.

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