FATIGUE BEHAVIOR OF LASER SURFACE HARDENING FOR AZ31B MAGNESIUM ALLOY

EMAN ALI ASHUR* & SAHIB MOHAMMED MAHDI

Research Scholar, Department Materials Engineering, Mustansiriyah University, Iraq

ABSTRACT

The study has been implemented with the use of 4 groups; each group has fifteen samples, of laser surface hardening treated AZ31B Magnesium alloy. The first group has been as received specimens, the second group has been laser surface hardening with variable parameter of peak power (watt) specimens, third group was laser surface hardening with variable parameter of frequency (KHz) specimens and fourth group was laser surface hardening with variable parameter of pulse duration (ms) specimens. Fatigue tests are carried out at deflection value of (2, 2.5, 3, 3.5, and 4), and all these deflections transform into stresses. The stresses are (20.4, 25.5, 30.6, 35.7 and 40.8 Mpa). Equations as well as fatigue curves were recorded and determined with regard to laser surface hardening of AZ31B Magnesium alloy treatment; also, the specimens have been subjected to hardness as well as surface roughness test. The results show that the laser surface hardening treated alloy groups in the case, when put to comparison with as received group fatigue. The as received specimens have a ductile fracture with high number of cycling, while the laser treated specimens have a brittle to brittle-ductile fracture and with a lower number of cycling. These are due to surface roughness and alloy brittleness. KEY WORDS: AZ31B Magnesium Alloy; Pulse Duration; Roughness; Laser Surface Hardening; Peak Power; Hardness; Fiber Laser; Frequency & Fatigue Test

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1. INTRODUCTION

Interest in lightweight materials has recently been created to reduce the greenhouse emissions as well as enhancing the fuel economy, with regard to transport industries. Such elevated interests in the lightweight materials shifted the researches on wrought as well as the cast magnesium (Mg) products due to their high resistance to fatigue, in addition to the high strength-to-weight ratio [1]. Magnesium's attractive mechanical properties and alloys improve its use in many technological applications in automotive, aerospace parts, household appliances, etc. Magnesium alloys' characteristic properties offer a lot of benefits like effective recycling properties, low density, high damping capacity, high specific strength (σ / ρ), and so on. [2]. Due to their energy as well as weight-saving properties, the magnesium alloys have been specified as excellent candidates for certain products including telephones, PC's, as well as automotive parts. Recently, and with regard to these applications, the necessity for magnesium alloys has been rapidly increasing. Yet, because of their poor resistance to wear in addition to the poor resistance to corrosion, their applications were majorly limited. The fatigue characteristics related to the magnesium alloys have been of high importance when utilized as structural components; also, the Mg alloys typically have high mechanical strength and fatigue resistance in comparison to the cast Mg alloys because of the limited inclusion sizes as well as the hardening precipitation following extreme processing deformations [3]. When magnesium extends in to more essential applications in the powertrains, chassis as well as the body areas, wrought magnesium products like AZ31B need to be produced with enhanced mechanical properties such as fatigue resistance. AZ31B finds use in a

wide range of applications including medical implants, aircraft fuselages, mobile phones, laptop cases, speaker cones and concrete equipment. AZ31B can be super shaped at high temperatures to create a wide range of intricate components for automotive applications [4].

Shahad J. Mohammed and Sahib M. Mahdi: Studied the fatigue behavior of AZ31B magnesium alloy heat treated. This research shows the comparison between as received group of AZ31B Mg alloy and heat treated AZ31B Mg alloy by (Recrystallization, Annealing and Solution treatment) and performed the fatigue crack characteristic and analysis the fracture mechanism of the specimens [5].

Sotomi Ishihara et al: The effects of AZ31B magnesium alloy lamellar structure on fatigue characteristics have been analyzed by using extruded AZ31B magnesium alloy and comparing the curves (S – N). And, determined crack initiation propagation, small crack formation and the surface form of fracture. By using 2 types related to specimens, with the axial directions parallel (assigned as EP specimen) as well as vertical (assigned as EV specimen) to lamellar structure [6].

K. Tokaji et al: Axial fatigue experiments were conducted using smooth AZ31B magnesium alloy CT specimens and commercial specimens in the laboratory air at ambient temperature. The characteristics related to the fatigue strength as well as fatigue crack propagation (FCP) have been assessed; also the fracture mechanisms were examined based on crack initiation and surface fracture analysis. The study shows that FCP resistance has been considerably low in comparison to that of pure titanium and aluminum alloys [7].

2. EXPERIMENTAL WORK

2.1 Materials

Flat rectangle section specimens with dimensions as shown in figure 1, are made from AZ31B Mg alloy, the chemical composition can be found in the table 1.

Figure 1: Dimension and Shape Related to Fatigue Test Sample.

Table 1: The AZ31B Mg Alloy Specimen's Chemical Composition

Element	Al	Zn	Mn	Si	Fe	Cu	Mg
Wt%	2.9	0.9	0.36	0.013	0.0024	0.0089	Balance

2.2 Laser Surface Engineering (LSE)

This is a technology that is of high importance now in science, since there is a requirement in various companies for improving the surface performance related to material under corrosion (and/or wear environments that might not be achieved via traditional surface coatings as well as modifications. The laser surface Technology is used to enhance the material's surface properties. Laser surface hardening by re-melting a thin layer of surface is one of the (LSE) processes

resulting in higher hardness values and good machine parts wear resistance [8]. Furthermore, the surface hardening result in structural transformations related to the material via laser treatment. This might be achieved via irradiating the surface with laser pulse for quickly increasing the temperature of specimen to transformation phase. Also, the base metal simply cools the heated area through self-quenching following turning off the laser beam, thus the specimen's surface will be hardened, also the microstructure modified. Wear and resistance to corrosion have been increasing due to the compact as well as the homogeneous composition [9].

2.3 Fiber Laser

This is considered as a type related to solid-state laser, which applies optical fibers as gain medium, like rare earth elements. The fiber lasers have been possibly the most innovative revolutionary laser technology emerging in the last 10 years, spanning CW lasers of kilowatt class as well as pulsed lasers from nano-seconds to ultrafast, also wave-lengths from $1\mu\text{m}$ to $2\mu\text{m}$ [10]. Starting from the most initial demonstration related to glass fiber laser in the 1964, the fiber lasers were advancing in ultra-short width, output power, line width, pulse energy, as well as spectral coverage. Their applications extend to various fields including security, researches, industries, medicine, as well as defense [11].

The major advantage of fiber laser, however, is its energy efficiency. The important **advantages** of fiber lasers compared to gas lasers or solid state lasers are:

- Excellent beam efficiency (Optical fiber light-concentrating projector).
- Fast, lightweight, electrical and optical (small footprint and low fiber amplification power consumption);
- Compatibly efficient and effective (realized as pumping light by high amplitude, high power semiconductor lasers).
- Maintenance free (without lenses, mirrors, all optical fiber setups).
- Lower operating cost [12].

Laser surface treatment is performed in this research using: fiber laser beam type Q-switched optimum points at constant wavelength of 1064 nm with variable parameters are recorded in table 2:

Table 2: Best Parameters Found by the Experimental Tests

Pulse duration(ms)	0.1
Full peak power(Watt)	30
Work Frequency(KHz)	20
Present energy(mJ)	1mJ/20KHz
Scanning speed (mm/sec)	1000

2.4 Roughness Test

Surface roughness is the measure of deviations from its ideal form in the direction of the normal vector of a real surface. If the deviations are small, they are smooth, and the surface is rough. When trying to find out whether a surface is appropriate for a given purpose, it is an essential parameter. Hard surfaces also wear out faster than softer surfaces. Rougher materials are usually more vulnerable to corrosion and cracks, but adhesion can also be assisted. A roughness test shows both the measured depth of roughness and the mean value of roughness (R_a) in micrometers or microns (μm) [13].

The results related to roughness test were recorded and discussed for evaluating its impact in the table 3:

Table 3: Surface Roughness Test Results

Specimens State	Ra (μm)	Ra av. (μm)
As received specimen	1.55, 1.69, 1.31	1.51
Pulse duration specimen	3.44, 2.81, 4.51	3.58
Peak power specimen	5.11, 4.65, 4.79	4.91
Frequency specimen	5.59, 5.01, 5.82	5.47

2.5 Micro Hardness Test

In metallurgical, hardness has been specified as the capability for resisting material's plastic deformation. Often, it is referred to as indentation hardness that has been the resistance to material's indentation. Also, it is indicated as temper or stiffness, or resistance to bending, cutting, abrasion, or scratching. It might be defined as the material's property giving the capability for permanently resisting being deformed in the case when applying a load. With the increase in the hardness of the material, the resistance to deformation will be also increased [14].

The hardness that is related to magnesium alloys AZ31B has been estimated for examining the impact of fiber laser beam on the value acquired. The micro-hardness test has been performed using Micro Vickers device with holding time of (10) seconds and weights of (1.5) Newton. The average Value of (3) readings along the surface of as received specimen, and fiber laser specimens was taken to get the hardness value.

The results are showing improvements in the hardness value with the laser surface hardening sample because of the grains refinement.

The results for micro-hardness test were recorded for evaluating its effect in table 4:

Table 4: Vickers Micro-Hardness Test Results

Specimens State	HV kg/cm^2	HV av. kg/cm^2
As received specimen	111.4, 86.61, 90.5	96.17
Pulse duration specimen	134.1, 201.6, 188.7	174.8
Peak power specimen	235.9, 310.8, 229.7	258.2
Frequency specimen	341.9, 244.8, 289.4	292.03

2.6 Fatigue Test

Fatigue has been localized, gradual, irreversible structural change which happens in the materials subjected to fluctuating stresses as well as strains which, following adequate number of fluctuations might be causing fractures or cracks [15]. Fatigue test was implemented via (HSM20 Bending Fatigue machine), as can be seen in the figure 2. This machine induces an alternating bending stress to the free end of a cantilevered test specimen at rotational speed (24) revolutions per second in order the fatigue fail the part.

Figure 2: Fatigue Testing Machine.

The magnitude related to load (p) through Newton and stress value (σ) Mpa of the specimens is measured and acquired from utilizing the equation:

$$\text{Max. Bending stress } \sigma = 6 P L / b t^2 \sigma = 1.5 \delta E t / L^2$$

$$\text{Free end deflection } \delta = P L^3 / 3 E \delta = 4 P L^3 / E b t^3$$

$$\text{And Load } P = \delta E b t^3 / 4 L^3$$

Where the strip cantilever are:

b is the wide = 10 mm,

t is the thickness = 2 mm and

L is the length = 100 mm of the fatigue test specimen (mm).

E is the modules of elasticity for AZ31B alloy = 34 Gpa

δ is the deflection value = (2, 2.5, 3, 3.5 and 4)

3. RESULTS AND DISCUSSIONS

The data have been recorded for each test and after that discussed for determining its effect. The fatigue studies have been carried out for four groups; fifteen specimens of each group. Fatigue tests are carried out at deflection value of (2, 2.5, 3, 3.5, and 4) and these deflections are converted to stresses. The stress values are (20.4, 25.5, 30.6, 35.7 and 40.8 Mpa) and the forces values P were calculated (1.36, 1.7, 2.04, 2.38 and 2.72 N), respectively.

At each of these deflection stages, three tests are performed, and average number related to cycles before failure occurs has been reported via auto display unit that has been directly coupled to D.C motor drive shaft. Also, the fatigue testing has been implemented at room temperature, while the load's deflection remains constant till specimen fails. Fatigue test will immediately stop when specimen fails.

3.1 -As Received Group

The results related to such test have been indicated in the table 5, and figure 3 shows fatigue test diagram S-N curves. The fatigue curve behavior is obey with equation for this group ($Y = 41280 X^{-4.71}$)

Table 5: The Fatigue Tests of AZ31B Alloy with as Received Condition

Specimens No.	Deflection Value (δ)	Applied Load (N)	Applied Stress σ (Mpa)	Failure Cycles (Nf)	Average Cycles (Nav.)	Log No. of Cycle to Failure (Nf)
1,2,3	2	1.36	20.4	87736,101560,70871	86722	4.938
4,5,6	2.5	1.7	25.5	68229,77613,50161	65334	4.815
7,8,9	3	2.04	30.6	46029,58773,44310	49704	4.696
10,11,12	3.5	2.38	35.7	27142,25339,36464	29648	4.472
13,14,15	4	2.72	40.8	19575,23220,16513	19769	4.295

Figure 3: As Received Fatigue Test Diagram.

3.2 -Peak Power (watt) Group

The results related to such test have been indicated in the table 6, also S-N curves related to fatigue test diagram in figure 4. The fatigue curve behavior is obey with equation for this group ($Y = 34498 X^{-4.77}$)

Table 6: The Fatigue Tests of AZ31B Alloy with Peak Power Condition for Fiber Laser Treatment

Specimens No.	Deflection Value (δ)	Applied Load (N)	Applied Stress σ (Mpa)	Failure Cycles (Nf)	Average Cycles (Nav.)	Log No. of Cycle to Failure (Nf)
1,2,3	2	1.36	20.4	33679,52614,41238	42510	4.628
4,5,6	2.5	1.7	25.5	33602,32175,40015	35264	4.547
7,8,9	3	2.04	30.6	30445,31642,26010	29365	4.467
10,11,12	3.5	2.38	35.7	18063,20118,16712	18297	4.262
13,14,15	4	2.72	40.8	9056,15756,8994	11268	4.051

Figure 4: Peak Power Group Fatigue Test Diagram.

3.3 -Frequency (KHz) Group

The results related to such test have been indicated in the table 7, also S-N curves of the fatigue test diagram in figure (5). The fatigue curve behavior is obey with equation for this group ($Y = 75240 X^{-6.84}$)

Table 7: The Fatigue Tests of AZ31B alloy with Frequency Condition for Fiber Laser Treatment

Specimens No.	Deflection Value (δ)	Applied Load (N)	Applied Stress σ (Mpa)	Failure Cycles (Nf)	Average Cycles (Nav.)	Log No. of Cycle to Failure (Nf)
1,2,3	2	1.36	20.4	39661,34163,48814	40879	4.611
4,5,6	2.5	1.7	25.5	40315,27317,32631	33421	4.524
7,8,9	3	2.04	30.6	20531,27315,30475	26101	4.416
10,11,12	3.5	2.38	35.7	19148,22341,17760	19749	4.295
13,14,15	4	2.72	40.8	13561,12751,19013	15108	4.179

Figure 5: Frequency Group Fatigue Test Diagram.

3.4 -Pulse Duration (ms) Group

The results related to such test have been indicated in the table (8), also S-N curves of the fatigue test diagram in figure 6. The fatigue curve behavior is obey with equation for this group ($Y = 1 E + 07 X^{-8.74}$)

Table 8: The Fatigue Tests of AZ31B Alloy with Frequency Condition for Fiber Laser Treatment

Specimens No.	Deflection Value (δ)	Applied Load (N)	Applied Stress σ (Mpa)	Failure Cycles (Nf)	Average Cycles (Nav.)	Log No. of Cycle to Failure (Nf)
1,2,3	2	1.36	20.4	24620,21552,39127	28433	4.453
4,5,6	2.5	1.7	25.5	19820,25643,18616	21359	4.329
7,8,9	3	2.04	30.6	23640,29671,19843	24384	4.387
10,11,12	3.5	2.38	35.7	18915,19543,16621	18359	4.263
13,14,15	4	2.72	40.8	12249,10559,16732	13180	4.119

Figure 6: Pulse Duration Group Fatigue Test Diagram.

Figure 7 showing as received group fatigue results compared to frequency, peak power, as well as pulse duration groups treatment results, failure occurs in a high number of cycling due to the fact that alloy has been made of hotrolling that's mean that the hardness is very low in this group. While in frequency group and pulse duration group failure happens at number of cycling low in comparison to the as received group, because of the increase in the hardness value which makes the magnesium alloy more brittle. These groups are going to be fractured at low number of cycles due to the fine grains in the (HCP) structure related to the magnesium alloy. Lastly, in peak power group, the failure occurs in cycling numbers below the three groups due to the higher hardness value and fine grains rendering the Mg alloy more brittle. Figure 7: Now plots the outcomes of the four separate S-N curves.

Figure 7: Comparison between Four Cases of Fatigue Testing.

According to table 9, it surmises the fatigue cycling failure at minimum and maximum loading. For low loading, the fracture duration is as shown in the figure8; the highest was in the as received specimens, while the lowest was for pulse duration of fiber laser variable. The peak power and frequency variables of fiber laser were in between. These are true for high loading tests, except the lowest fracture duration was recorded for peak power variable instead of pulse duration.

Table 9: Shows the Results of Average Failure Cycle According to the Max. and min. Stress Value

Specimen Type	Max. Stress Value (Mpa)	Average Failure Cycle	Min. Stress Value (Mpa)	Average Failure Cycle
As received	40.8	19769	20.4	86722
Peak power	40.8	11268	20.4	42510
Frequency	40.8	15108	20.4	40879
Pulse duration	40.8	13180	20.4	28433

Figure 8: Relation between Fractures Stresses and Average Cycle Value.

These can be explained according to the fracture section observed. With regard to as received group **fracture type** has been dark and rough, it is ductile fracture as shown in figure 9a. While figure 9b show the fatigue fracture section for the frequency laser variable, it is seems as partial brittle fracture, and also that is true for the pulse duration laser variable figure 9c the fracture is brittle-ductile. But for peak power laser variable group, figure 9 d type of fracture has been smooth, also light and brittle. The regions related to fracture samples are displayed in the figure 9.

Figure 9: The Regions of Fracture of the Samples.

4. CONCLUSIONS

- As received specimen AZ31B, has a high endurance fatigue compared to the other groups.
- The views related to laser-treated specimens for fatigue fracture have been brittle and smoother for the laser variable for peak power, and ductile-brittle for other variables.
- Laser beam can help to increase hardening of the surface. The higher values are the hardness of the peak power laser variable specimens group, leading to lower cycling fatigue.
- There has been little difference in the fatigue equations which are recorded with regard to all types regarding

AZ31B Mg alloy specimens.

- Surface roughness related to laser treated specimens are higher in comparison to the received one, that's indicate the laser beam can increase the surface roughness.

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