Laser Treatment Influence on Estimated Fatigue Life of AA2017

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Abstract. This paper deals with improving the fatigue strength of AA2017-T0 aluminium alloy by using laser surface treatment. A set of rotating fatigue specimens were machined and prepared for this rezone. Half number of them was surface-treated using 1 Joule laser machine. The fatigue tests for the treater and as reserved specimens were used for different loads to draw the S-N curves. It was shown that the laser treatment was improving the fatigue strength for the alloy. The effect of varying the stress amplitude through-loading life was studied. It was shown that the (high-low) loading types give a longer life than the (low-high) loading types. The results show that the thermal laser treatment of the surface of the aluminium alloy AA2017 gives higher hardness and generates compression residual stresses that improving the mechanical properties of the alloy. Comparing experimental and numerical finite element results gives a good agreement with maximum error not exceeding (9.68%).

Keywords. AA2017 Aluminium alloy, Fatigue properties, Laser treatment Effect.

1. Introduction

Aluminium alloys have recently taken more interest as essential engineering materials in many industries. Especially; high-resistance alloys 2xxx, 6xxx and 7xxx because of their high resistance in addition to lightweight. Due to the improvements in these alloys' mechanical properties and microstructure through surface treatments such as laser technique. These alloys have been widely used in various industries and as substitutes for steel in many applications. It is, therefore, necessary to understand the properties of the fatigue for this type of alloys. The 2017 aluminium alloy, in the as-rolled condition. It is unsuitable for aerospace application since it lacks strength and ductility due to elongated grains, regions of high energy, and the absence of dispersed second-phase particles in its microstructure. These microstructural features require proper precipitation-strengthening or age-hardening heat treatment to the alloy for aerospace application. Due to the impartment of fatigue behaviour for materials, multi researchers investigated them for various ways. To modify the fatigue properties of materials, and measured the modification of the fatigue behaviour for materials with the effect of constant and variable applied load, [1-2]. Researchers focus on modifying composite materials' fatigue behaviour by reinforcement with different fibre and powders [3]. Therefore, due to aluminium alloys' impartment, it was necessary to investigate different ways to modify various aluminium alloys' fatigue behaviour. At, 2013, Y. Li et al., [4], investigated the effect of laser shock with high-temperature processing on the fatigue behaviour for K417 nickel alloy. Where the shock by laser leads to modified the fatigue characterization for its alloy. Thus, the investigation included used
for the experimental technique to shock the alloy with a laser at 900 oC per ten-hour. Where the modify of fatigue life lead to 2.5 times of non-treatment alloy. H. J. M. Al-Alkawi et al., 2015 [5-6], studied the effect of shot peening with plasma on the fatigue life and mechanical properties of aluminium alloy (2024-T3) material. Where, various parameters for peening processing were investigated as, time for peening, peening speed, the distance for peening, and other parameters. ed s investigation showed that the modified for material elongation leads, besides, the investigation showed that the modified for material elongation leads to from 32% to 56% for different peening processing and modifications of fatigue life. Also, they presented the effect of peening of plasma on the fatigue life of aluminium alloy type 6061-T6. Therefore, its investigation has shown that the effect of peening lead to modified the elongation for its materials was about 25% to 31% for various peening time processing and modified the fatigue behaviour of materials. H. J. M. Alalkawi et al., 2017 [7-8], showed the effect ultrasonic peening in the fatigue life and mechanical properties for aluminium alloy type 2017A-T3. The investigation showed that the ultrasonic peening led to modified the mechanical properties from 6.6% to 10.3% for ultimate stress and improved the yield stress from 27% to 30.7% by various surface peening parameters processing. Also, the fatigue life for its materials modified by peening processing with various values depending on the peening processing parameters. Also, they investigated the effect of coating for the surface with laser peening, of aluminium alloy types 2017A-T3, on fatigue characterizations. The investigation included used the experimental technique to show the effect of coating on its material fatigue. The investigation included studied different surface coating with laser peening with room temperature and stress ratio equal to -1. The study showed that the fatigue life modifies wit 18% to 35% by coating materials surface with different parameters. A. Kurek et al., 2017 [9], modified the fatigue life of aluminium alloy type 2017A-T4 using various stress types. The two types for applied load investigated compressive-tensile load and bending load and then compared the results. There, the experimental techniques in addition to the differential equation were used to calculate the fatigue life for alloy under different load effect.

K. K. Resan et al., 2018 [10], investigated modified of fatigue behaviour for the aluminium alloy with temperature effect of friction stir welding processing. Where, the investigation includes applied different temperature under various fraction stir welding processing to modified the mechanical properties of aluminium alloy used, and then, improvement for the fatigue behaviour form its materials. W. Hussein et al., 2018 [11], studied the fracture and fatigue behaviour of aluminium alloy with various friction stir welding parameters effect. Where the investigation included study the fatigue behaviour of welding joint with various effect. There, the experimental technique was used to calculate the fracture behaviour and the fatigue life for its materials. S. S. Hassan et al., 2018 [12], investigated the effect of shock peening by laser on the fatigue behaviour for aluminium alloy type 7075-T6 with confining layer for hydrofluoric acid and pure water. The investigation included using the experimental technique to peen the alloy surface by laser with low time and use for pure water and acid to hardness the materials’ surface. Then, the fatigue of materials was modified to 9.78% and 154.3% with various peening parameters and modified the hardness for its alloys. H. Zhang et al., 2019 [13], investigated the effect of quenching for laser on t riumium alloy's fatigue characterization. The investigation included using the experimental technique to calculate the fatigue life for its alloy with the effect of quenching laser and different materials conditions for the surface. The results have shown that the quenching laser leads to hardness the material surface, increasing fatigue life for an alloy. The modifying for fatigue life, by using quenching laser leads to about 110.78% with low level of stress, and the modified of fatigue leads to about 17.56% at a high level of stress. Then, from previous researchers can be the conclusion that the modify for the fatigue life of different materials can be made by using various techniques as peening with laser or ultrasonic for materials surface, by coating materials surface, or with applied different load types on the materials, in addition to other techniques. Nevertheless, previous researchers’ best technique is to treat the surface of the material by using a laser with different temperature effects. In this paper treatment the AA2017-T0 aluminium alloy by using the laser to modifying the fatigue properties. The investigation included using
experimental tests with constant and variable amplitude, the numerical simulation by the finite element method applied to calculate the fatigue behaviour for alloy and then compare the obtained results with experimental results.

2. Experimental work
The experimental work includes evaluating fatigue life for AA2017 aluminium alloy with the effect of surface laser treatment. Thus, the experimental work first required to analyze the materials composition by using chemical analysis. The standard and measured chemical composition and mechanical properties are given in Table (1) and (2), respectively. The fatigue life and endurance limit were calculated for treated and non-treated samples and then compared the results to the percentage modified for fatigue characterizations. Two loading types (L-H) and (H-L) were used to study the cumulative fatigue damage under variable amplitude. Also, the fatigue results will be compared with numerical results. All fatigue specimens were machined using CNC turning machine. AA2017 aluminium alloy was used as base metals with a 10 mm diameter. The test specimens are shown schematically in figure (1). The machined specimens were classified into two groups; Table (3) illustrates both groups. After machining, all specimens for fatigue tests are grinding and polishing. The grinding with wet silicon carbide papers was starting 400, 800, 1000, and 1200. It was polished with cloth and alumina with 1/3 micron particle size. Distilled water was used to clean the specimens, followed by washing them with alcohol.

Table 1. Chemical composition of AA2017 aluminum alloy.

|     | Cr  | Cu  | Fe  | Mg  | Mn  | Si  | Ti  | Zn  | Al  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Measured | 0.11 | 4.13 | 0.32 | 0.66 | 0.19 | 0.045 | 0.045 | 0.085 | Rem. |
| Standard, [14] | 0.1 | 3.5-4.5 | 0.7 | 0.4-0.8 | 0.4-1 | 0.2-0.8 | 0.15 | 0.25 | Rem. |

Table 2. Typical mechanical properties of AA2017 aluminum alloy.

|                | Ultimate strength (MPa) | Yield strength (MPa) | Elongation | Hardness (HB) |
|----------------|-------------------------|----------------------|------------|---------------|
| Measured       | 185                     | 78                   | 19         | 48            |
| Standard, [14] | 179                     | 68.9                 | 22         | 45            |

Table 3. Specimens groups.

| Series | Materials | Heat treatment |
|--------|-----------|----------------|
| A      | 2017      | As received    |
| B      | 2017      | Laser treatment |

Figure 1. Dimensions of the fatigue test specimen.

To study the effect of laser treatment for the surface of AA2017 aluminium alloy. The study's laser system was high energy-pulsed neodymium (Nd)-YAG laser with a wavelength of 1.064 µm. The pulse energy was 1 Joule, and the repetition rate was 6 Hz. Four shocks for each specimen with 1mm diameter around the small diameter of fatigue sample were selected. Table (4) shows the laser's main characteristics, and Figure (2) shows the laser device in Laser Engineering Department/ University of Technology.
Table 4. The main characteristics of Nd: YAG laser.

| Parameter              | Value       |
|------------------------|-------------|
| Wavelength             | 1.064 μm    |
| Energy                 | 1 J         |
| Shock diameter         | 1 mm        |
| Power density          | Watt/cm²    |

The fatigue tests were carried out in the Mechanical Engineering Department / Al-Nahrain University. A rotating bending fatigue-testing machine was used to execute all fatigue tests, with constant and variable amplitude. For a constant amplitude, the specimens were subjected to an applied load from the right side of the perpendicular to the specimen's axis, developing a bending moment. Therefore, the specimens' surface is under tension and compression stresses when it rotates with stress ratio R= -1. Twelve Specimens for each group were used to perform (S-N) curves (two for each stress applied) i.e. six stress values, as shown in figure (3) which are used to study the effect of laser treatment on fatigue life of these alloys. Then, it samples to test using bending rotating fatigue machine, shown in Figure (4) to calculate the fatigue life and endurance limit. Figure (5) given the fracture occur of samples due to fatigue fracture. The accumulative fatigue damage of the 2017 aluminium alloy samples was studied. Two samples were divided into two case studies where the samples were subjected to variable amplitude (two steps) until failure. Two levels of stress, 240 MPa and 320 MPa were used for each test to estimate the accumulative fatigue damage and obtain fatigue life at these two levels of stress. Figure (6) shows the amount of loading per case.
3. Numerical technique
The numerical technique is a an approximant solution for evaluating fatigue life of AA2017 aluminium alloy with and without laser treatment effect. Thus, the numerical solution included using the finite element method by using ANSYS program for the finite element method, which is a given the Ansys program for the finite element method, which gave agreement results for the engineering application under static or dynamic loading. Therefore, to solve the fatigue problem, first, selected the required element types given the best results for fatigue behaviour, where, can be using element (Solid 187) for this application, given in Figure (7). After this, the fatigue sample was modelled, and then, the mechanical properties were inputted, calculated by experimental work [15]. Then mesh the model.
by selected the required element and node number, with using mesh generation to calculated the best element number can be used, [16], as presented in Figure (8). Finally, solution the fatigue problem with rotation bending load applied and calculate fatigue stress and the number of cycles. Where the fatigue fracture for an element can be shown in Figure (9). Besides, comparison the numerical results with experimental results to given the agreement for obtained results.

![Figure 7. Element type, solid 187.](image)

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![Figure 8. Mesh of fatigue sample.](image)

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![Figure 9. Fatigue fracture of AA2017 aluminum alloy.](image)

Figure 9. Fatigue fracture of AA2017 aluminum alloy.

4. Results and discussion

The results included evaluating fatigue life for AA2017 aluminium alloy with laser treatment and comparing the experimental results with numerical results, Figure 10, show the comparison for fatigue results. The Figure can be seen that the maximum error did not exceed about (9.68%).

![Figure 10. S-N Experimental diagram and Numerical representation.](image)

Figure 10. S-N Experimental diagram and Numerical representation.
4.1. Constant amplitude

S-N Curve was obtained after testing for the AA2017 aluminium alloy samples. Figure (11) shows the fatigue life curve of the AA2017 aluminium alloy as received and after treatment with laser, which is expressed mathematically by the following equations.

\[ \sigma_f = 2649.4 N_r^{-0.186} \] for laser treatment specimens

\[ \sigma_f = 858.7 N_r^{-0.13} \] for non-treated specimens

This curve was 140 MPa for the non-treated alloy, as given in Figure (12a). While in laser surface treated alloy becomes 210 MPa. Figure (12.b) represents the fatigue life curve of the two groups used in this research. It was shown that the fatigue strength for treatment samples are more than the fatigue strength for non-treatment samples. Thus, the endurance limit calculated at 10⁶ cycles. The decline of stress - number of cycles in high stresses is higher than the decline in the low stresses near the fatigue Limit, and this is due to the elastic strain energy in the high stresses that are close to the strain energy of the necessary stress failure. Therefore, the fatigue life is small because it is within this high range of stress. The results show that the thermal laser treatment of the surface of the AA2017aluminum alloy gives high hardness and generates residual compression stresses to improve the alloy's mechanical properties. The control of the laser surface treatment process parameters gives the best combination of tensile properties and hardness, and because of the relationship of the properties of the fatigue with the properties of tensile, hardness and ductility. They are affected by the laser treatment parameters. The properties of the fatigue life improve with improvement other mechanical properties. This is because the surface hardness increases the resistance of the fatigue. After all, it does not allow the formation of cracks early. The residual stresses generated on the surface due to surface thermal treatment of laser improve fatigue life resistance because it reduces effective stress at the surface. After all, residual tension stress reduces the resistance of the fatigue.

The fatigue life depends on the growth of fatigue cracks. So the dispersion in the fatigue life is related to the dispersion of the size of the defect, which is the stress concentration for creating fatigue cracks. The laser surface's thermal treatment generates residual stresses; the degree of residual compression stresses relaxation due to the cycling load, which changes with the rate of applied stress. At the highest stress ratio, the change in the residual stresses prevails at the initial load, while at the lowest stress ratio, the relaxation in the residual stresses depends on the value of the cycling load and the number of fatigue cycles.

![Figure 11. Comparison of S-N curves of treatment and laser-treatment of AA2017 alloys.](image-url)
4.2. Variable amplitude

Two of the AA2017 aluminum alloy samples, surface treatment with laser, were subjected to variable amplitude test with two-steps, (high-low) and (low-high) type at loading ratio \( \frac{n_1}{N_f} = 0.25 \), Table 5 shown test results. From the results of the tests shown in Table (5), the cycling stresses of the variable amplitude type (high - low) lead to an increase in life of the fatigue more than the increase in loading of the type (low - high). The increase in fatigue life for the high-low load type is that the high initial stress (320 MPa) causes the plastic zone to be large at the top of the crack. This leading a delay in the growth rate of the crack. The reasons for increasing the fatigue life of the variable amplitude, type (low - high) that occurs in the laser treatment samples, is due to the high degrees of the closure of the cracks caused by the second high load (320 MPa) when moving from the level of the lower stress (240 MPa). This degree of cracks closure, which occurs due to the stress intensity factor (K), which is more valuable higher than the threshold, leads to a reduction in the force leading to the growth of cracks for high stress and this leads to the value of \( \frac{NT}{N_{f\text{exp}}} \) less than one. Fatigue damage gradually decreases with strain cycling, and often intense change occurs in the final stage of the fatigue. This is a very low density of cracks at this stage due to docking or rapid integration of micro-cracks within the material, and this leads to the value of \( \frac{NT}{N_{f\text{exp}}} \) more than once, as shown in Table (5).

| No. | Loading type | \( \sigma_1 \) (MPa) | \( n_1 \) (Cycle) | \( \sigma_2 \) (MPa) | \( n_2 \) (Cycle) | NT (Cycle) | Nf.exp (Cycle) | \( \frac{NT}{N_{f\text{exp}}} \) |
|-----|--------------|---------------------|------------------|---------------------|------------------|-------------|----------------|----------------|
| B1  | L - H        | 240                 | 75750            | 320                 | 321180           | 396930      | 303000         | 1.31           |
| B2  | H - L        | 320                 | 41550            | 240                 | 726294           | 767844      | 166200         | 4.62           |

5. Conclusions

- The thermal laser treatment of the surface for AA2017 aluminum alloy gives high hardness and compression residual stresses that improve the alloy's mechanical properties.
- Because of the relationship of the fatigue properties with the properties of tensile, hardness and plasticity, they are affected by the parameters of laser treatment, so control of the variables of laser surface treatment process gives the best results.
- The surface hardness increases fatigue resistance because it does not allow the growth of cracks early. Also, the compression residual stresses generated on the surface due to surface thermal treatment of laser improves the resistance of the fatigue because it reduces the effect of effective stress at the surface of aluminum alloy materials.
- Variable cyclic stresses of the type (high - low) lead to an increase in fatigue life more than the increase in the type (low – high) load.
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