Engineering and Technology Journal
Journal homepage: engtechjournal.org

Effect of Laser Shock Peening on Fatigue Stress Concentration of Polyester Reinforced by Al-Micro Powder Composites

Ahmed N. Al- Khazraji [a], Ammar A. Mutasher [b]*

[a] University of Technology- Mechanical Eng. Dep., Baghdad, Iraq. dr_ahmed53@yahoo.com

[b] University of Technology- Mechanical Eng. Dep., Baghdad, Iraq. ammar1199011@gmail.com

*Corresponding author.

Submitted: 10/06/2019 Accepted: 07/08/2019 Published: 25/03/2020

K E Y W O R D S

Fatigue Life, Endurance Limit, Composite Materials, Laser shock peening, Polymer Matrix Composites, notch sensitivity factor, fatigue strength reduction.

A B S T R A C T

Laser shock peening is a widely common process for materials treatment and typically used for fatigue strength enhancement especially for metals. In this paper, its effect on polymeric composite materials studied experimentally. Unsaturated polyester was used as a matrix in order to composites preparation and Aluminum powder as fillers. A Hand lay-up technique has been used for composites making. Composites with three volume fractions of Aluminum powder were prepared (2.5%, 5%, and 7.5%). Fatigue specimens as a standard and with (1mm) semi-circular notch are prepared for testing. The fatigue test was performed at room temperature and stress ratio (R=-1). Laser shock peening with two levels of energy have been applied (1Joule, and 2Joule). The results showed an increase in the endurance strength of the notch for 7.5% volume fraction especially at 1J laser energy by about 26.7056% compared with the un-treatment notched state, which in turn reduced the fatigue stress concentration by about 21.0508% compared with standard fatigue stress concentration. On the other hand, the presence of notch effect on endurance strength was increased after laser treatment of composites with 2.5% volume fraction and the reduced was by about 39.698% at 2J laser energy.

How to cite this article: A. N. Al- Khazraji and A. A. Mutasher, “Effect of laser shock peening on fatigue stress concentration of polyester reinforced by Al-micro powder composites,” *Engineering and Technology Journal*, Vol. 38, Part A, No. 03, pp. 325-334, 2020.
DOI: https://doi.org/10.30684/etj.v38i3A.345

1. Introduction

Composite materials precisely polymeric types are involved in a wide range of industries and manufacturing of different structures and mechanical component since they are easy to prepare and consider as lightweight materials. Composite materials are two different materials mixing to share their properties and forming a new distinct material [1]. Polymeric matrix composites are the most common type. Polymers are commonly reinforced with particles as fillers to get special thermal and mechanical properties. Polymeric composite materials, especially those reinforced by fillers, are widely used in different applications. They are used in manufacturing, such as abrasive and cutting tools, internal parts of an airplane and automotive, also for welding as a (plastic welder) of the breaking metallic component. Notches and holes are common forms, which are found in approximately all engineering parts, and usually used for joining those parts with each other. Notches and holes are treated as discontinuous geometry in components. The presence of discontinuous geometry in the parts, reducing the strength due to local stress concentration and leads to catastrophic failure. Fatigue is commonly defined as the relationship among the stress that applied against several cycles to failure. The criterion of this failure is because of that the micro cracks first initiate into the matrix material then propagates and at last leads to failure [2]. Laser shock peening (LSP) is a process for surface treatment used to improve the fatigue strength, metallurgical and mechanical properties of metals by modifying and treating the surface and introducing compressive residual stresses by using a high energy laser pulse run into the material's surface [3]. LSP easy to be applied to the region have a high stress concentration such as notches and holes compared with shot peening or other peening types. The influence of peening operation is different in composite materials compared with metals, especially polymeric matrix composite (PMC). The reason for that it consists of two or more constituent; each of them has distinct metallurgical and mechanical properties leads in various effects from one point to others and results in a complicated attitude hard to be predicted.

Mohammed [4] studied the laser treatment influence on fatigue strength of composite materials. The composite material was used construct from polyester resin as a matrix and was reinforced with steel layer and fiber e-glass in the form of laminate composite material with (1mm) thickness and [+45/-45]s and [0/90]s fiber angles. Two types of the laser beam were used for this investigated (band and pules). Laser treatment in the different position was applied. The result showed an increase in properties after treatment by about 23% compared with un-treated state.

Alkhazraji et al. [5] investigated the influence of shot peening process on fatigue strength of polymeric composite materials. Polyester as a matrix material was utilized, and two various types of reinforcement materials were used. Continuous unidirectional fiber E- glass was the first reinforcement material with 33% volume fraction, whereas the other one was Al powder with 2.5% volume fraction. Fatigue test was carried out with stress ratio (R=-1) at room temperature. The result manifested an increase in the fatigue endurance strength of polyester\ fiberglass after shot peening treatment, and the increment by about 25% at (6 min) peening time compared with unpenned state. On the other hand, a reduction was occurred in endurance strength of polyester\Al powder reach by about 29% after treatment by shot peening with (6 min) peening time.

Beyene et al. [6] investigated the effect of the notch on fatigue flexural performance of composite materials. The investigation was done on composite was made from Twill E-glass/epoxy. Un-notched specimens and specimens with various kinds of notches configuration like (circular holes, transverse ellipse, longitudinal ellipse and slot geometry), were prepared from composite sheet. The results of standard coupons are then compared with those specimens of which have the chosen notch geometries. The results showed that various notched geometry behave differently in fatigue loading. For composite specimens subjected to fatigue loading, it has found that the notch size and geometry becomes a dominant parameter for failure.

Al-Khazraji et al. [7] studied the shot peening influence notch sensitivity factor (q). Aluminum (AA7075-T6) was chosen to make the investigation. Fatigue specimens with notches in two different radii were used (1, 1.25 mm). Shot peening was performed at two different durations (10 and 20 min). The result observed a decreasing in the notch sensitivity factor (q) by about 22.35%, at 10 min shot peening time and notch radius 1.25mm.

Benedetti et al. [8] studied the fatigue behavior of shot peened notched specimens. By using aluminum (7075- T651). Moreover, the result was showed that the shot peening process increases the endurance fatigue strength even in the presence of geometrical discontinuous. Therefore, in this current research, the notch effect and the LSP influence on the fatigue behavior of particulate composite materials will be investigated.

2. Theoretical Part

I. Stress concentration factor

The theoretical stress concentration factor (often called stress raisers) is knowing as the ratio among the maximum stress in a component due to notch or hole and the nominal stress in the same section concerning the net area. Mathematically, as follow [9]:

$$K_t = \frac{Maximum\ stress}{Nominal\ stress} \quad (1)$$

The stress is concentrating in such location due to the geometric discontinuity, and the reduction in cross sectional area causes an increase in the level of stress, especially at the location of the abrupt area changing. Fatigue stress concentration occurs when a machine or component is subjected to cyclic repeating or fatigue loading, the value of fatigue stress concentration factor (K_f) (or fatigue strength reduction) shall be applied instead of theoretical stress concentration factor. Also, because of the calculation of fatigue stress concentration factor is not an easy task, so from experimental tests is defined as [9,10]:

$$K_f = \frac{Endurance\ limit\ without\ stress\ concentration}{Endurance\ limit\ with\ stress\ concentration} \quad (2)$$

The value of (k_t) is a function the natural of loading and geometry while the magnitude of (k_f) is a function of loading, geometry and material. The theoretical stress concentration (k_t) of semi-circular notch can be predicted according to the following relations [11]:

$$K_t = 1.894 - 2.784\left(\frac{2t}{H}\right) + 3.046\left(\frac{2t}{H}\right)^2 - 1.186\left(\frac{2t}{H}\right)^3 \quad (3)$$

Where t and H, are the notched specimen dimension, as shown in Figure 1.

II. Notch sensitivity factor

The notch sensitivity of a material is a metric of how material sensitive for geometric irregularities or notches. The sensitivity of a material to crack propagates and fracture is increased within the presence of a surface inhomogeneity such as a sudden change in a section, notch, crack, or scratch. Low sensitivity to notch is generally related to ductile materials, whereas high notch sensitivity founded in brittle materials. The reason that somewhat materials tend to be less or more "sensitive" to the presence of stress concentrations as a consequence of utilizing elastic stresses to predict the nonlinear attitude of materials [9,10].

Notch sensitivity factor (q), is the extent to which the theoretical (geometrical) stress concentration effect during the component is subjected to dynamic load. So, it's usually calculated using the following Neuber equation [10]:

$$q = k_f - 1/k_t - 1 \quad (4)$$

q - Notch Sensitivity Factor

k_f – Fatigue Stress Concentration Factor.

k_t - Theoretical Stress Concentration Factor.

3. Experimental Work

I. Fabricating of the fatigue specimens

The composites were prepared in a sheet form with size (300x280x4) mm, according to reference Mahdi [12]. The unsaturated polyester resin as a matrix phase was used for the preparation of composites, and the properties are illustrated in Table 1. Aluminum powder was utilized as a reinforcement material; it has a filler with particles size (50-100) µm, Table 2 observed the properties of it. The hand lay-up process was used for fabrication since it is simple and can be used for producing composites in different sizes and forms. The mold was prepared from clean glass, coated first by Vaseline then covered by Al foil to prevent the adhesion that occurs between the material and the mold. 1.5% (MEKP) abbreviation to (Methyl Ethyl Ketone Peroxide) from the net volume of unsaturated polyester was appended to the mixture and then Al powder was mixed and dispersed into the matrix during the reaction has begun. Composites with three volume fractions were prepared in this study (2.5%, 5% and 7.5%).

II. Specimens' preparations

Two set forms of specimens were prepared; the first form was according to fatigue instrument manual [15], which was used for un-notched SN curve drawing, as shown in Figure 2. The second form of specimens is prepared with (1mm) notch in order to notch fatigue strength calculation, as shown in Figure 3. Notch was performed using a CNC machine to perfect fitting.

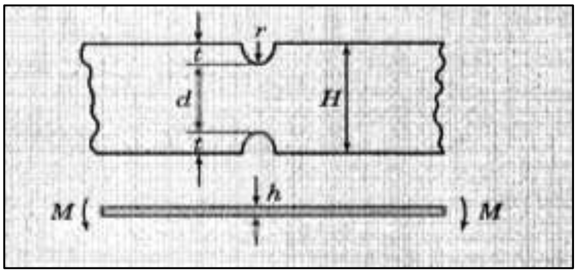

Figure 1: The semi-circular notch [11]

Table 1: The properties of polyester resin [13]

Density (ρ ($\mathbf{kg/m^3}$)	Elastic Modulus E (GPa)	Poisson Ratio (v)
1211	1.0602	0.38

Table 2: The properties of Al powder [14]

Density (ρ($\mathbf{kg/m^3}$)	Elastic Modulus E (GPa)	Tensile Strength $\boldsymbol{\sigma_{Ult}}$ (MPa)
2700	71	60

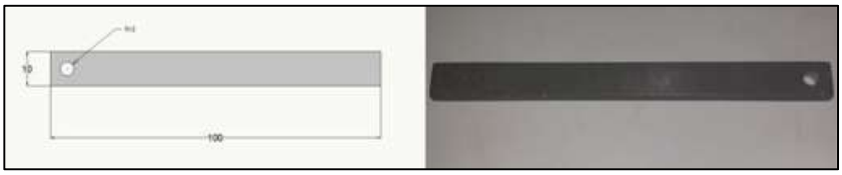

Figure 2: Fatigue specimen according to fatigue instrument [15] (all dimensions are in mm)

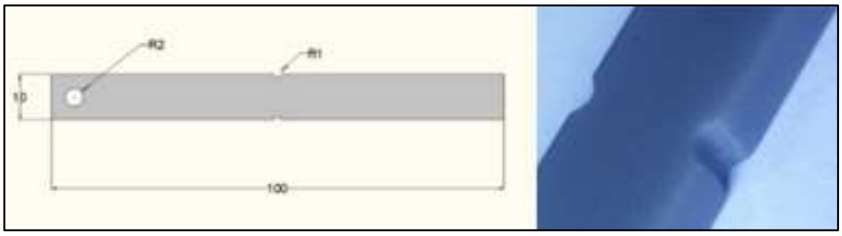

Figure 3: Notched fatigue specimen (all dimensions are in mm)

III. Fatigue test

The fatigue test was accomplished by using (bending-alternating HSM20), as shown in Figure 4. This instrument is displacement-controlled fatigue and can be utilized by applying a constant amplitude deflection to the edge of the cantilever beam. The test was executed at room temperature with zero mean stress (stress ratio (R= -1)) and 25Hz frequency. The dimensions and geometry of specimens were chosen according to the machine's manual [15], as in Figures 2 and 3. This test was carried out at Department of Mechanical Engineering/ University of technology- Baghdad. The notched specimen before and after being tested is shown in Figure 5.

IV. Laser shock peening

LSP process builds on several parameters, like laser plasma pressure, the type of laser source, plasma confinement layer, and material condition [16]. The plasma pressure can be prophesied by the following experimental equation while using water for confining [17]:

$$p(GPa) = 1.02\sqrt{I_o\ (\frac{GW}{cm^2})} \quad (5)$$

Where I_o is the laser intensity, which depends on the energy per pulse in (Joule) of the laser beam, spot size, pulse duration, and wavelength [18]. The type of laser beam, which was used to prepare this study is Q-switched (Nd-Yag) laser pulse and applied on the specimen's surface to generate a shock wave, as in Figure 6. The shock generation procedure, which was utilized in this study, is similar to that followed in metals [19]. The parameters that are chosen in this research are listed in Table 3. The surface was first painted with a black dye as a protective layer and the efficiency of the energy absorption increased. In addition, the specimen was immersed in water at an altitude about (2-3) mm from the peening area. The aim of that is to confined and protect the specimen's surface from the high thermal energy that may occur. The treatment was done by peening the upper and lower surface in additional to the notch root. Figure 7 shows the notched fatigue specimen when being treated by LSP.

Figure 4: Bending-alternating fatigue device HSM20

Figure 5: Notched fatigue specimen before and after being tested

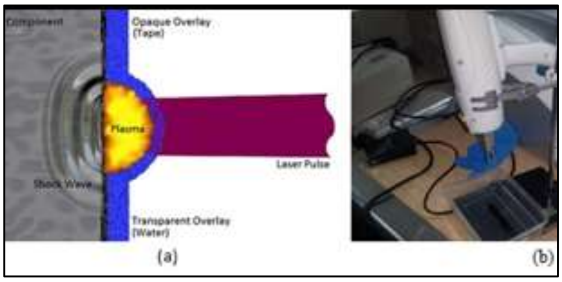

Figure 6: (a) Basic principle of laser peening, (b) Q-switched Nd-Yag laser pulse

Table 3: The parameter of laser peening

Energy (Joule)	Wave length (nm)	Spot size (mm)	Water height (mm)	Pulse duration (ns)
1	1064	3	3	7
2	1064	3	3	7

Figure 7: Notched specimens after treatment

4. Results and Discussion

The fatigue test was done for the SN curve drawing of different volume fraction composites to make a comparison between smoothed-notched specimens results firstly, then among notched specimens before and after treatment with (1J and 2J) LSP energy. More than (6 specimens) tested for each SN curve and obtained the results. The endurance strength of every SN curve was calculated at 10^6 cycles using the following fitting equation (Basquin equation) [2]:

$$\sigma = A * {N_f}^{-b} \tag{6}$$

I. Before LSP

Figure 8 shows the fatigue results of smooth specimens for polyester\Al powder with different volume fraction (2.5%, 5% and 7.5%). Figures 9, 10 and 11 observe the smoothed and notched fatigue results for 2.5%, 5% and 7.5% respectively. Table 4 shows the standard endurance strength with different volume fraction for smoothed and notched fatigue test the notch sensitivity factor was calculated. The endurance limit of smoothed specimens increased with the increasing of volume fraction. To the increasing of filler leads to more binding and more fatigue resistance [12]. In addition, it's obvious that the presence of notch reduces the endurance limit by about 21.437%, 16.335% and 13.901% for 2.5%, 5% and 7.5% volume fraction subsequently. As clear that the effect of notch was reduced with the increasing of volume fraction. The fatigue stress concentration and the notch sensitivity factor were also reduced inversely with the increasing of volume fraction. The notch sensitivity factor (q) was 0.6044, 0.4333 and 0.3577 for 2.5% and 5% and 7.5% volume fractions respectively. This mainly due to hard Al powder particles which stopped the propagation of cracks due to blunting effect, and give more resistance to the presence of discontinuous geometries in component, see Table 4 [13].

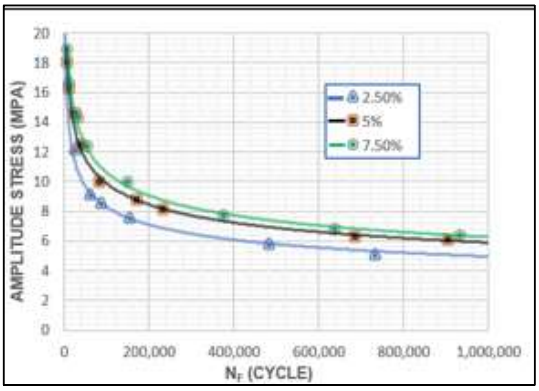

Figure 8: SN curve with different volume fraction

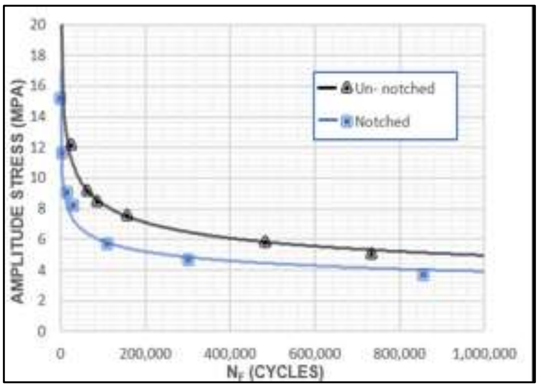

Figure 9: SN curve of un-notched and notched fatigue for 2.5% volume fraction

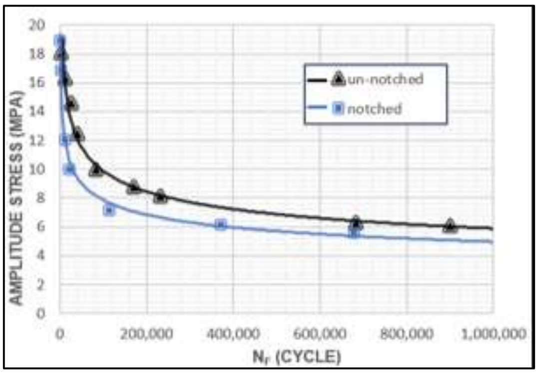

Figure 10: SN curve of un-notched and notched fatigue for 5% volume fraction

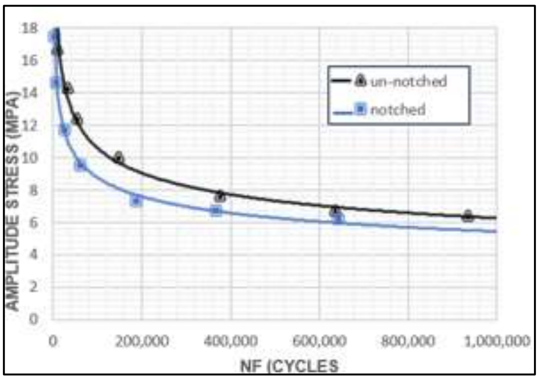

Figure 11: SN curve of un-notched and notched fatigue for 7.5% volume fraction

Table 4: The values of endurance strength for notched and un-notched specimens, fatigue strength reduction and notch sensitivity factor without any treatment

Type	σ_e (MPa)	σ_e of notch (MPa)	Reduction in σ_e (%)	K_f	K_t	q
2.5%	4.965767311	3.901241	-21.437	1.272	1.45	0.6044
5%	5.91167211	4.945982	-16.335	1.195	1.45	0.4333
7.5%	6.291949376	5.417276	-13.901	1.161	1.45	0.3577

II. After treatment

Figures 12, 13 and 14 in addition to Tables 5 and 6 show the fatigue results of notched specimens before and after peening by 1J and 2J laser energy for composites with 2.5%, 5% and 7.5% volume fractions. It is obvious that LSP was reduced the notch strength for 2.5% and 5%. The reduction in endurance notch strength for 2.5% was about 20.204% and 39.698% when treated by 1J and 2J laser energy respectively. On the other hand, the reduction in strength was slightly less in 5% volume fraction compared with 2.5%, and was by about 6.9204% and 28.3911% when treated by 1J and 2J laser energy respectively. This prove that the composite became more resistance to the destructive. This destruction attitude mainly was due to the high brittleness at low volume fraction caused more cracks into the composites after LSP process [5]. With 7.5% volume fraction the materials exhibit an enhancement in the strength of the notch compared with the un-treatment state. The increment in the endurance strength of notch was by about 26.7056% and 23.8482% at laser energy 1J and 2J respectively. Figure 15 shows a comparison between notched fatigue states before and after LSP with un-notched state of composite materials with 7.5% volume fraction, and also the endurance strength was listed in table 5. The endurance strength of notched specimens after LSP was increased in a level more than for un-notched state and was by about 9.091% and 6.631% at level of laser energy 1J and 2J respectively. This behavior was due to the compressive residual stress that induced into the composite using LSP [4,5]. The changing in fatigue stress concentration results after notch treatment by LSP were listed in table 6. For 2.5% and 5% it's obvious that the LSP is a destructive process and led to increase the fatigue strength reduction due to notch presence. This increment was continuous with increased the energy level of laser beam to 2J. For composite materials with 7.5%, LSP was reduced the sensitivity of notch due to reducing the stress concentration in materials and this reduction was about 21.0508% and 19.293% when was treated by 1J and 2J LSP energy respectively.

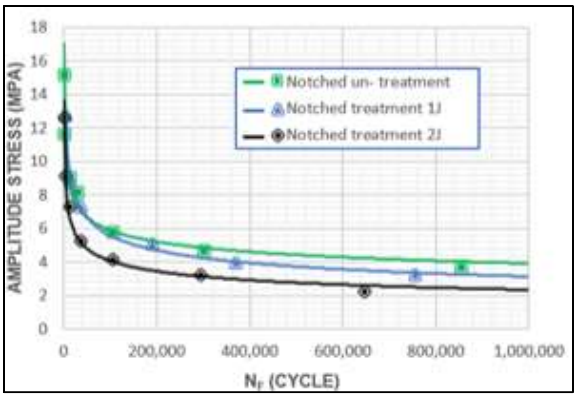

Figure 12: SN curve of (2.5%) volume fractions for notched specimens treated and un-treated

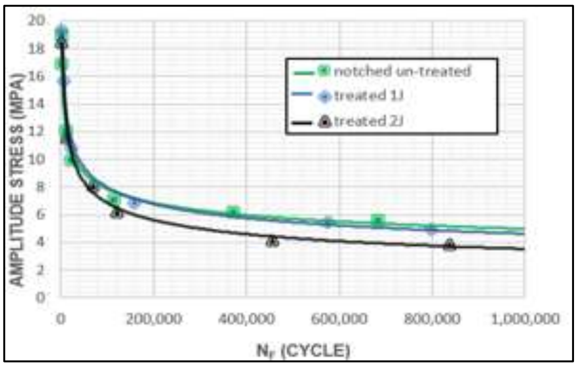

Figure 13: SN curve of (5%) volume fractions for notched specimens treated and un-treated

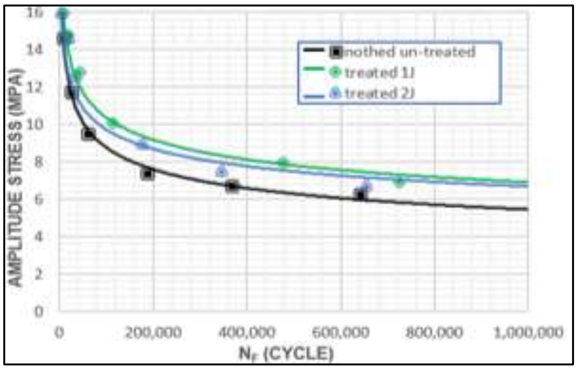

Figure 14: SN curve of (7.5%) volume fractions for notched specimens treated and un-treated

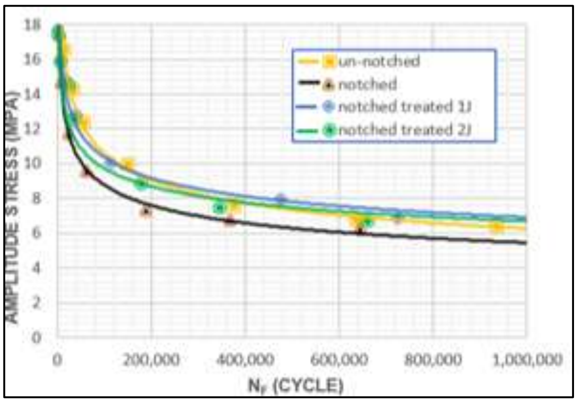

Figure 15: SN curve of (7.5%) volume fractions for notched specimens treated and un-treated

Table 5: The values of endurance strength for notched and un- notched specimens, fatigue strength reduction and notch sensitivity factor

Volume fraction (%)	Standard un-notched	Standard notched	Treated 1J		Treated 2J	
			MPa	%	MPa	%
2.5	4.96576	3.901241	3.113009	-20.204	2.35249164	-39.698
5	5.91167	4.945982	4.6037	-6.9204	3.541762	-28.3911
7.5	6.29194	5.417276	6.863997	26.7056	6.709202	23.8482

Table 6: The values of fatigue strength reduction before and after LSP

Volume fraction (%	Standard K_f	K_f after treatment (1J)		K_f after treatment (2J)	
	Value	Value	%	Value	%
2.5	1.272	1.595	25.393	2.1108	65.943
5	1.195	1.284	7.4476	1.669	39.665
7.5	1.161	0.9166	-21.0508	0.937	-19.293

5. Conclusions

The main point, which was concluded from the last observed results as follow:

I. The increment in the volume fraction of Al powder to 7.5% reduced the fatigue stress concentration, and in turn, reduced the sensitivity to the presence of semi-circular notch in the component.

II. LSP treatment with 1J and 2J energy levels reduced the sensitivity of the notched composite materials specimens with a 7.5% volume fraction by reducing the stress concentration due to notch root.

III. Composite materials with 2.5% and 5% volume fraction of Al powder, when treated by LSP leads to increase sensitivity to the presence of the notch.

IV. The increasing of the laser beam energy to 2J leads to more destructive in composite with 2.5% and 5% volume fraction.

References

[1] I. M. Daniel and O. Ishai, “Engineering mechanics of composite materials,” New York Oxford, 1994.

[2] Y. Murakami, “Metal fatigue: effects of small defects and nonmetallic inclusions,” Elsevier- Science Ltd, 2002.

[3] M. R. Hill, A. T. DeWald, J. E. Rankin and M. J. Lee, “Measurement of laser peening residual stresses,” Journal of Materials Science and Technology, Vol. 21, Issue 1, pp.1-23, 2005.

[4] A. J. Mohammed, “Effect of laser treatment on fatigue test for composite materials with presence of steel reinforcement,” The Iraqi Journal for Mechanical and Material Engineering, Vol.16, No.1, pp. 1-17, 2016.

[5] A. N. Al-Khazraji and M. N. M. Shareef, “Comparison of fatigue life behavior between two different composite materials subjected to shot peening at different times,” Al-Khwarizmi Engineering Journal, Vol. 10, No. 3, pp. 1- 12, 2014.

[6] A. T. Beyene, G. Belingardi and E. G. Koricho, “Effect of notch on quasi-static and fatigue flexural performance of T will E-glass/epoxy composite,” Elsevier- Composite Structures, Vol 153, pp. 825-842, 2016.

[7] A. N. I. Al-Khazraji and T. A. H. AL-Taie, “The effect of shot peening on the notch sensitivity factor and neuber characteristic length for 7075-T6 aluminum alloy,” Journal of Engineering and Development, Vol.19, No.4, pp. 200- 218, July 2015.

[8] M. Benedetti, V. Fontanari, B. Winiarski, P. J. Withers, M. Allahkarami and J. C. Hananc, “Fatigue behavior of shot peened notched specimens: effect of the residual stress field ahead of the notch root,” Elsevier-Procedia Engineering, Vol. 109, pp. 80-88, 2015.

[9] J. E. Shigley and C. R. Mischke, “Standard handbook of machine design,” 2nd edition, McGraw-Hill Inc, 1996.

[10] R. S. Khurmi and J. K. Gupta “A textbook of machine design,” Eurasia Publishing House (PVT.) LTD, 2005.

[11] R. E. Peterson, “Stress concentration factor,” 2nd Edition, John Wiley & Son, 1997.

[12] M. N. M. Shareef, “Effect of shot peening on mechanical properties and endurance limit of composite materials,” M.Sc. Thesis, Mechanical engineering Department, University of Technology, Baghdad, Iraq, 2014.

[13] D. Hull “An introduction to composite materials,” University of Liverpool, Cambridge University, England, (1981).

[14] W.D. Callister, JR, "Materials science and engineering- an introduction" 6th Ed, John Wiely and Sons Inc, New York, (2003).

[15] N. P. Roberts and Nigel R. Hart "Alternating bending fatigue machine (HSM20),” Instruction Manual, Hi-Tech Ltd. UK. 2001.

[16] M. Tsuyama, Y. Kodama, Y. Miyamoto, I. Kitawaki, M. Tsukamoto and H. Nakano, “Effects of laser peening parameters on plastic deformation in stainless steel,” JLMN-Journal of Laser Micro/Nanoengineering Vol. 11, No. 2, pp. 227- 231, 2016.

[17] K. Ding and L.Ye, “Laser shock peening performance and process simulation,” Woodhead Publishing limited, Cambridge England, 2006.

[18] A. M. Mostafa, M. F. Hameed and S. S. Obayya “Effect of laser shock peening on the hardness of AL-7075 alloy,” Journal of King Saud University–Science, 2017, http://dx.doi.org/10.1016/j.jksus.2017.07.012.

[19] A. Azhari, S. Sulaiman and A. K. Prasada Rao, “A review on the application of peening processes for surface treatment,” IOP Conference Series: Materials Science and Engineering, Vol. 114, 2016.