



Effect of Laser Shock Peening on the Fatigue Behavior and Mechanical Properties of Composite Materials

Ahmed N. Al-Khazraji*

Ammar A. Mutasher**

*, **Department of Mechanical Engineering/ University of Technology

*E-mail: Dr_ahmed53@yahoo.com

**E-mail: ammar1199011@gmail.com

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Abstract

In this study, Laser Shock Peening (LSP) effect on the polymeric composite materials has been investigated experimentally. Polymeric composite materials are widely used because they are easy to fabricate and have many attractive features. Unsaturated polyester resin as a matrix was selected and Aluminum powder with micro particles as a reinforcement material was used with different volume fraction (2.5%, 5% and 7.5%). Hand lay-up process was used for preparation the composites. Fatigue test with constant amplitude with stress ratio ($R = -1$) was carried out before and after LSP process with two levels of energy (1Joule and 2Joule). The result showed an increase in the endurance strength of 25.448% at 7.5% volume fraction when peened is 1J laser energy. Also, the ultimate strength and Young's modulus were increased by 6.474% and 10.588% respectively after LSP with the same laser energy. On the other hand, composites with (2.5% and 5%) volume fraction manifested a reduction in the mechanical and fatigue strength especially when treated by 2J laser energy.

Keywords: *Fatigue Life, Endurance Limit, Fatigue and mechanical properties, Composite Materials, Laser shock peening, Polymer Matrix Composites.*

1. Introduction

Many researches have been prepared to study the composite materials and the enhancement of mechanical and fatigue properties. Composite materials are defined as the mixture of two or more constituents, and this is usually done at the microscopic scale without any soluble of one into another [1]. Polymers are usually reinforced with particles fillers to have a special mechanical and thermal properties. Polymeric composite materials; especially reinforced by fillers have a wide range of applications. These types of composites are used in the manufacturing as abrasive and cutting tools, internal parts of automotive & airplane, and for welding such a plastic welder of the breaking metallic component. This wide range of usage is

due to features such as minimum weight, slightly acceptable stiffness and easy to prepare [2].

Fatigue is widely defined as the relation between stress applied and number of cycles to fail. This failure is due to the micro cracks in the matrix material from first initiates, propagates and finally leads to failure [3].

LSP is a surface treatment process used to enhance the fatigue strength, metallurgical and mechanical properties of metal by treating and modifying the surface and introducing compressive residual stresses via high energy laser pulse impacting material's surface [4]. The behavior of peening process is different in composite materials, especially polymeric matrix composite (PMC) since it is basic consist of more than one constituent. Each one has roughly higher mechanical and metallurgical properties than the

other which causes various effects from point to point and leads to a complicated behavior that is hard to be predicted.

Aseel Jasim Mohammed [5] investigated of the laser treatment influence on the fatigue strength composite materials. The composite material that was used consisting of polyester resin as a matrix and 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 laser were used for this investigated (band and pules). The result observed that the fatigue strength after treatment was increased by about 23%. Mahdi N. M. Shareef [6] studied the effect of conventional shot peening on the fatigue life and mechanical properties of composite materials. Polyester/Al powder with volume fractions 2.5%,5% and 7.5% was used. Shot peening at three different durations was investigated. The result demonstrated that the mechanical properties of 7.5% Al powder were increased with rising shot peening time. Also, the fatigue results for 5% Al powder composites depicted, the fatigue strength was increased after 2 min shot time. For 7.5% Al powder composites, the fatigue strength was improved to maximum level at 4 min shot time. Ahmed N. Al- Khazraji et. al. [7] investigated of the shot peening effect on fatigue and mechanical properties of two types of composite materials. The first material was prepared from unsaturated polyester reinforced with fiber E-glass by 33% volume fraction. The other material was unsaturated polyester with 2.5% volume fraction of Al powder. The result was showed an improvement in mechanical and fatigue properties of polyester/fiberglass after shot peening process. On the other hand, the properties of polyester/Al powder were reduced after treatment. Alexander Becker [8] studied the effects of both (LSP) and shot peening (SP) on the fatigue strength using aluminum alloy in two conditions 7075-T6 and 7075-T0. The results displayed increase in the fatigue strength in both LSP and SP process compared with un-peened specimens. LSP doubled the fatigue strength and SP increased the fatigue strength about 1/6 compared to un-peened specimens. Also, the LSP exhibited no hardening effect determined, on other hand, the SP process showed a significant hardened area on the surface. Abdullahi K. Gujba et. al. [9] investigated the effect of LSP on the materials properties by using Q-switched laser beam pulses type to study the surface modification and showed that the LSP introduced a compressive residual stress about 4-5 times in depth across the surface of material than conventional SP techniques. Also, the

enhancement in fatigue and surface properties of steel and aluminum was revealed by dislocation peening effect at the dynamic precipitation. Fadhel Abbas Abdulla et. al. [10] studied the effect of ultraviolet irradiation on the fatigue life of the natural composites, the polyester resin was used as a matrix with egg shell, date nuclei and palms leaf as a reinforcement by using (20%, 40% and 60%) volume fraction. Ultraviolet was applied for three different times (100, 300, 500) hours. The result depicted that the increasing time of ultraviolet results in reduction of tensile and endurance stresses. Najwa J. Jubier et. al. [11] studied the effect of ultraviolet on the fatigue behavior of composite materials, by using epoxy with SiO₂ nanoparticles and different volume fractions (1%,3%,5%,7% and 10%) reinforced with 6 layers of chopped mat E-glass fiber. Fatigue behavior was investigated for un-irradiated and ultraviolet irradiated composites for (240 hours) at ambient temperature and stress ratio (R=-1). The results demonstrated the increasing in the fatigue strength after applying of ultraviolet radiation due to the formation of crosslinking structure. According to the literature review, there are little researches have been paid attention to study the effect of surface treatment and LSP effect of polymeric composite materials, and no published research was found which studied LSP effect on particulate composite materials. In this research paper will be investigated the influence of laser peening with water confined layer on mechanical and fatigue properties of polymeric composites reinforced by fillers.

2. Experimental Work

The experimental procedure which was used for this research preparation can be explain briefly as follow:

2.1. Preparation of the Specimens

The materials were prepared in a plate with size (300x280x4) mm according to Mahdi [6]. The matrix is unsaturated polyester resin and its properties are listed in Table (1). Aluminum powder was used as a reinforcement material and it's a filler with particles size (50-100) μm; Table (2) shows the properties of it. Hand lay-up technique was used for the fabrication process since it is easy and can be used to produce composites in different forms and sizes. The mold was made from clean glass, coated by Petroleum

jelly (Vaseline) and covered by Al foil to avoid the adhesion that happen between the materials and the mold. 1.5% MEKP (abbreviation to Methyl Ethyl Ketone Peroxide) from the volume of unsaturated polyester was added to the mixture and then Al powder was added during the reaction has begun. Composite materials were prepared with three different volume fraction of Al powder (2.5%, 5% and 7.5%).

Table 1,
The properties of polyester resin [12].

Density (ρ) (kg/m ³)	Elastic Modulus E (GPa)	Poisson Ratio (ν)
1211	1.0602	0.38

Table 2,
The properties of Al powder [13].

Density (ρ) (kg/m ³)	Elastic Modulus E (GPa)	Tensile Strength σ_{Ult} (MPa)
2700	71	60

2.2. Laser Shock Peening

Laser shock peening (LSP) process depends on several parameters, such as type of laser source, laser plasma pressure, loading time of laser-induced shock wave, material condition, and plasma confinement layer [14]. The laser plasma pressure can be predicted by the following equation when using water as a confining layer [15]:

$$P(GPa) = 1.02\sqrt{I_o} \quad \dots(1)$$

$$I_o = \frac{k}{t/A} \quad \dots (2)$$

Where (I_o) is the laser intensity (GW/cm²), (k) energy per pulse of laser beam, (A) spot area and (t) pulse duration. LSP usually done with laser intensity I_o reach by about several (GW/cm²) for the plasma pressure being enough for inducing of compressive residual stresses [15,16]. Q-switched Nd-Yag laser pulse was used to generate the shock wave on the surface of the specimen, Figure (1(a)). The peening procedure, which was used is to prepare this study, is the same as that followed in metals [17]. The surface was coated at the beginning with a black paint as a protective layer and to increase the efficiency of the energy absorption. Also, the specimen was submerged in water at a height about (2-3) mm from the specimen’s surface to work as a confining layer and protect the specimen’s surface from the high thermal energy that may happen, Figure (1(c)). LSP was applied on the two upper and lower surfaces. The parameters that used in this research study, are illustrated in Table (3), and the selection of these parameter was done to applied laser intensity between (1-5) GW/cm² according to equation (2). Figure (1(b)) shows the distribution of laser peening and the fatigue specimen after being treated by LSP.

Table 3,
The parameter of laser peening.

Energy (Joule)	Wave length (nm)	Water height (mm)	Pulse duration (ns)	laser intensity (GW/cm ²)
2	1064	3	7	4.04408
1	1064	3	7	2.02204

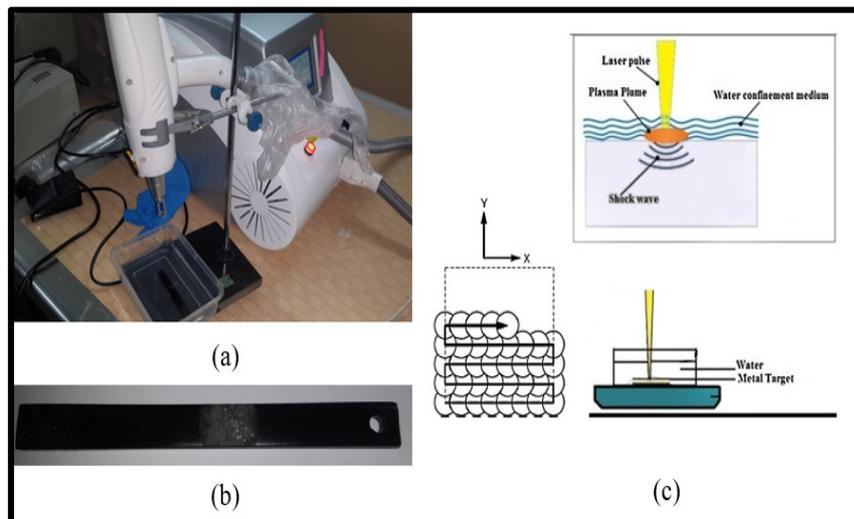


Fig. 1. (a) Q-switched Nd-Yag laser pulse, (b) Fatigue specimen when treated by laser peening and (c) Schematic diagram and basic principle of laser peening.

2.3. Fatigue Test

The fatigue test was done by using (bending-alternating HSM20, as shown in Figure (2)), it's available in the Department of Mechanical Engineering at University of technology/ Baghdad. This device is a strain-controlled fatigue and used by applying a constant deflection to end of the cantilever beam. The test was carried out at room temperature with zero mean stress ($R = -1$) and 25Hz frequency. The size and shape of specimens selected according to the machine's manual [18], as shown in Figures (3).

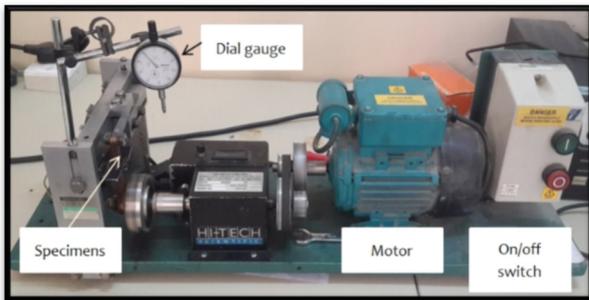


Fig. 2. Bending- alternating fatigue device HSM20.

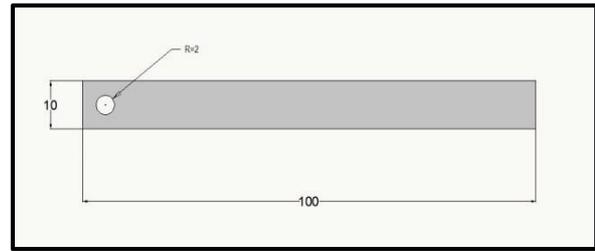


Fig. 3. Fatigue specimen according to the machine's manual [18] (all dimensions are in mm).

2.4. Tensile Test

The test was done to investigate the mechanical properties (ultimate stress and Young's modulus) before and after laser peening. The tensile specimens were cut and prepared according to ASTM D638 [19], shown in Figure (4), then tested and the results were obtained. The test was performed at speed (2 mm/min) by using (Tinius Olsen (H50KT)) which, is available found in Mechanical Engineering Department/ University of Technology- Baghdad.

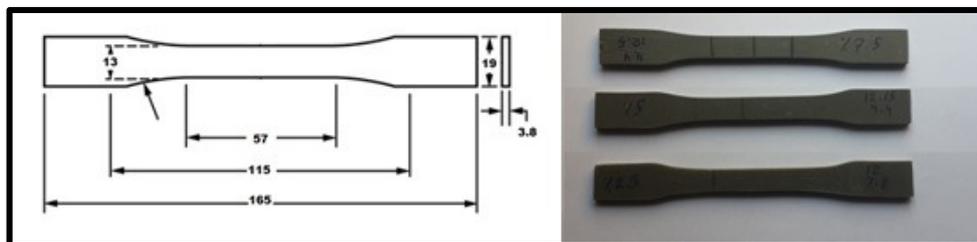


Fig. 4. Tensile specimens according to ASTM D638 (all dimensions are in mm).

3. Results and Discussion

Three samples of composite materials were prepared to study the LSP effect on the mechanical and fatigue properties. The testing was done before and after LSP treatment.

3.1. Mechanical Properties

Figures (5, 6, 7 and 8) and Tables (4 and 5) manifest tensile results of untreated and LSP treated polyester/Al powder composite materials under two levels of laser pulse energy (1J and 2J). Figure (5) shows stress- strain diagram for 2.5%, 5% and 7.5% volume fraction of Al powder. All the mechanical properties were increased with

increasing the volume fraction, this attitude is normal because of the rise of reinforcement material which leads to catch the matrix phase and give more binding, and was proved in many previous researches [6]. After treating by laser, Figures (6, 7 and 8) depict the comparison among un-treated stress-strain curve and those after treated by 1J and 2J laser pulse for (2.5%, 5% and 7.5%) volume fraction respectively. From Figure (6), it is obvious that all mechanical properties of 2.5% volume fraction were decreased with the increasing laser energy, and this behavior is due to cracks formation at the matrix material due to the high brittleness of polyester at low volume fraction which was weak to endure the shock wave. Figure (7) show the stress- strain curves for composite at 5% Al, and as clear, when 1J laser energy was used for LSP the mechanical properties slightly not

affected, but it decreased with amount approximately smaller than that observed with 2.5% volume fraction after the increasing of laser beam energy to 2J. This is an evidence that the composite material with this volume fraction became more resistance to the peening process. For 7.5% volume fraction as shown in Figure (8), the treatment by laser leads to increase the ultimate stress and the modulus of elasticity, and the best case was observed at 1J laser energy. This behavior is due to the thermomechanical process increased the adhesion among the two phases which construct this type of composite, and inducing compressive residual stresses into the matrix materials leads to microstructure change which increased the mechanical properties [9].

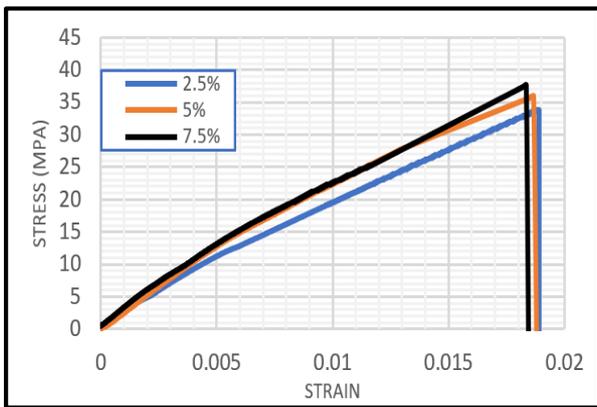


Fig. 5. Tensile results with different volume fractions.

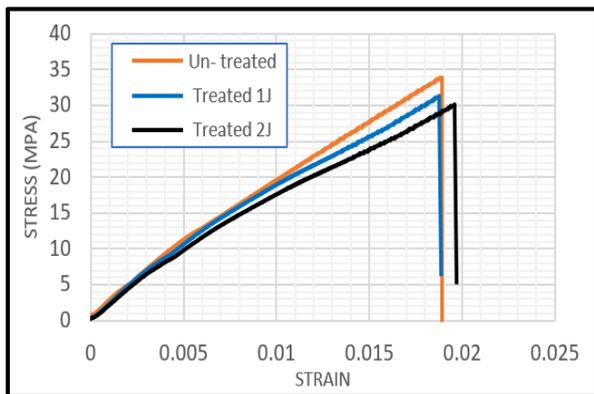


Fig. 6. Tensile results of 2.5% volume fraction with and without treatment.

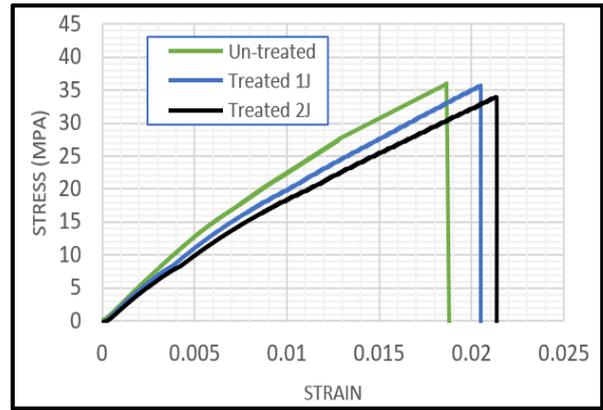


Fig. 7. Tensile results of 5% volume fraction with and without treatment.

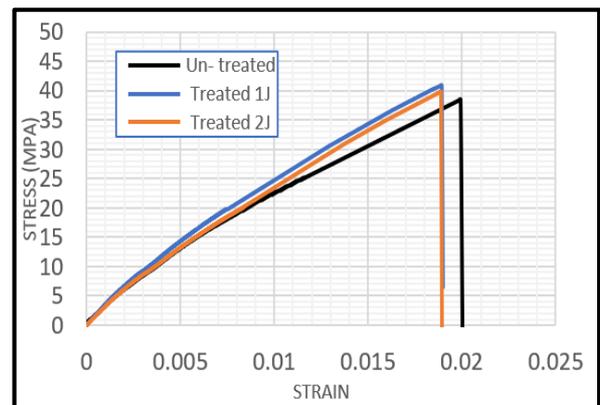


Fig. 8. Tensile results of 7.5% volume fraction with and without treatment.

Table 4, The mechanical properties of the composites (All values are in MPa).

Volume fraction (%)	Ultimate stress	Young's modulus
2.5	33.837	2170
5	35.91	2532
7.5	38.52	2921

Table 5,
The mechanical properties after treatment by laser.

Volume fraction (%)	Treated by 1 J		Treated by 2J	
	Ultimate stress (%)	Young's modulus (%)	Ultimate stress (%)	Young's modulus (%)
2.5	-7.474	-8.741	-11.002	-16.58
5	-0.556	-1.974	-5.43	-7.071
7.5	6.474	10.588	3.411	5.7925

3.2. Fatigue Life

Figure (9) elucidate the SN curves for different volume fractions of Al powder composite samples, and it is clear that 7.5% volume fraction have the higher fatigue strength comparing with 2.5% and 5%. This behavior due to as referred above that the increasing of reinforced material leads to more binding of the matrix and increased the fatigue strength [6]. Figures (10, 11 and 12) evince the SN curves with different laser energies at (2.5%,5%, and 7.5%) volume fraction, respectively. It is clear that for 2.5% and 5% Al powder composites, the increasing of laser beam energy leads to reduces the fatigue strength, and this reduction is due to the cracks that were happened into the matrix materials. The reduction in fatigue strength was clearly less at 5% volume fraction after LSP comparing with 2.5% volume fraction, also the using of 1J laser energy for peening the fatigue strength of composite with 5% Al powder slightly not affected. This was an evidence that the increasing in volume fraction gives the composite materials more resistance to the shock wave and crack initiation. Composite materials with 7.5% volume fraction exhibited an increase in the fatigue strength with the two values of laser beam energy, and the higher fatigue strength was obtained at 1J and then slightly reduced after using of 2J laser energy. LSP was increased the fatigue life of 7.5% volume fraction, this was mainly due to the thermomechanical process which produced by laser peening that reducing the tensile residual stresses through the surface, which in turn preventing crack initiation leads to increasing of fatigue strength [9].

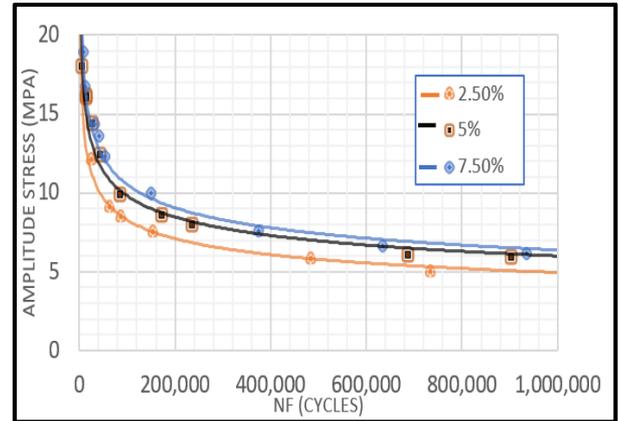


Fig. 9. SN curve of Polyester/Al powder with different volume fractions.

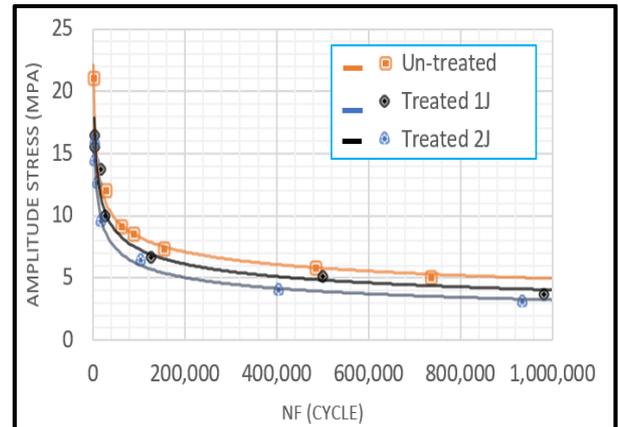


Fig. 10. SN curve of Polyester with 2.5% volume fraction Al powder when peening by laser energy 1J and 2J.

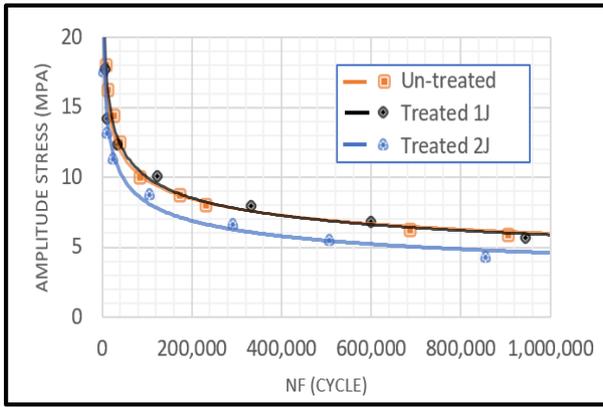


Fig. 11. SN curve of Polyester with 5% volume fraction Al powder when peening by laser energy 1J and 2J.

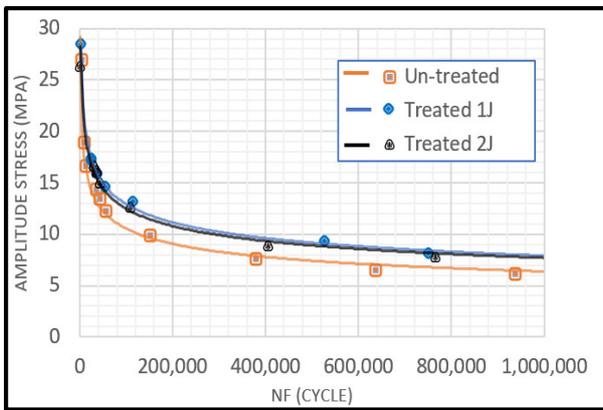


Fig. 12. SN curve of Polyester with 7.5% volume fraction Al powder when peening by laser energy 1J and 2J.

Table (6) shows the endurance strength of each type of composites with and without treated by laser which was calculated at 10^6 cycles by using

Table 6, Endurance strength before and after peening by laser.

%	Un-treated (MPa)	Treated by (1J)		Treated by (2J)	
		MPa	%	MPa	%
2.5	4.9657	4.0653	-18.133	3.1936	-35.686
5	5.9116	5.8761	-0.6	4.5981	-22.219
7.5	6.2919	7.8931	25.448	7.6886	22.197

4. Conclusions

The main points that can be concluded from the achieved results of the present research are:

1. Laser peening treatment of polyester/Al powder composites with 7.5% volume fraction increased the fatigue endurance strength by about 25% due to inducing of compressive residual stresses.
2. The ultimate stress and Young's modulus of

the following fatigue estimation equation (Basquin equation) [3]:

$$\sigma = A * N_f^{-b} \quad \dots (3)$$

Where A and b are constants. The endurance limit of 2.5% and 5% Al powder was reduced when treated by laser, and as shown the high reduction was occur at treated the 2.5% volume fraction composite with 2J laser energy, which reduced by about 35.686%. The reduction is slightly less for 5% volume fraction which was reach by about 22.219% at treated by 2J laser. On the other hand, the laser treatment enhanced the fatigue endurance strength at 7.5% volume fraction, which was increased by about 25.448%, and 22.197% when used by 1J and 2J laser energy respectively. Figure (13) also demonstrate the effect of laser beam energy and various volume fraction on the endurance strength of Polyester/Al, it's clear the resistance to crack formations by laser impact was increased with the increasing of volume fraction.

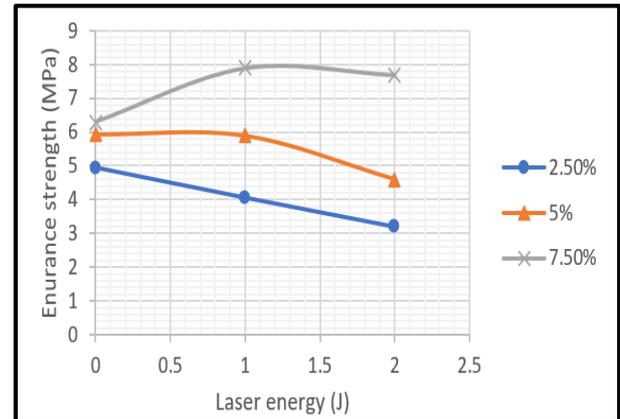


Fig. 13. Changing in endurance limit with increasing laser energy.

polyester/Al powder composites with 7.5% volume fraction were increased by about 6.474% and 10.588% respectively due to compressive residual stresses after treatment by 1J laser peening.

3. Laser peening process is not suitable for polyester/Al powder composites with 2.5% and 5% volume fractions, because it increases the cracks into the composites. So, it's not

recommended to use at these volume fractions of composites.

4. The resistance of polyester/Al powder to laser shock wave was increased with the increasing of volume fraction to 7.5%.
5. Laser peening with 1J energy accompanied by 7.5% volume fraction was the best state which increased the endurance strength and other mechanical properties.

5. References

- [1] Isaac M. Daniel and Ori Ishai, "Engineering mechanics of composite materials," New York Oxford, 1994.
- [2] Ibtihal A. Mahmood, Wafa A. Soud and Orhan S. Abdullah, "Effects of different types of fillers on dry wear characteristics of carbon-epoxy composite," *Al-Khwarizmi Engineering Journal*, Vol. 9, No. 2, pp. 85 -93, 2013.
- [3] Yukitaka Murakami, "Metal fatigue: effects of small defects and nonmetallic inclusions," Elsevier- Science Ltd, 2002.
- [4] Michael R. Hill, Adrian T. DeWald, Jon E. Rankin and Matthew J. Lee, "Measurement of laser peening residual stresses," *Journal of Materials Science and Technology*, Vol. 21, Issue 1, p.p.1-23, 2005.
- [5] Dr.Aseel Jasim 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, p.p 1-17, 2016.
- [6] Mahdi Noaman Muslim 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.
- [7] Ahmed N. Al- Khazraji and Mahdi 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.
- [8] Alexander Becker, "The Effect of laser shock peening and shot peening on the fatigue performance of aluminium alloy 7075," M.Sc Thesis, Center of materials engineering Department, University of Cape Town, South Africa, 2017.
- [9] Abdullahi K. Gujba and Mamoun Medraj, "Laser peening process and its impact on materials properties in comparison with shot peening and ultrasonic impact peening," *Materials*, Vol. 7, Issue. 12, pp. 7925-7974, 2014.
- [10] Fadhel Abbas Abdulla, Nader Majed Moustafa and Ammar Fadhil Hussain, "Effect of UV- radiation on fatigue behavior of natural composite materials," *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)*, Vol. 8, Issue 4, pp. 695- 707, Aug 2018.
- [11] Najwa J. Jubier, Kawakib J. Majeed and Ekram A. Ajaj, "Effect of UV Irradiation on Fatigue Behavior of Epoxy/ SiO₂ Nanocomposites Reinforced with E Glass Fiber," *International journal of application or innovation in engineering & management (IJAIEM)* Vol. 3, Issue 2, pp. 31- 40, February 2014.
- [12] Hull, D, "An introduction to composite materials," University of Liverpool, Cambridge university, England, (1981).
- [13] W. D. Callister, JR, "Materials science and engineering- an introduction," 6th Ed, John Wiely and Sons, Inc., New York, (2003).
- [14] Miho Tsuyama, Yasuteru Kodama, Yukio Miyamoto, Ippei Kitawaki, Masahiro Tsukamoto and Hitoshi 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.
- [15] Qiao Hongchao, "Experimental investigation of laser peening on Ti17 titanium alloy for rotor blade applications", *Applied Surface Science*, Vol. 351, 2015, pp. 524-530.
- [16] Omar Hatamleh, "The Effects of laser peening and shot peening on mechanical properties in friction stir welded 7075-T7351 Aluminum," *Journal of Materials Engineering and Performance (JMEPEG)- Springer*, Vol. 17, No. 5, pp. 688–694, October 2008.
- [17] 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, Conference. 1, 2016.
- [18] Alternating Bending Fatigue Machine Instruction Manual HSM20.
- [19] American Society for Testing and Materials (ASTM), "Standard test method for tensile properties /D638," *Annual Book of ASTM Standard*, 2003.

تأثير العصف بالليزر على سلوك الكلال و الخواص الميكانيكية للمواد المترابطة

احمد نايف ابراهيم الخزرجي* عمار عبدالإير طشر**

**، قسم الهندسة الميكانيكية/ الجامعة التكنولوجية

*البريد الإلكتروني: Dr_ahmed53@yahoo.com**البريد الإلكتروني: ammar1199011@gmail.com

الخلاصة

تهدف هذه الدراسة الى تأثير العصف بالليزر على المواد المترابطة البوليمرية حيث تمت دراسته بشكل عملي. كون ان المواد المترابطة البوليمرية شائعة الاستخدام بشكل واسع وذلك لسهولة تحضيرها ولامتلاكها خصائص فريدة وتم استخدام البولي استر غير المشبع مادة أساس، مع مسحوق الألمنيوم بحجم دقائق مايكروني كمادة مدعمة حيث استخدم لتحضير نماذج لمواد مترابطة وبكسور حجمية مختلفة (2,5%، 5% و 7,5%)، عملية القولية اليدوية استخدمت في تحضير النماذج باستخدام قالب من الزجاج. اختبار الكلال تم بسعة اجهاد ثابت مع نسبة اجهادات (R=-1) والذي تم قبل وبعد المعالجة الليزرية و مع استخدام طاقة ليزر مختلفة (J1 و J2). وظهرت النتائج زيادة ملحوظة بمقاومة الكلال في المواد المترابطة بكسر حجمي 7,5% حيث وصل مقدار الزيادة حوالي 25% عند طاقة ليزر J1. ان اعظم اجهاد ومعامل يونك قد ارتفع بنسبة حوالي 6,47% و 10,58% على التوالي بعد المعالجة الليزرية وبمستوى طاقة الليزر نفسها. اما بالنسبة للمواد المترابطة المدعمة ب 2,5% و 5% من مسحوق الألمنيوم فقد لوحظ بان الخصائص الميكانيكية ومقاومة الكلال قد انخفضت بعد اجراء المعالجة الليزرية وخصوصا عند طاقة ليزر J2.