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Comparison Between Confined and Unconfined Laser Peening Effect on the Fatigue Life of Composite Materials

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Abstract

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Confinement layer is considered as the most important parameter during the laser shock peening (LSP) treatment. In this paper, its effect on the surface treatment effectivity of composite materials was investigated. The composite used in this research was fabricated using hand lay-up as a manufacturing process. The matrix material was built from unsaturated polyester resin and reinforced with 2.5% volume fraction of micro particles of aluminum powder. Fatigue test was conducted at room temperature with constant amplitude stress and a stress ratio of R =-1, before and after LSP treatment. LSP was applied with and without confinement layer at the same level of energy after the specimens were coated with a black paint. The results manifested that the laser peening without confinement layer increased the endurance limit by about 13.296% compared with the untreated state. Whereas using water as a confinement layer during treatment reduced the endurance strength by about 18.133% compared to the untreated state. Also, it was observed that the difference between confined and unconfined LSP effects on the endurance limit was about 31.429%.

Keywords: Fatigue Life, Endurance Limit, Fatigue and Mechanical Properties, Composite Materials, Laser Shock Peening.

مقارنة بين تأثير العصف الليزري المخمد وغير المخمد على عمر الكلال للمواد المركبة

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الخلاصة

تعتبر طبقة التخميد ذات أهمية كبيرة أثناء المعالجة بالعصف الليزري (LSP). في هذا البحث ، تم دراسة تأثيرها على فعالية المعالجة السطحية للمواد المتراكبة. تم تصنيع المادة المتراكبة المستخدمة في هذا البحث باستخدام القولبة اليدوية كعملية تصنيع. المادة الاساس هي راتنجات البولي استر غير المشبعة ، معززة بدقائق من مسحوق الألمنيوم وبحجم حبيبات مايكروي بكسر حجمي بنسبة 2.5٪ . تم إجراء اختبار الكلال في درجة حرارة الغرفة مع سعة إجهاد (R = −1) ، وقد تم ذلك قبل وبعد المعالجة الليزرية. تم تطبيق العصف الليزري مع وبدون استخدام الماء كطبقة التخميد ضمن نفس المستوى من طاقة الليزر بعد أن تم طلاء العينات باللون الأسود. أظهرت النتائج أن المعالجة الليزرية بدون طبقة تخميد ادت إلى رفع حد التحمل بحوالي (13.296٪) مقارنة بالحالة غير المعالجة. في حين أن استخدام الماء كطبقة تخميد أثناء المعالجة يقلل من قوة التحمل

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بنحو (18.133 ٪) مقارنة بالحالة غير المعالجة. ولوحظ أيضًا أن الفرق بين تأثير العصف الليزري بوجود وعدم وجود طبقة تخميد على حد التحمل كان بحوالي (31.429٪).

1. Introduction

Laser shock peening (LSP) is one of the advanced surface treatment processes usually used for hardening or strengthening the surface to enhance fatigue strength and metallurgical and mechanical properties of metals by introducing compressive residual stresses using a high intensity laser pulses impact upon the material's surface [1]. The basic principle of LSP is that, when the laser falls on the surface of a metal, it will be ionized to produce plasma pressure. The surface is usually covered with black paint or aluminum foil as an ablation layer to absorb the laser energy and protect the surface from the high pressure. This process may be performed with or without confinement layer. The confinement layer is usually made of water, which exists to confine the plasma pressure against the surface for inducing compressive residual stresses into the material. The unconfined condition is performed without water or any other confinement and applied using a warm LSP to harden the surface, which in turn reduces the tensile residual stresses. Also, the confinement layer is known as a transparent overlay and it has an important role in increasing the impact pressure through the LSP process [1, 2, 3].

Composite material is a special case of materials that consists of the mixture of more than one constituent, where the base material is called the matrix whereas the added material is called the reinforcement [4]. Commonly, to achieve a polymer material with specific mechanical and thermal properties it must be reinforced with some special material that usually involve particle fillers. Polymeric composite materials are used in industrialization, such as abrasive and cutting accessories, internal parts in automobiles and airplanes, and in welding as in the plastic welder of the breakage metallic component. Their wide range of applications is because of the special attractive features they own, such as minimum weight, simplicity in preparation, and generally acceptable stiffness [5, 6].
Composite materials are basically different from metals, so that the action of the treatment process is different. Specifically, polymeric matrix composite (PMC) is made up of more than one constituent with roughly very highly different mechanical and metallurgical properties.

Mohammed [7] studied the laser treatment influence on the fatigue strength of composite materials using a direct ablation method. The composite material consists of polyester resin as a matrix and is reinforced with fiber e-glass in the form of laminate composite material with four layers. Composites with unidirectional fiber orientations, including [+45/-45]s and [0/90]s, were introduced. Laser with two types (continuous and pulses) was investigated where the fatigue strength was enhanced after treatment by laser. Alakawi et. al. [8] investigated the LSP effect of different ablation and confinement layers on fatigue life. Aluminum alloy was used to achieve their aims. Fatigue with constant rotating bending stress and a stress ratio of R=-1 at room temperature was applied using laser peening technique. The treatment was carried out with air laser peening (ALP), water laser peening (WLP) and black paint laser peening (BPLP). The results showed that the BPLP was more effective as compared to WLP and ALP. Also, it was observed that the treatment with ALP reduced the fatigue strength. Takata et. al. [9] studied the effects of the confinement layer on laser ablation and Cavitation Bubble through laser peening. LSP process was used with short pulsed laser focused and irradiated to the material covered by transparent overlays such as glass or water. Acoustic Emission (AE) technique coupled with high speed camera was applied to investigate the effects of the confinement layer on the LSP process. The results showed that confinement layer parameters such as temperature, thickness and viscosity had strong effects on the formation and collapse of the cavitation bubble. Polese et. al. [10] investigated water confinement on LSP process, using laser pulses with short duration and high intensity to initiate shock wave for compressive residual stresses, inducing on the surface of the metallic component. The implosion of a single spherical bubble was experimented via the laser induced optical breakdown using a Q-switched Nd:YAG laser. The dynamics of the process were studied in distilled water by the shadowgraphy technique. The results indicated that the application of LSP requires a water layer with the purposes of confining and enhancing the maximum pressure pulse to the metallic component. From the literature, it can be observed that little research was dedicated to study LSP effect on composite materials. No study investigated the confinement effect on laser effectivity during LSP process of composites. Therefore, in this research, the confinement layer effects during composite material treatment by the laser are studied.

2. Experimental Work

2.1. The manufacturing process of the specimens

The composite material was prepared in the form of a plate with a size of 300x280x4 mm according to Mahdi [11]. The matrix material was made of unsaturated polyester resin with a thermoset polymer type, the properties of which are listed in Table-1. Aluminum powder was used to reinforce the matrix at 2.5% volume fraction, as a filler with microparticles size of 50-100 µm, the properties of which are shown in Table-2 . Hand lay-up technique was used for fabrication since it is considered as easy and can be used to produce composites in various forms and sizes. Clean glass was used to make the mold, which was then coated by petroleum jelly (Vaseline) and wrapped by aluminum foil to obviate the adhesion that occurs between the casted material and the mold. 1.5% Methyl Ethyl Ketone Peroxide (MEKP) from the total volume of unsaturated polyester was appended to the mixture and aluminum powder was then added upon the beginning of the reaction.

Table 1-The properties of polyester resin [12]

Density (□□ (kg/m^3)	*Elastic Modulus E (GPa)*	*Poisson Ratio (□□*
1211	1.0602	0.38

Table 2-The properties of Al powder [13]

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

2.2. Laser shock peening

LSP process generally depends on different parameters, such as the laser source, laser plasma pressure, laser duration, material type, and confinement layer [14]. The pressure of plasma that is induced using laser peening can be calculated by the following equation [15]:

$$p = 0.01\sqrt{\frac{\alpha}{2\alpha+3}}\ \sqrt{Z\, I_o} \qquad \text{….(1)}$$

$$I_o = \frac{k}{t/A} \qquad \text{…. (2)}$$

where (p) is the maximum pressure (GPa), I_0 is the laser power intensity (GW/cm^2), (α) is the interaction's efficiency, (Z) is the shock impedance, (k) is the energy per pulse of laser beam (Joule), (A) is the spot area (m^2), and (t) is the pulse duration (seconds). During the interaction, the total laser energy is transformed into two parts; the first part of the energy contributes to the establishment of the pulse pressure, whereas the other part is cooperative to the ionization and formation of plasma. Thus, generally, the efficiency of the operation is commonly between α= 0.2–0.5. The combined shock impedance can be predicted as follows [16]:

$$\frac{2}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} \qquad \text{… (3)}$$

where Z_1 and Z_2 are the shock impedance values for the material and the confinement, respectively. Since the material conditions are constant, the maximum pressure totally depends on the impedance of the confinement layer. If a confined ablation layer with water overlay is utilized in the process, the maximum pressure is approximately the square root of the incident laser power density [16]. Whereas the presence of the confining overlay reduces the maximum generated pressure.

Experimentally, the generation of laser pulses was accomplished using a laser device (type Q-switched Nd-Yag), as shown in Figure-1(a). The surface was first coated with a black paint to increase the energy absorption efficiency. The treatment was then carried out with the two laser parameters; for the first one, the specimen was immersed in water to work as a confinement layer and to protect the specimen's surface of the high thermal energy that had generated. In the second method, the specimen was impacted by the laser directly without any confinement layer. The application of LSP was performed on the two upper and lower specimen's sides. Table-3 illustrates all the parameters that were used in the preparation of this study. Figure-1(c)) shows the distribution and method of laser peening process, while Figure-1(b)) shows the fatigue specimen when being treated by LSP.

Table 3-The parameters of laser peening

Energy (Joule)	Wave length (nm)	Water height (mm)	Pulse duration (ns)	laser intensity (GW/ cm^2)
1	1064	No	7	2.02204
1	1064	3	7	2.02204

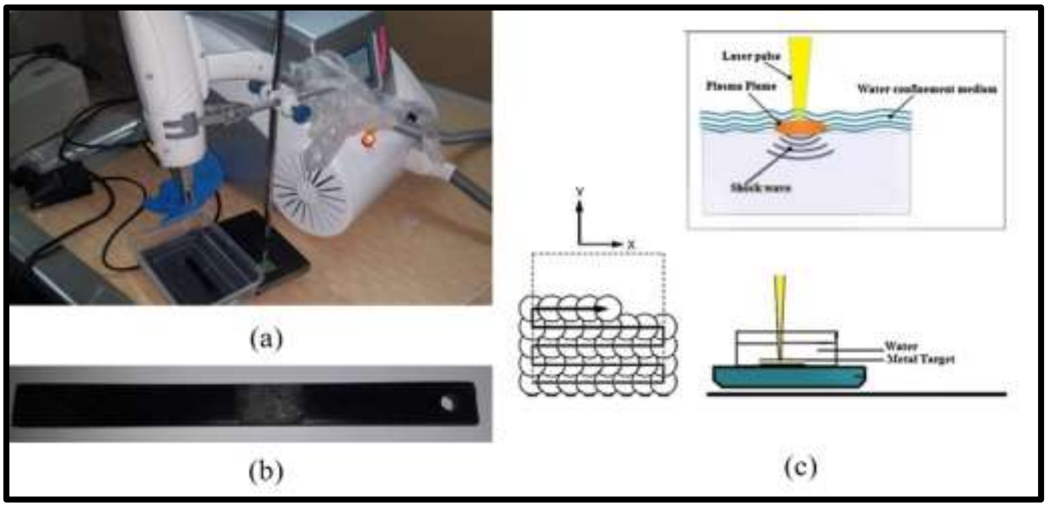

Figure 1(a)-Q-switched Nd-Yag laser pulse, (b) Fatigue specimen when treated by confined laser peening and (c) Schematic diagram and basic principle of laser peening [16]

2.3. Fatigue test

The fatigue behavior is defined as the number of cycles that a component can be endued during being subjected to dynamic load [17]. The fatigue test was carried out by using bending- alternating HSM20, as shown in Figure-2, in the Department of Mechanical Engineering at the University of Technology/ Baghdad. This instrument is strain-controlled fatigue and work by subjecting the end of the cantilever beam to a constant deflection. The test was accomplished at room temperature with zero mean stress (R= -1) and 25Hz frequency. The dimensions of fatigue's specimens were performed according to the machine's manual [18], as shown in Figure-3.

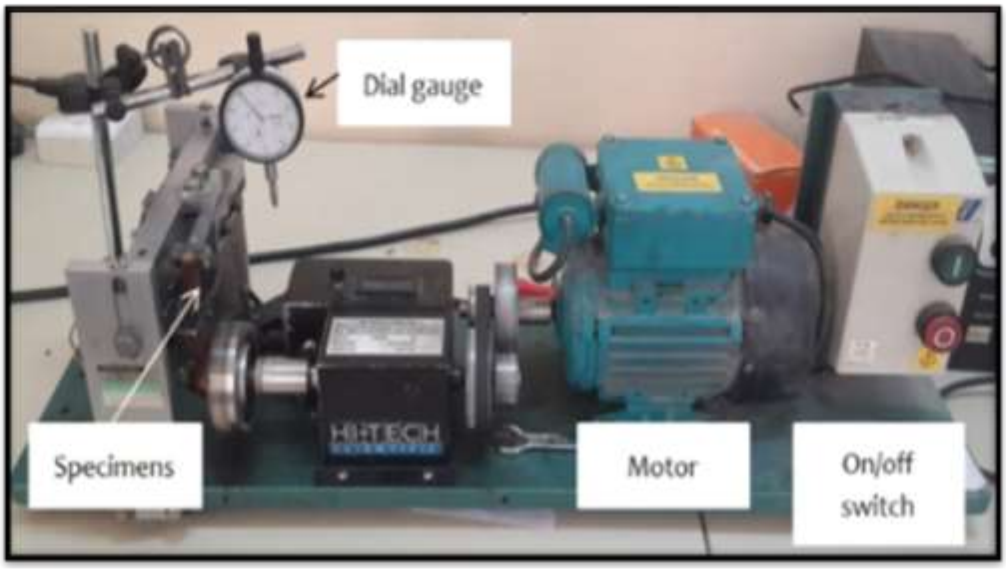

Figure 2- Bending- alternating fatigue device HSM20.

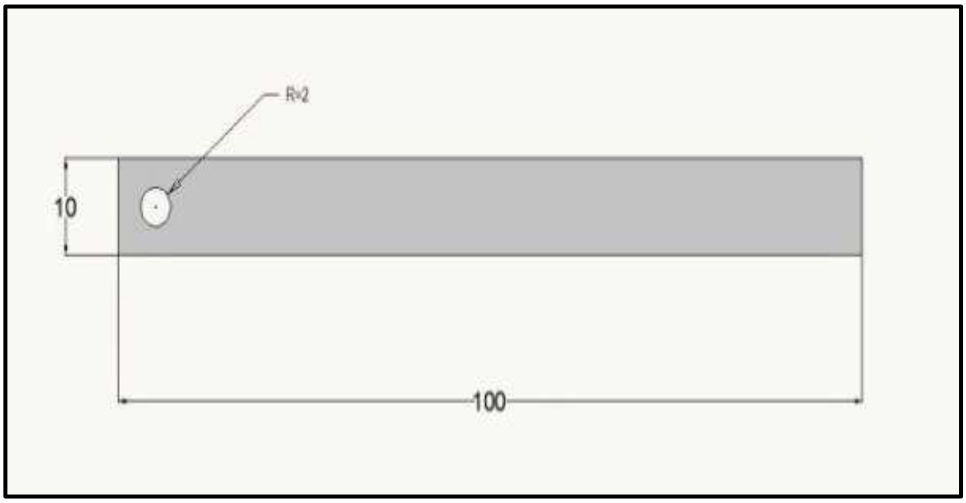

Figure 3- Fatigue specimen according to the machine's manual [18] (all dimensions are in mm).

The endurance strength of the selected composite material, with and without treatment by laser peening, was determined at (10^6) cycles by the following fatigue fitting equation (Basquin equation) [17]:

$$\sigma = A * N_f^{-b} \qquad \ldots\ldots (3)$$

3. Results and Discussion

Figure-4 demonstrates the S-N curve of polyester reinforced with 2.5% volume fraction of aluminum powder. Alternating bending fatigue was carried out for data obtaining, where each point was tested with more than one specimen for more accuracy. Baquine equation was used for curve fitting, which can be described the by following equation:
$y = 108.14x^{-0.223}$

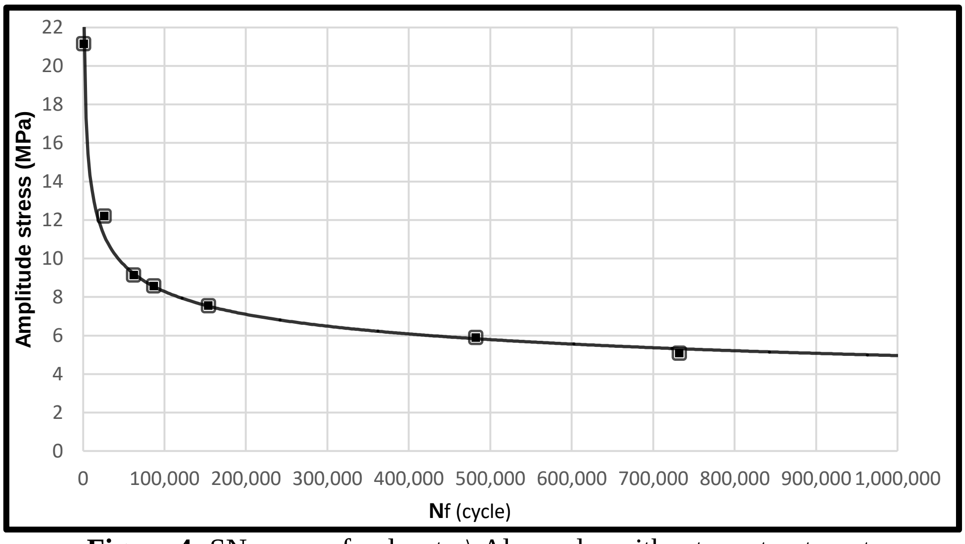

Figure 4- SN curve of polyester\ Al powder without any treatment.

Laser peening treatment was conducted to observe the effect on fatigue strength. Confined and unconfined laser peening conditions were investigated and the results were obtained to make a comparison between the two states. Laser peening with 1J energy for the two states was maintained.
The presence of water confines the plasma pressure against the material, which leads to an increase in the compressive stress. Figure-5 demonstrates fatigue results in the form of S-N curve before and after laser treatment of the composite with a water confinement layer. Table-4 illustrates the endurance limit of different states with the percentage change. The results showed that after treatment of the composite material, a reduction happened in the fatigue strength and the endurance limit was reduced

by about 18.1332%compared with the standard state. This behavior was due to the high pressure which is confined and produces high stress, leading mainly to increase the tensile residual stress, lead to cracks initiation into the composite reduced the fatigue strength.

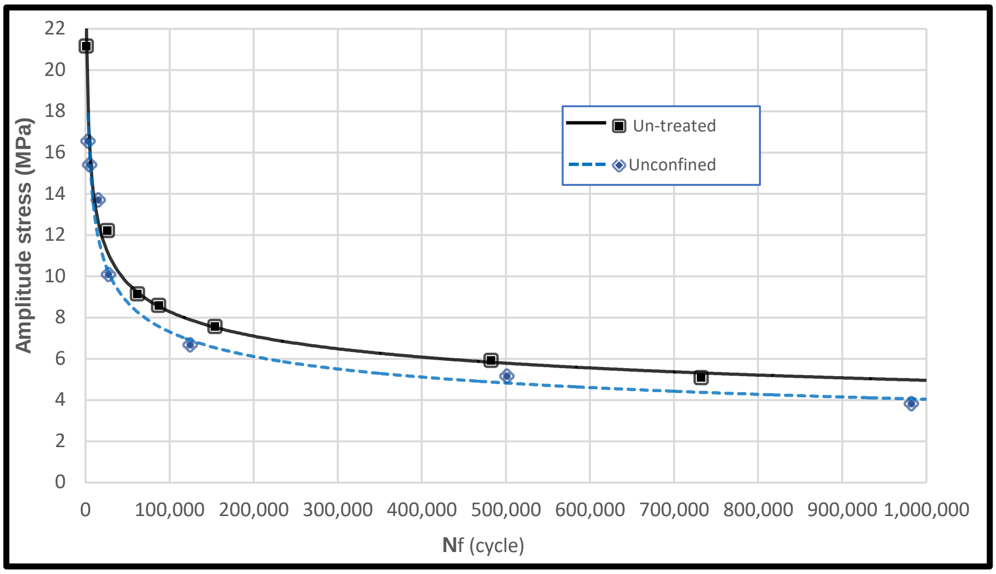

Figure 5-Comparison between SN curves of polyester\Al powder without and with treatment by water confined laser peening.

The absence of any confinement material reduced the pressure while increased the instantaneous temperature, providing a thermo-mechanical treatment to the surface during peening. Figure-6 shows the S-N curves before and after treatment by laser without any confinement layer. The results revealed an increment in the endurance limit of the composite material by about 13.296% compared with untreated state. It is evidence that a compressive residual stress was induced due to the thermomechanical process. Also, as obvious in Table-4, the confined laser peening with 1J energy reduced the fatigue strength, whereas the unconfined laser peening with the same energy increased the fatigue strength. This behavior is due to the observation that laser peening in the presence of water as a confinement layer produces high pressure against the surface and reduces the instantaneous thermal energy, making it a cold process that gives the composite more tensile residual stress and more cracks into the matrix materials. On the other hand, the process without confinement layer and the same laser energy produces less pressure against the surface with a high instantaneous thermal energy, causing stress relaxation, while more compressive residual stress into the matrix leads to reducing the probability to crack initiation.

Figure-7 manifests the S-N curves of the confined and unconfined LSP. By comparing these results with each other, it can be observed that there was an approximately great difference in strength between the two states, since the confined LSP reduced the original fatigue strength whereas the unconfined LSP increased fatigue strength. The difference between the endurance limit values of the two states reached about 31.4292%, and that was big in influence on the materials of the two parameters one of them destructive and the other beneficial. This is an evidence of the significant effects as well as the difference in the final induced residual stresses into materials due to the two processes.

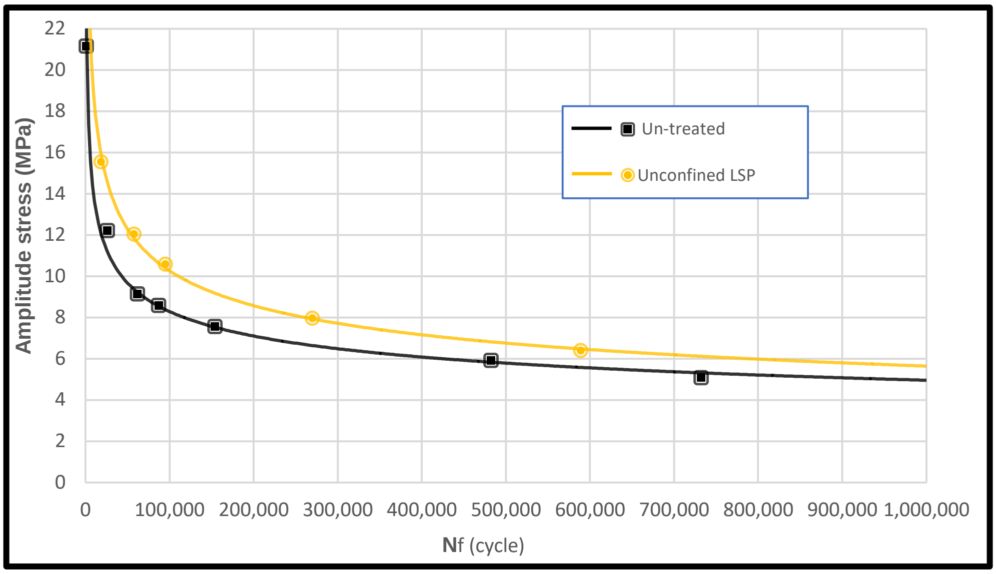

Figure 6-Comparison between S-N curves of polyester\ Al powder without and with treatment by unconfined laser peening.

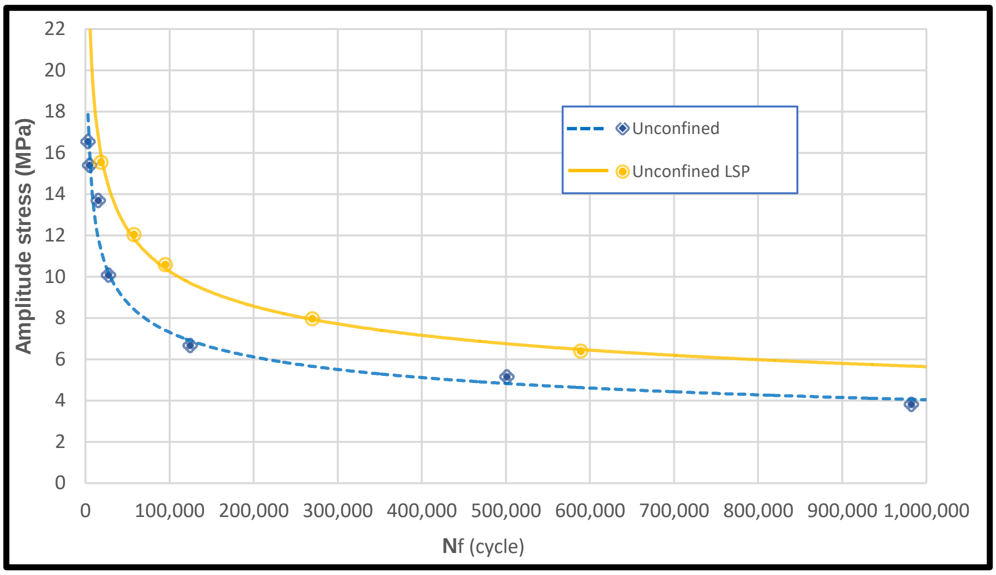

Figure 7-Comparison between S-N curves of polyester\ Al powder after treatment by unconfined and confined laser peening.

Table 4-The endurance strength before and after laser treatment

Untreated state	Confined treatment		Unconfined treatment	
MPa	MPa	%	MPa	%
4.965767311	4.065312382	-18.1332	5.626062972	13.296

4. Conclusions

The results of this study showed that the treatment of composite materials with 2.5% volume fraction by laser without using any confinement layer increased the fatigue strength. On the other hand, using water as a confinement layer when treating the composites reduced the fatigue strength. Also, showed that the unconfined laser shock peening is better than confined laser shock peening due to its beneficial effects on fatigue strength in this type of composite. Finally, the difference in endurance limit due to the confined and unconfined LSP was slightly high which refers to the remarkable difference between the two laser parameters.

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