Experimental Investigation of Laser Shock Peening Effects on Mechanical and Fatigue Properties of AA7075- T651 Utilizing Two Confinement Liquid Layers

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ABSTRACT
A well-recognized technique for producing compressive residual stresses beneath the surface of metal is laser shock peening (LSP), which increases the material's durability to wear and corrosion and improves fatigue life. Comparing LSP to traditional mechanical shot peening, it provides a more dependable surface treatment and may minimize microstructural damage. This surface treatment method involves directing a powerful laser pulsation at the superficial in extremely tiny pauses. Due to the capabilities available in this alloy AA7075-T651. As an important formability, automation and corrosion resistance, it will certainly have very large uses, including aircraft structures, and to improve the properties of this alloy, this technical method was used. The treated surface of Al-alloy 7075-T651 was made harder and more desirable during this investigation by employing a novel approach that involved the use of pure water and hydrofluoric acid (HF) as confinement layers. It was found that applying Hydrofluoric Acid (HF) significantly extended the pieces' fatigue life after laser peening as compared to unpeened specimens and pure water. Additionally, the Vickers hardness test results revealed that LSP with the utilized two confinement liquid, as well as unpeened samples, exhibited hardness values of 153HV30, 121HV30, and 94HV30, respectively, demonstrating a substantial improvement in hardness properties.
The test results show that, when compared to unpeened samples, every site of interest deal with the in-elevation cycle fatigue zone by LSP with two confinement liquid achieved a considerable improvement in life and strength, arriving at 88%and 72%, respectively. The SEM images showed that the untreated specimens had surface crack initiation location. The peened specimens showed two regions, the hardened and non-hardened region. The depth of the hardened area of the peened specimens was measured. The results of the experiment support the assumption that peening increases the fatigue life of alloys. The hardened surface and compressive residual stress field created by peening make it harder for cracks to initiate and propagate.

Keywords: AA 7075-T651, Acid, fatigue, Laser shock peening, Pure water, SEM.

NOMENCLATURE

AA	Aluminum Alloy
ASTM	American Society for Testing and Materials
LIP	Fatigue life improvement factor
LSP	Laser Shock Peening
L–H	Low–High
H–L	High–Low
HV	Vickers Hardness
HF	Hydrofluoric acid
IP	Percentage of improvement
mj	Millijoule
Mpa	Megapascal
R	Stress ratio
RT	Room temperature
SIP	Fatigue strength improvement factor
S–N	Stress–Number of cycles
SP	Shot peening
T651	Heat treatment process
σ_f	Stress to fatigue
f	Fatigue

INTRODUCTION

The method involves the generation of compressive residual stress near to the treated component surfaces by utilizing laser-produced power pulses, thus extending the fatigue life expectancy, has seen almost 40 years of continual development. This method has garnered increasing attention due to its demonstrated benefits in various successful applications within the aerospace and industrial sectors (A. H. Clauer,1983). A smaller amount microstructural impairment, deeper dispersion of the compressive residual stress beneath the superficial, and more organization in the application process are some advantages of LSP over traditional peening (C. Montross et al, 2002). It is noteworthy that it is also feasible to execute LSP without incorporating an ablative layer, wherein the surface alloy itself undergoes vaporization. Nonetheless, the circumstance may be significantly more intricate in this instance and across all instances, it may necessitate a comprehensive resolution and elucidation of a multi-physics quandary.

LSP's influence on fatigue properties was investigated in slotted 7075-T6 aluminum alloy plates (X. Zhang et al, 2015). Application of LSP on both sides of the slot led to micro-dents and compressive residual stresses, resulting in delayed micro-crack formation, altered fatigue crack initiation location, and reduced fatigue striation spacing. Consequently, the fatigue life of treated specimens was significantly increased. In another study, the efficiency of LSP on uniform samples with varying widths was explored (V. Granados-Alejo et al, 2018). At the life of fatigue, significant improvements appeared on the examination samples up to 300%, these results show the outcome of LSP on those samples. The microstructure and tensile of the sample 2024-T351 were examined also. (Troiani, E., Zavatta, 2019). LSP without Coating is used on the superficial of a notch in samples prepared of 6082-T6 AA. Three-point bending fatigue tests are used to evaluate the treated specimens, and their fatigue life is compared to that of unprocessed samples of duplicate geometry. The fatigue life of the processed samples is estimated to be 1.7 to 3.3 times extended. The measurements of Brinell hardness show that the surface hardness increased by approximately 50% after the treatment. and compressive residual stresses are calculated. At the notch, stress can extend up to -210 MPa.

(Y. Gao et al, 2021). Through LSP, which generated surface roughness and residual stress as crucial factors in enhancing fatigue properties, and this research indicated the outcome of surface properties on fatigue manners as the LSP was affected on the resistance of corrosion of AA 5083 (Y. Yang et al, 2019). Tests of corrosion behavior, surface morphology and electrochemical properties showed that there was an improvement in surface properties and corrosion resistance, indicating that LSP without an ablative coating has the potential and strong ability to improve corrosion resistance and microstructural of 7075 aluminum alloy (Zhang, J., Cheng, X., Xia, Q., & Yan, C., 2020). In this study, because of using the LSP method, a residual compressive stress layer was stimulated on the superficial, where the results showed that the average size of the affected grains due to this method was refined to 30-20 μm using this technique. Improvement of grain and residual compressive stress is able to enhance the strength and fatigue properties of AA 2024-T351 (X.-k. Meng et al, 2020).

To increase fatigue life through reduced crack initiation and growth rates, in the context of fastener holes, LSP treatment led to treatment of refined grains, compressive residual stress and nano hardness. All this was finalized by examining the outcome of this technique on the fatigue properties of the AA 2024-T3 (R. Sikhamov et al, 2020). As a result of the use of LSP technology, the deep compressive pressures resulting from this technique enhanced the life of fatigue and presented a restorative effect on fatigue cracks, as the healing range was linked to the length of the initial crack. Finally, the fatigue properties were verified using this technique by examining the corrosion joint welded of L316 stainless steel. Furthermore, (Sanchez, A., You, C., Leering, M., Glaser, D., Furfari, D., Fitzpatrick, M., Wharton, J., & Reed, P., 2021) In the same direction of this research, for AA7075-T651, a (LSP) handling was applied to maximize fatigue improvement. Micro-hardness, SEM-EBSD, and microstructural characterization techniques revealed that LSP surface amendment was restricted and that LSP created profound compressive residual stresses reach to −300 MPa.

Also, this study (Ding, X., Ma, S., Zhang, J., Jiang, Z., Li, H., Wang, S., Wang, C., & Zhong, J., 2023) examines how laser shock peening improves a material's properties through simulation and experimentation. The following are the primary findings: The results of the fatigue test demonstrated that, with the 3J procedure having the greatest impact, laser shock peening can significantly progression the example's fatigue life under the same stress load. The 3J procedure has the best grain refinement effect, according to EBSD analysis. The measurement outcomes of the X-ray diffraction technique confirmed the sound effects of LSP. Besides, (Wang, C., Shu, B., Zhang, L., & Ren, H., 2022) This study examines the AA 2024-T351's laser shock force, which is determined using a PVDF piezoelectric sensor. The finite element model in ABAQUS software is used after the pre-stressed laser peening forming experiments are carried out. It has been confirmed that the numerical model is a useful tool for observing the equivalent plastic strain and impact pressure.

According to the findings, the load subroutine in conjunction with a simulation model that loads laser pulses can increase computation accuracy by 15.6%. Moreover, (Abeens, M., Muruganandhan, R., Thirumavalavan, K., & Kalainathan, S., 2019) This research laser taking dissimilar pulsation energies of 200, 300 and 400 mJ with black paint and water as the ablative layer and confinement layer individually are utilized to reconsideration the variations in the mechanical properties. A distorted film thickness of about 500 μm with hardness of 236 Hv at the surface is attained with pulse energy of 400 mJ. Moreover, the determined compressive residual stress prompted in the sample is 317 MPa and a wear rate of 1.18×10^{-6} g m^{-1} is measured. Additionally, (Hassan, S., Hamzah, M., & Abed, R., 2018) This investigation used a novel technique to harden and enhance the handled surface of AA 7075-T6: pure water and acid (HF) as a coating layer. When compared to unpeened specimens, the life of fatigue of laser-peened samples increased to 154.3% and 9.78%, correspondingly, for (HF) and pure water. Likewise, a considerable improvement in the hardness property was demonstrated by the results of the Vickers hardness test for laser shock peening with acid, pure water, and unpeened samples, which were 165.2HV30, 143.95HV30, and 134.7HV30, respectively. Finally, the effect of LSP on welded 316L stainless steel joint corrosion resistance was investigated (Y. Li et al, 2022). Optimal corrosion resistance was achieved after two peening treatments, with subsequent declines attributed to stress changes and microstructural transformations.

This literature review examines the outcome of laser shock processing (LSP) proceeding various mechanical and properties of corrosion of different metallic alloys. Laser shock peening (LSP) is a well-established surface treatment method that induces compressive residual stresses and microstructural changes in materials. The research literature clearly shows that there are modifications and enhancement in the characteristics. of the alloy used in this research with a large similarity in the method of research and the use of similar tools and devices for different alloys. The determination of this research is to scrutinize how the utilized acid and pure water affect the fatigue properties of laser by covering their surface layer. As a distinct and influential tool and using acid technology that has an effect and has not been used previously.

EXPERIMENTAL WORK

A typical aluminum alloy used for aircraft structural components and other extremely demanding structural applications is aluminum 7075-T651, which was used as the test material in this study where high strength and excellent corrosion resistance are essential. The workpiece's profile and dimensions were in accordance with the (DIN 50133) standard, as depicted in Fig. 1. At the State Company for Inspection and Engineering Rehabilitation, in Baghdad, experimental examinations were carried out. Tables 1 – 2 represent the chemical composition and the properties The AA7075-T651. The generation of the S-N curve for each instance listed in the test design is the principal objective of the investigative testing. As shown in Fig.2, a reverse cyclic bending loading test was carried out at various cycle rates utilizing the AVERY fatigue testing mechanical apparatus. Based on the bending moment and deflection angle applied to the specimens, the applied load was determined. An engine was connected to a revolution mechanical counter in order to record the number of cycles.

LSP process

There are numerous ways to boost the laser's absorption power. Water is used for acting as a suppression layer. This power can be increased by using black tape on the workpiece's surface with precision. This is a surface-pulsed, high-energy laser pulsation. The process primarily concentrates on proceeding the laser pulses to display a degree of distortion or plasticity, enabling the material's surface to acquire quality by introducing compressive residual stress. The process is complicated because it comprises water-abetted, laser-prepared, besides the utilize of an absorptive film, which all have an additional impact. First, the surface that must be treated with is shielded with a layer of black absorbent tape. In any case, the absorptive coatings allow the alloy to absorb the laser pulsations. Following, the treated surface of the item to be peened is ready for the clean water streaming or stagnate to pour over it. Third, the substance to be peened is targeted by the laser's remarkable beat.

Like a shot (bead) in shoot peening, these pulses of laser power. To enhance the potency of the laser that touches AA 7075-T651, (HF) acid was employed in this work. This layer's treated surface vaporizes and continues to absorb energy, producing plasma. The water protects the plasma's extension, causing a very quick increase in pressure that causes a shockwave to form inside the material and plastically deform the near-surface area. To avoid the acid-alloy reaction, apply a 100 µm layer of nylon-based to the workpiece's substrate. put 1-2 mm of the utilized acid on the workpiece's touched section, as illustrated in Fig.3. The piece of work is then covered with black adhesive tape.

Using 200 emery paper, the sample surface was levelled to provide Ra (average roughness) about o.6 µm, this action preceding to the laser handling. Related to alternative mechanical shoot peening equipment, there are perfect advantages that let laser shock peening to remain a considerably more popular procedure. And this can be referred to through, the residual compressive stress in the samples is completely greater than that caused by processing than the rest of the treatment. It can also be seen that the roughness of the laser-handled surface is better than the rest of the treatments. Note that laser treatment does not need to be changed and modified in the equipment used, unlike the rest of the known treatments. It can also be noted that the laser treatment is remote, stable and can be repeated accurately, which gives quality and accuracy in the results.

Device of laser peening usage

The Q-switched neodymium YAG laser (Nd: YAG laser) was employed as a laser appliance to generate a toughened surface on the samples. The laser system utilized for laser peening is represented in Fig.4. The properties of the laser include a wavelength of approximately 1.065 µm, a pulse duration of 7 nanoseconds, a pulsation energy of 300 mJ, and a typical laser spot diameter of 5 mm.

Device of SEM

A comparison of scanning electron microscopy (SEM) images taken from treated and untreated specimens of AA 7075-T651 is presented and discussed in this paper. As shown in Fig 5-6. SEM observations of the specimens' surfaces reveal a variety of changes. Fatigue failures usually start at the surface, where bending loads cause the highest cyclic stress amplitudes. The fracture surface of AA 7075-T651 treated by LSP with HF acid is characterized by a small density of deep dimples due to the highly ductile nature of this alloy. In addition, it is noticed that the surface nonhardened layer reveals striations, and micro voids are coalescing due to localized fracture deformations. Two regions, the hardened and non-hardened region, have appeared. The depth of the hardened region is 0.919 mm.

RESULTS AND DISCUSSION

Compressive residual stresses induction

Black adhesive tape was used to cover the area that needed to peened, which was the target of the shocks, which serves as both a thermal securing covering and an ablative. For the purpose to absorb the vitality and thermal shock from the laser pulse, water was allowed to stagnate over the specimens. Photon transmission into the liquid, it produces plasma within the fluid that is aided., is the most common source of ionization and vaporization during liquid supported peening. The collection of plasma in the water produces striking waves which immediately penetrate the specimen's handled surface and cause the surface to compress plastically. The plastic strain then strengthens residual compressive stress inside the samples to a distance of around 1 to 8 mm, dependent on the laser pulses and additional technique factors. Particularly for materials with some degree of plasticity already present, laser shock peening causes a considerable hardness and increase in wear resistance on the treated surface. Regarding acid and water laser shock peening, in addition to unpeened specimens. The results of the Vickers hardness test were found to be 153HV30, 121HV30, and 94HV30, respectively. Surface compressive residual stress extends fatigue life and improves wear resistance by reducing the possibility of an early failure. This is particularly beneficial for parts experiencing frictional and shear stresses. Engineering components anticipated usable life can be ascertained by evaluating quantifiable fatigue test resulting by life of stress (S/N) or strain life (e/N) methods, or by applying fracture mechanics methodologies.

Schemes S-N

S-N curves were plotted using the fatigue life data for both treated and unpeened specimens, and the results are shown in Fig 7. These curves have three recorded data points for each of the five stress levels. The test findings show that the life of fatigue and strength of the treated samples that were exposed to high-cycle fatigue by laser shock peening with pure water and HF acid significantly improved. The S-N curves for shock laser using unpeened alloy, pure water, and HF acid were created using the following equations: $б f = 880.16 * Nf^{-0.12}$, $б f = 761 * Nf^{-0.12}$ and $б f = 871 * Nf^{-0.12}$, respectively.

Mechanical properties

Experimental results for three types of laser peening, RT, water, and HF acid are presented in Table 3. The mechanical properties for a specific cycle count, ranging from 10^3 to 10^7. and the percentage of improvement (IP). It is evident that specimens subjected to laser shock peening exhibit greater resistance to dynamic loading fatigue compared to their unpeened counterparts. This is due to the creation of a harder superficial and compressive residual stresses on both the surface and subsurface levels.

Fatigue strength and life

Three cases are presented in Table 4, which shows the fatigue strength and fatigue life of AA 7075-T651 at 10^7 cycles. The strength and life of fatigue were enhanced by pure water and HF acid, as demonstrated in the table below, based on the strength and life results at (RT) peening. This indicates that the increase in the fatigue strength and fatigue life reached 35.18% and 63.56%, respectively compared to un-peened specimens.

In most application for laser shock peening, the advantage gained is the straight result of the residual compressive stress which is represented by (SIP%) and (LIP %) improvement factor as shown in Table 5. This improvement is attributed to the energy absorbed in the plasma generating powerful shock waves within the material, resulting in the formation in elevation levels of compressive residual stress. The resulting S-N curve data for the shock laser, when applied to acid, purified water, and unpeened alloy, can be accurately described by the equations utilized in constructing the S-N drawing.

The application of acid laser peening and purified water does not yield a substantial enhancement in the life of fatigue of low cycle fatigue (LCF) when compared to the unpeened condition. Considering that fatigue cracks cannot spread sufficiently quickly, this is mostly because of the applied load's dominant influence. However, in the high cycle fatigue (HCF) region, the compressive residual stress generated by acid laser peening becomes the primary contributing factor. Consequently, the deliberate suppression of crack growth leads to an improved life compared to the unpeened condition in LCF.

It is important to note that the primary purpose of acid peening is not surface temperature reduction. Instead, it plays a crucial role in confining the plasma produced during laser pulsing. Since acid has the capacity to carry laser power, the opaque overlay surface acts as a conduit for the laser pulses to pass through, which consists of synchronized electrical and magnetic waves. Thus, the acid effectively transmits the laser wave. This leads to the following three points.

The impact of HF acid laser on cyclic fatigue is dependent on the level of stress affected, causing an escalation in high cycle life of fatigue. The fatigue life of unpeened specimens is significantly less when subjected to lower stresses. The main factor controlling crack growth is the high stress, which results in large increments in overall stresses at higher stresses. This acceleration in crack propagation results in a faster crack growth rate compared to lower stress levels. Compressive residual stress plays an essential role in preventing the initiation and propagation of cracks, thus significantly improving fatigue resistance. Practical investigations show that HF acid-laser peening is a more effective influence surface handling technology than water-laser peening.

Additionally, the results, as illustrated in Fig. 8, showed an escalation in the load limit and bending strength through bending. Tensile forces apply on the bottom sector of the structure, which may result in fracture if the tensile stress exceeds the structure's ultimate tensile strength. The higher portion of the structure, on the other hand, is in compression, resulting in a condition of equilibrium at the middle plane. By applying further compressive stress to the minor layer where tensile tension is acting, laser shock peening efficiently reverses positive tensile stress into negative compressive stress, preventing the sample beginning cracking.

By enhancing the material's obstruction to crack initiation and growth from surface weaknesses, this surface treatment procedure raises the material's capacity to withstand bending loads. The bending strength of the material is increased by adding a surface film of compressive stress by surface treatment techniques like laser shock peening. This enables the handled material to tolerate greater bending strengths than the unhandled material under comparable bending situations. The following is an explanation of the basic idea behind laser peening using HF acid confinement and clean water. Instead of cooling the surface, pure water and HF acid peening are essential for confining the plasma produced during the procedure. HF acid is effective in transmitting the laser influence due to its ability to carry the combined electrical and magnetic waves of the laser pulses efficiently. As such, the specimens treated with HF acid laser demonstrated longer fatigue lifetimes in comparison to specimens treated with pure water laser and specimens that were not peened. By comparison with the behavior of the basic metal, this extension offers an additional safety factor.

CONCLUSIONS

Form this study the following conclusion could be concise:

- A successful improvement in the strength and fatigue life of AA 7075-T651 using HF acid through the interaction of laser peening. The use of pure water or HF acid as a layer for the mechanical characteristics improved expressively after laser shock opening. of AA 7075-T651, including tensile strength, yield stress, fatigue strength, and Vickers hardness.
- Fatigue properties such as fatigue endurance limit or strength of fatigue was improved form 50 MPa at (RT) to 67.59 MPa at pure water and 81.78 MPa at HF acid due to the interaction of these layer with laser shock peening. Compared to (RT), the life of fatigue for laser pure water and laser HF acid was increased by 72% and 88% respectively.
- Also, the SEM images supported the practical experiments and showed two regions, the hardened and non-hardened region. It showed the depth of the hardened area treated by laser shock peening, demonstrating better in elevation cycle fatigue characteristics and surface strengthening of AA 7075-T651, leading to enhanced safety measures compared to the base metal finish.

Further comprehensive fatigue testing, microstructural analysis, finite element simulations, and investigation of process parameters are essential to fully understand the mechanisms and potential of Hydrofluoric acid-laser peening in enhancing fatigue performance and surface durability in engineering applications.

FIGURES AND TABLES

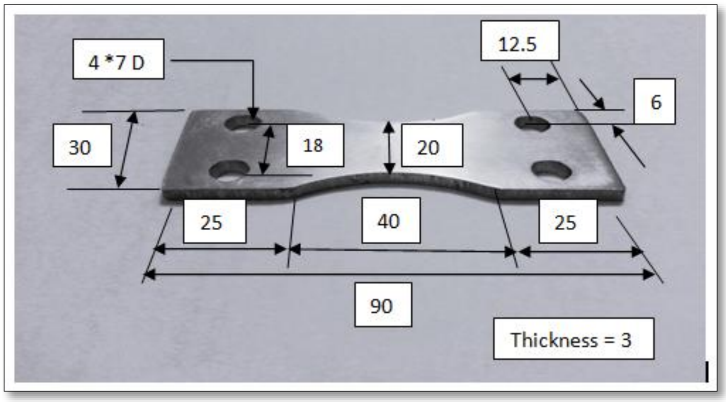


Fig.1. Sample of the fatigue specimen corresponds with the din 50133 standard requirement.

Table 1. Standard and experimental aluminum chemical compositions. 7075-T651, wt%, [ASTM].

AL Alloy 7075-T651					
Component	% Si	% Fe	% Cu	% Mn	% Mg
Standard	0.4	0.5	1.2-2	0.3	2.1-2.9
Actual	0.105	0.246	1.61	0.0475	2.35
Component	% Cr	% Zn	% other		% Al
Standard	0.218	5.1-6.1	≤ 0.15		Reminder
Actual	0.18-0.28	5.67	0.097		Reminder

Table 2. Three Al-alloy 7075-T651 specimens have average mechanical properties.

Property	**Experimental**	**Standard**
Ultimate Stress	609 MPa	572 MPa
Yield Stress	590 MPa	563 MPa
Fatigue Strength	250 MPa	245 MPa
Modulus of Elasticity	71 GPa	71.7 GPa
Poisson's Ratio	0.33	0.33

Elongations %	11	11

Fig.2. Bending machine for fatigue.

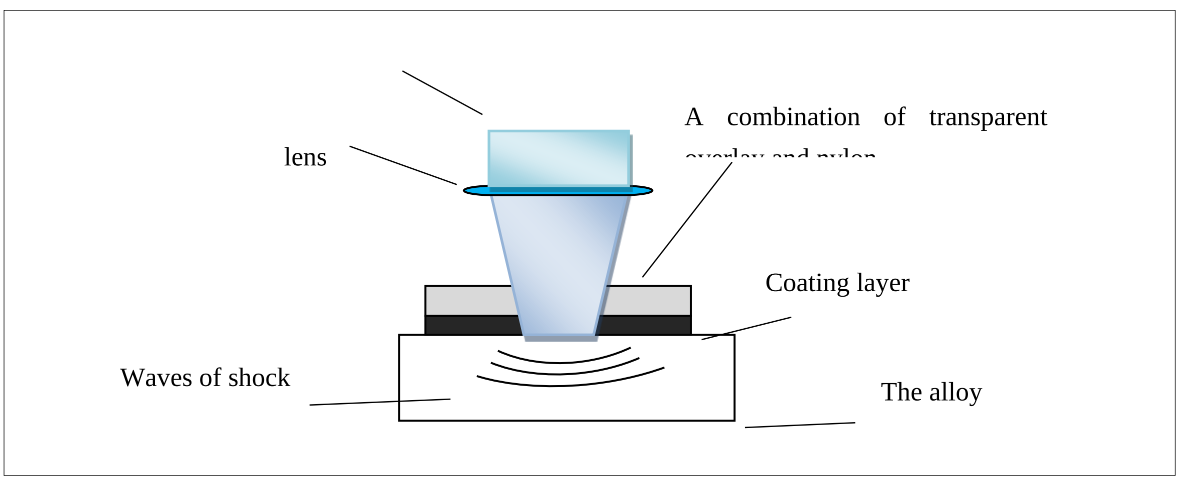
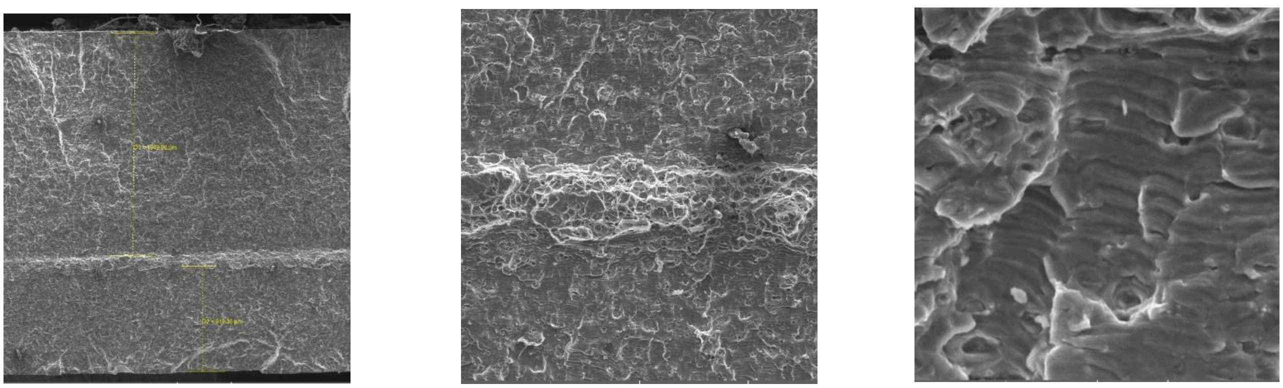


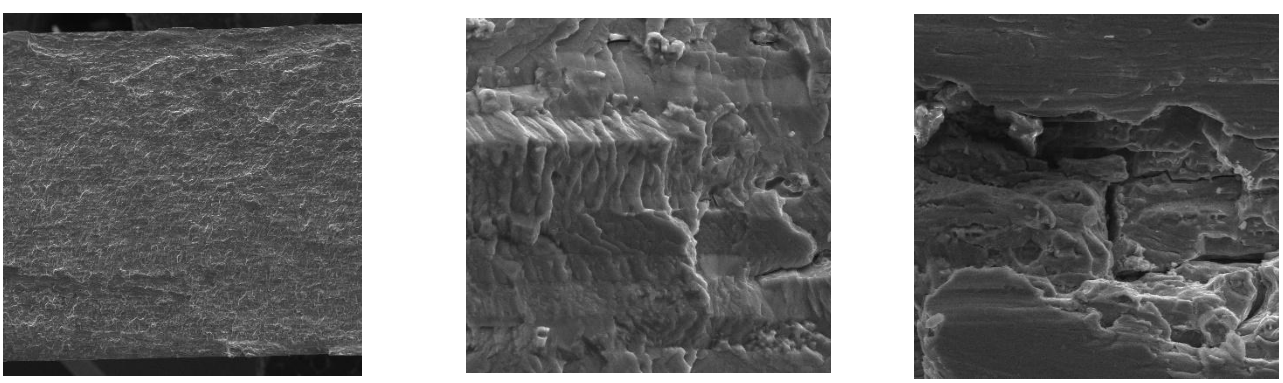
Fig.3. The essential idea of laser shock peening.

Fig.4. Applying laser energy to samples.



a c
d

Fig. 5. SEM images of aa 7075-T651 treated by LSP with HF acid; (a) the measured hardened area, (b) fracture surface contains a small density of deep dimples due to highly ductile behavior, (c) SEM image showing the depth of the striations.

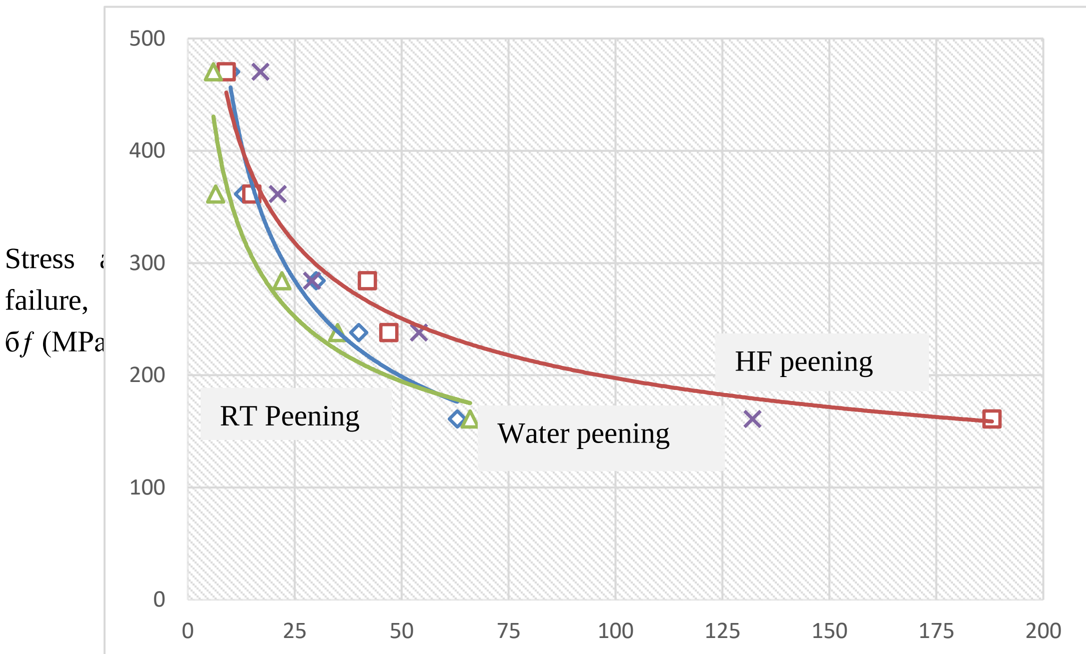


a
b c

a c

d

Fig.6 SEM images of untreated aa 7075-T651 specimen; (a) cracks initiated at the surface with small dimples, (b) striations are distributed randomly the fractured surface, (c) micro-cracks oriented along the length of the striation.



Nf (cycles to failure*10^3

Fig. 7. S-N Curves for laser shock peening and unpeened processes using HF acid and clean water under constant load.

Table 3. Mechanical properties of the three conditions of testing, RT, water, and HF acid

RT peening				**Water peening**				**HF Acid peening**			
σ_u	σ_y	$\sigma_{F.L}$	HV	σ_u	σ_y	$\sigma_{F.L}$	HV	σ_u	σ_y	$\sigma_{F.L}$	HV
609	590	250	94	651	617	274	121	686	635	302	153
				Improvement percentage (IP %) water peening				**Improvement percentage (IP %) HF Acid peening**			
				6.45	4.37	8.75	22.31	11.22	7.08	17.2	38.56

Table 4. Fatigue and life at 120 MPa stress level

Fatigue strength (MPa)			**Fatigue life at 120 (MPa) level cycles**		
RT Temp.	Pure water	HF acid	RT Temp.	Pure water	HF acid
50	67.59	81.78	77371	276600	645359

Table 5 Strength and life (SIP%) and (LIP %) improvement factor

Fatigue strength improvement factor (SIP%)		**Fatigue life improvement factor (LIP%)**	
Pure water	HF acid	Pure water	HF acid
26	38.86	72	88

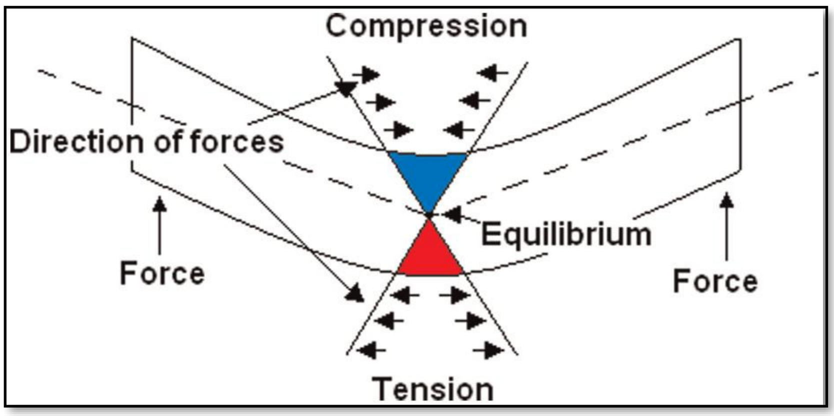


Fig. 8. The graph shows how the stress is distributed throughout the material as it is bent (Shukla PP, Swanson PT, Page CJ, 2014).

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