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LASER SURFACE COATING FATIGUE INTERACTION OF 2017A-T3 (ALUMINUM ALLOY)

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ABSTRACT :-

The interaction of fatigue and laser peening with different surface coatings was studied for 2017A-T3 aluminum alloy under stress ratio R= -1 and room temperature (RT) .
This interaction is a major issue in the practice life assessment of aircrafts. The current work examined the effect of laser surface with different coatings i.e. ALP (Air laser peening), BPL (Black paint laser peening) and WLP (Water laser peening) on cumulative fatigue. The experimental results observed that the fatigue strength was improved by 18% and 35% under BPL and WLP respectively. A new non-liner damage model was derived to predict the cumulative fatigue lives . This model showed safe and satisfactory predictions for unpeend and peened specimens for all cases of surface coatings. While Miner theory indicated not always suitable for life prediction of cumulative fatigue loading .

Keywords: Interaction of fatigue, fatigue strength, cumulative fatigue laser peening, surface coatings, 2017A-T3 AL-alloy .

التداخل الكلالي مع التغطيه السطحيه الليزريه لسبيكة الالمنيوم 2017A-T3

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الخلاصه:-

تمت انجاز دراسة التداخل الكلالي مع التصليد الليزري لعدة حالات من تغطية سطح عينة سبيكة الالمنيوم 2017A-T3 عند نسبة اجهاد R= - 1 وبدرجة حرارة الغرفه . يعتبر هذا التداخل عمليه مهمة الاستخدام في تحديد اعمار اجزاء الطائرات. في هذا العمل اجريت الفحصات الكلاليه لبيان تاثير الليزر باختلاف التغطية والتي هي التغطيه الهوائيه، الصبغ الاسود والتغطيه المائية.اوضحت النتائج العمليه ان مقاومة الكلال تحسنت بنسبة 18% و35% عند استخدام الصبغ الاسود والتغطيه المائيةعلى التوالي. تم اشتقاق انموذج جديد لاخطي لتخمين اعمار الكلال التراكمي حيث اعطى هذا الانموذج تخمين امين ومقنع للعينات غير المصلده والمصلده ليزريا لجميع حالات التغطيه بينما اعطت نظرية ماينرالخطية تخمين غير ملائم في بعض حالات التحميل الكلالي التراكمي.

الكلمات المرشدة :التداخل الكلالي، مقاومة الكلال، الكلال التراكمي المصلد ليزريا، التغطيه السطحيه، سبيكة الالمنيوم 2017A-T3 .

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NOMENCLATURE :-

σ_u	Ultimate tensile strength	**MPa**
σ_y	Yield strength	**MPa**
E	Modulus of elasticity	**GPa**
σ_f	Failure stress in tension	--
RA%	Reduction in area percentage	--
$\in$%	Ductility	--
R_a	Average roughness	μ**m**
R_t	Max. roughness	μ**m**
N_f	No. of cycles to failure	**cycles**
R^2	Correction factor	--
D	Damage	--
ni	Applied No. of cycles	**cycles**
X	Loading sequences and surface treatment factor	--
σ_L	Low stress level	**MPa**
σ_H	High stress level	**MPa**
A	Basquin exponent	--

Abbreviations:

WLP: water laser peening

ALP: Air laser peening

BLP: Black paint laser peening

INTRODUCTION :-

Laser shot peening (LSP) impacts have been a competitive alternative technology to improve fatigue life, corrosion and wear resistance of metallic component which depend strongly on the generated surface profile and plastic deformation in the surface layer [K.Y. Luo, T. Lin,2015].Mechanical and microstructure responses of AA 2017-T451 and AA 2624-T351 aluminum alloys to dynamic impact loading were investigated. Although both alloys were subjected to the same impact loads, the strain rate developed in the AA 2017 alloy was higher and the peak stress in the dynamic stress–strain curve is observed to be higher for the AA 2624 alloy, [A.A. Tiamiyu, Ritwik Basu,2015].The effect of laser peening on microstructures and properties of TiAl alloy is show that surface micro-hardness increases by up to 30%, roughness increases to 0.37 lm, compressive residual stress increases to 337 MPa,[Qiao Hongchao, Zhao Jibin 2015]. U. Trdan was study the effect of laser shock peening without coating parameters on the microstructure evolution. The results have confirmed that dense dislocation structures during ultra-high plastic deformation with the addition of shear bands producing ultra-fine (60–200 nm) and nano-grains (20–50 nm) [U. Trdan , M. Skarba 2014].C. Correa studies the effect of a significant parameter of LSP on stainless steel 316L samples using experiments and 3D finite element analysis. Fatigue life in laser peened specimens was increased from +166% to +471% by optimizing the pulse sequence[C. Correa' , L. Ruiz de Lara 2015]. Laser shock processing is a recently developed surface increase treatment designed to improve the mechanical properties and fatigue performance of materials, by inducing a deep compressive residual stress field. Experimental and numerical results indicate a residual stress anisotropy, and a better surface stress homogeneity with an of impact overlap, [Neila Hfaiedh , Patrice Peyre 2014]. Laser pulses are generally overlapped and scanned in a zigzag-type pattern to cover completely the surface to be treated. However, zigzag-type scanning patterns induce residual stress anisotropy as collateral effect. This paper is to describe and explain, for the first time and with the aid of the numerical model developed by the authors, the influence of the scanning pattern directionality on the residual stress tensor. As an effective solution, the authors propose the application of random-type scanning patterns instead of zigzag-type in order to reduce the mentioned residual stress anisotropy [C.correa, D. Peral, J. A. Peral 2015].The proposed model of Re-laser peening approach, proven to be able to obtain optimal process parameters for improving the fatigue resistance of the component, can significantly reduce the costs for experimental testing [Anoop Vasu, Koorosh Gobal 2015]. The effect of laser shock peening without coating (LSPwC) on the corrosion behavior of AA6082-T651 alloy in a near natural chloride environment. The results confirmed LSPwC as an effective method, yielding lower anodic dissolution ($E_{sw} - E_{corr}$), improved repassivation ($E_{corr} - E_{rp}$) as well as corrosion current reduction. It was found that LSPwC reduces crystallographic and surface-hemispherical pitting, as well as intergranular attack [Uroš Trdan , Janez Grum 2014].3D finite element model for predicting the residual stresses that result from the LSP of aluminum alloy Al2024-T351 to increase the fatigue life. Three different laser shock processing strategies (pulse sequences) were performed on fatigue specimens and their fatigue life was compared. The numerical model has been established [C. Correa' , L. Ruiz de Lara 2014].The effect of laser peening without coating on aluminum alloy Al-6061-T6 with a 300 mJ infrared laser. The surfaces of peened and unpeened were studied. Laser peening without coating can significantly improve surface compressive stress and micro-hardness with trivial increase in surface roughness. [S. Sathyajith, S. Kalainathan 2013].Finite element models, using the eigenstrain approach, are described that predict the residual stress fields associated with (LSP) applied to aerospace grade aluminum alloys. The model was used to show that interactions between the LSP process and geometric features are the key to understanding the subsequent fatigue strength,[M. Achintha[a, ,] , D. Nowell 2013].Coupons of a Ni base super alloy, Inconel alloy 718 (IN718) were laser shock peened with and without an ablative layer. The surface shows presence of a non-uniform recast layer which increases the roughness of the surface and also results in a tensile state of residual stresses on surface [Amrinder S. Gill[a], Abhishek Telang 2015].The laser peened samples displayed approximately 60% increase in the yield strength of the material. In contrast, shot peening exhibited only modest improvement to the tensile properties when compared to the unpeened specimens,[Omar Hatamleh 2008].This paper includes the analysis and discussion of the experimental and theoretical results for the fatigue behavior of 2017A-T3 AL-alloy with the effect of laser peening and study the surface treatment on other properties of this alloy. Also, the empirical relationships which are derived to describe the experimental results were obtained.

EXPERIMENTAL STUDIES

Design of experiments

1. Material selected.

2. Three types of loading experiments were carried out as follows:

a. Tensile tests to obtain the mechanical properties before and after laser peening.

b. Constant amplitude tests to determine the S-N curves behavior in the above conditions.

c. Cumulative fatigue damage tests, Low-High and High-Low, were continued until failure for unpeened and peened specimens in order to know the effect of different peening on fatigue damage and life.

Material selection

The selected material is aluminum alloy 2017A-T3 which has (4.07% cu). It is primarily used in applications for many general engineering and aircraft structural. It is a wrought alloy with intermediate strength. All the investigation carried out in the current work were performed at room temperature (RT) and at stress ratio R= -1, using 2017A-T3 aluminum alloy. Chemical analysis of the metal used was carried out at state **(company for Inspection an Engineering Rehabilitation in Iraq).** The results, which are compared to the American Society for Testing and Materials, are summarized in **table 1**.

Tensile test:

The tensile test specimen prepared according to the American Society for Testing and Materials (ASTM-B211), have been installed in tensile test machine at **(University of Technology Baghdad)**, **figure 1** shows the tensile test machine and tensile specimen during the test.

Laser peening:

Laser peening test has been done by using rig (Nd-YAG laser system) as shown in **figure 2 and 3,** the following specifications of laser peening are listed below:

1. Laser wavelength is about 1.065μm**.**

2. Pulse duration (16, 26, 15) nano seconds.

3. Pulse energy (310,610,1000). mJ

4. The laser spot is about (6) mm in diameter.

5. The water height to the area that peened is about (10) mm.

6. The specimens were shock laser peening with energy pulse 310 mJ at 16 nano second.

The laser peening treatment has been done for three cases of laser hardening, water laser peening (WLP) **figure 2**, black paint laser peening (BPL) **figure 3** and air laser peening (ALP) **figure 4**.

The results of the above conditions are tabulated in **table 2.**

Fatigue test program:

Fatigue analysis are normally based on the results obtained from S-N curve then the first step was established the constant continuous cycling S-N curve.(12) specimens were tested under room temperature control stress. The second step(12) specimens were tested to find the S-N curve with black paint laser peening (BPL).The third step (12) specimens were tested to find the S-N curve which use water with LP, in order to do a comparison in life and strength. The fourth step (18) specimens were examined to find the cumulative results under loading without treatment and with BPL and WLP peening.

Fatigue Test Machine:

A fatigue test machine of type (SCHENCK) PUNN rotating bending was used to execute all fatigue tests, with constant and variable amplitude, as illustrated in **figure 5.**

The material 2017A-T3 Al-alloy was received from aircraft repairing factory in the form of rolled rods of 12mm in diameter. Rotating bending fatigue specimen having an hour-glass profile with large curvature was adopted in this study. Shape and dimensions of fatigue specimen are detailed in **figure 6.**

Roughness measurement:

The specimens were then numbered and polished. First, with grade 400,600,800,100 and1200 emery papers and then with diamond pastes of 3 and 1µm respectively, to reduce the probability cracks growth at the surface of specimens . Measurement of surface roughness for selected specimens was obtained by means of a Perthmeter M3A instrument. The output reading were, Ra, (the center line average CLA) and Rt (the maximum surface roughness).The results are presented in **table 3** for ten selected specimens.

$$\text{CLA or Ra (in microns)} = \frac{y_1+y_2+y_3+\cdots y_n}{n}$$

Where $y_1, y_2 \ldots y_n$ are the ordinates measured on both sides of the mean line and n is the number of ordinates.

RESULTS AND DISCUSSIONS :-

Table 4 and **figure 7** are shown the behavior of stress-strain diagram for tensile tested specimens with and without laser peening. The water laser peening (WLP) treatment resulting in an increase in $\boldsymbol{\sigma_u}$ (tensile strength) value by 4% and 20% for yield strength ($\boldsymbol{\sigma_y}$) as compared to the as-received specimens. This improvement in $\boldsymbol{\sigma_u}$ and $\boldsymbol{\sigma_y}$ is due to compressive residual stress induced at the surface as a result of water laser peening [P. Black 1972].[Richard et al 2003] explained the effect of water as a layer on the specimen surface not to cool the part but to increase the pressure developed by the plasma on the surface up to ten times when using the water with the laser for 7075-T7351 aluminum alloy. The fatigue behavior at constant amplitude testing for three different surface treatment peened with laser can be illustrated in **table 5** and **figure 8** shown the fatigue specimens at the beginning and end for three conditions above.

$$N_{f\,average} = \frac{N_{f1} + N_{f2} + N_{f3} + \cdots}{\text{No. of specimens tested}}$$

Table 5 shows a comparison of fatigue properties for 2017A-T3 AL-specimens subjected to laser peening with different surface treatments. The data illustrates the typical fatigue enhancement of laser peened specimens, including a 18% and 35% percent increase in fatigue strength for BPL and WLP respectively and an increase in fatigue life of about 2.6 and 6.88 times for BPL and WLP respectively. General Electric Aircraft engines investigated laser peening as a solution to increase the life of titanium fan blades. The improvement to high cycle fatigue performance was remarkable. Application of laser peening avoided over 59 million dollar in blade replacement costs [Richard et al2003]. Applications for laser peening are not limited to military parts. Laser peening used to improved fuel economy in automotive and truck parts such as transmission gears and axels rotating engine parts and impellers. Medical applications include treatment of orthopedic implants to improve the fatigue performance of hip and knee replacement joints. Laser peening is also expected to find applications in power generation equipment for land based and nuclear systems. [Richard et al2003], [A. H. Clauer, D. F. Lahrman 2001]. **Figure 9** shows a comparison of fatigue properties for 2017A-T3 specimens subjected to LP and dry fatigue at different conditions. It is clear that, the WLP is the preferable one compared with other. The reason is that water generates high pressure plasma, and the strength of material surface is improved due to the shock force by the plasma[Y. Sakion, K.Youshikawa 2009].

CUMULATIVE FATIGUE TEST RESULTS:

Table 6 gives the experimental results obtained from testing specimens at low to high and high to low loading sequences. It is clear, as illustrated in the above table, that an increase in fatigue life when using water as a layer coated the specimen surface. For low-high testing the fatigue life improved by 1.426 times and 1.228 times for high-low tests. While for ALP the fatigue life were reduced compared with BLP.

Non-linear cumulative damage model (proposed model):

One of the major problems in fatigue process is concerning the fatigue damage to be proportioned to each cycle in the fatigue life. The fatigue damage is made more difficult should the stress range vary in magnitude. The most widely used theory to assess damage is due to Palmgren and Miner [en.wikipedia.org 1996]. This rule assumes a linear summation of cumulative damage which may be mathematically expressed for individual stress levels as :

$$\sum\frac{n}{N_f}= [\frac{n1}{N_{f1}}]_{\sigma 1} + [\frac{n2}{N_{f2}}]_{\sigma 2} +[\frac{n3}{N_{f3}}]_{\sigma 3}+\cdots =1 \qquad \textbf{(1)}$$

Application of the above equation requires an experimental data and a conventional S-N curve. The fact that the summation is frequently less than unity as sometimes as large one [Miller K.J.,Mohamed Alalkawi H.J 1986] illustrates the dangers of applying the Miner rule.Following the work of Alalkawi et al 2014][Alalkawi H.J, Amer H.M 2015]and Perrire et al 2009], they suggested the damage due to fatigue for low- high and high- low stress levels as :

$$\text{D=damage= } [\sum\frac{ni}{N_{fi}}]^{X} \qquad \textbf{(2)}$$

Where X is a function of the applied load. In the present work X may be defined as the effect of loading sequences and surface treatment, here the surface treatment is used BPL and WLP.

Then:

$$\mathbf{X} = \frac{\sigma_L}{\sigma_H}\alpha \quad \text{For low- high stress levels} \qquad (3)$$

And

$$\mathbf{X} = \frac{\sigma_H}{\sigma_L}\alpha \quad \text{For high-low-stress levels} \qquad (4)$$

Where σ_L is the applied low stress, and $\sigma_H$is the applied high stress in MPa. α is the Basquin exponent determined from the S-N curve which may take the form:

$$\sigma_f = A\ N_f^{\alpha} \qquad (5)$$

For two blocks testing:

$$\textbf{Low- high D} = [\frac{n_1}{N_{f_1}}+\frac{n_2}{N_{f_2}}]^{\frac{-\sigma_L\alpha}{\sigma_H}} \qquad (6)$$

And

$$\textbf{High- low D} = [\frac{n_1}{N_{f_1}}+\frac{n_2}{N_{f_2}}]^{\frac{-\sigma_H\alpha}{\sigma_L}} \qquad (7)$$

Where *n* is the applied number of cycles.

For the present work: n=5000 cycles

for high cycle fatigue region (HCF) the desired applied cycles is 5000 cycles (Alalkawi, Amer 2015). For the present experimental results given in **table 6.**The damage calculated from the above model can be presented in **table 7** in comparison with Miner rule._The predicated fatigue life under different condition of laser surface treatments compared to the Miner theory lives can be illustrated in **table 8.** It can be seen from **table 8** that the Miner rule gives non- conservation predictions for some specimens because the rule assumes that damage accumulative in a linear fashion at all stress levels, while in reality damage accumulates in a complex manner [Zainab A.B 2014] . Furthermore the Miner method doesn't taking into account the effect of surface treatments. The present model gives good correlation with the experimental lifetimes see **table 8** which shows that a much better and conservative prediction of lifetime was obtained if the present model is available.

CONCLUSIONS :-

From the present work on the interaction of laser peening with different surface coating and fatigue of 2017A-T3 aluminum alloy, the following remarks can be drawn:

1. The mechanical properties i-e σ_u and σ_y were increased by 4% and 20% respectively when using WLP.

2. Constant fatigue lifetime was significantly increased about 2.6 and 6.88 times for BPL and WLP respectively.

3. Fatigue strength was improved by 18% and 35% for BLP and WLP respectively.

4. The non linear model showed safe and satisfactory estimations of cumulative fatigue lifetime.

5. Miner rule was not always applicable for life prediction under cumulative loading.

Table (1) Experimental and standard chemical composition of 2017A-T3 Al-alloy, wt%

Material	Zn	Ti	Cr	Fe	Cu	Mg	Mn	Si	Al
Standard (B211)	max. 0.25	max. 0.15	max. 0.1	max. 0.7	3.5-4.5	0.4-0.8	0.4-1	0.2-0.8	Balance
experimental	0.02	0.08	0.01	0.39	4.07	0.70	0.56	0.52	Balance

Table (2): mechanical properties of 2017A-T3 AL-alloy in three conditions of LP

Condition	σ_u (MPa)	σ_y((MPa)	E (GPa)	σ_f (MPa)	RA%	∈%
As received	455	270	72	407	26	22
ALP	435	250	72	405	26.5	20
BPL	450	323	73	402	26.5	20
WLP	472	325	75	400	26.5	18

Table(3) illustrates the roughness values for chosen specimens

Spec. No.	Min. diam. (mm)	Ra µm	Rt µm
1	6.39	0.25	0.75
2	6.41	0.35	0.82
3	6.382	0.19	0.65
4	6.401	0.125	0.45
5	6.375	0.28	0.85
6	6.381	0.37	0.62
7	6.407	0.4	0.85
8	6.402	0.44	0.9
9	6.338	0.29	0.77
10	6.408	0.38	0.89

Table (4) :Mechanical properties results under different laser peening

σ_u	σ_y	Percentage Increase (σ_u)	Percentage Increase (σ_y)	Condition
455	270	-	-	Asreceived
435	250	-4.4%	-7.4%	ALP
450	323	-1.1 %	+19%	BPL
472	325	+4%	+20%	WLP

Table (5)Constant fatigue results for three conditions of treatment for 2017A-T3

Without peening					
Specimens No,	**Applied Stress (MPa)**	**N_f Cycles**	**N_f Average**	**Basquin equation**	**R^2**
1,2,3	350	4000,5800 6200	5200	**$\sigma_f = 1953\ N_f^{-0.2}$**	**0.97**
4,5,6	275	11000 ,22000 16000	16300		
7,8,9	200	89600,113500 102000	101700		
10,11,12	150	333000,287000 344000	321500		
BPL					
Specimens No,	**Applied Stress (MPa)**	**N_f Cycles**	**N_f Average**	**Basquin equation**	**R^2**
13,14,15	350	6600, 5100 3900	5200	**$\sigma_f = 1544\ N_f^{-0.1747}$**	**0.96**
16,17,18	275	13000. 18000 20000	17000		
19,20,21	200	113000, 147000 126000	128600		
22,23,24	150	602000, 564000 710000	625300		
WLP					
Specimens No.	**Applied Stress (MPa)**	**N_f Cycles**	**N_f Average**	**Basquin equation**	**R^2**
25,26,27	350	6000, 4000 7000	5600	**$\sigma_f = 1370\ N_f^{-0.1158}$**	**0.94**
28,29,30	275	23000, 21000 26000	23300		
31,32,33	200	174000, 202000 188000	188000		
34,35,36	150	1080000 1200000 11120000	1133000		

Table (6) Cumulative fatigue results for 2017A-T3 (ALP)

Specimens No.	Applied stress Sequences (MPa)	N_f cycles	N_f av. Cycles
37,38,39	200-300 (L-H)	20000,26000,21000	22300
40,41,42	300-200 (H-L)	13000,12000,31000	18600
(BLP)			
43,44,45	200-300 (L-H)	24000, 30000, 44000	32660
46,47,48	300-200 (H-L)	14000,21000,27500	20600
(WLP)			
49,50, 51	200-300 (L-H)	31000, 73000,36000	46600
52, 53, 54	300-200 (H-L)	35000, 23000,18000	25300

Table (7) damage values obtained from the present model

Appliedloading sequences (MPa)	N_f aver cycles	Damage (present model)	R No. of program	Condition	D (Miner)
200-300 300-200	32660 20600	0.9121 0.4745	1.814 0.9438	unpeend	1
200-300 300-200	22300 18600	0.9145 0.4387	1.970 0.945	BPL	1
200-300 300-200	46600 25300	0.4019 0.3546	1.0623 0.9474	WLP	1

Table (8) comparison of life predictions based on the experimental life

Condition	$N_f$exp.	N_fMiner	$N_f$model	Loading sequences
Unpeend	32660 20600	19889 19889	18140 9438	L- H H- L
BPLP	22300 18600	21542 21542	19700 9450	L- H H- L
WLP	46600 25300	26434 26434	24623 11374	L- H H- L

Fig.(1);Tensile test machine in University of Technology with specimen before and after fracture

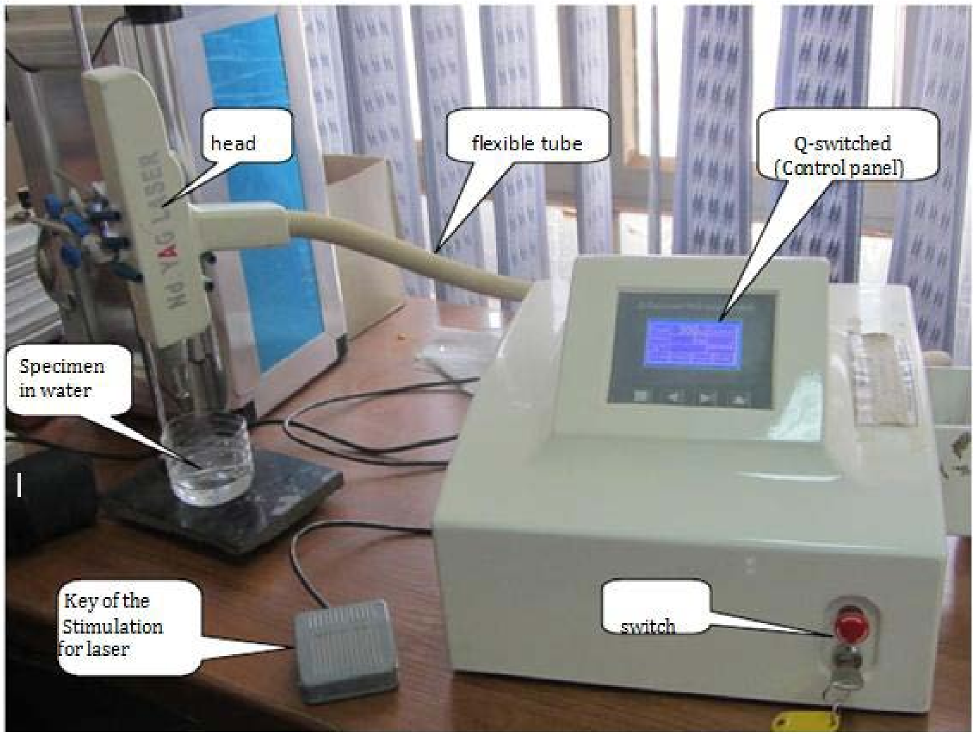

Fig. (2); Specifics of water laser peening test rig type(Nd-YAG laser)

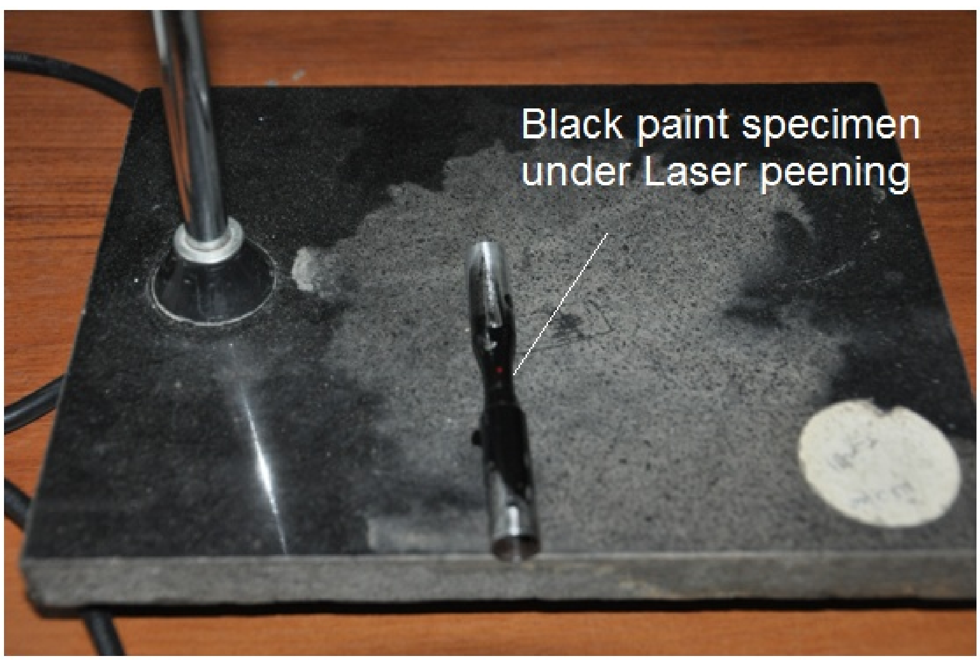

Fig.(3); Fatigue specimen under BLP

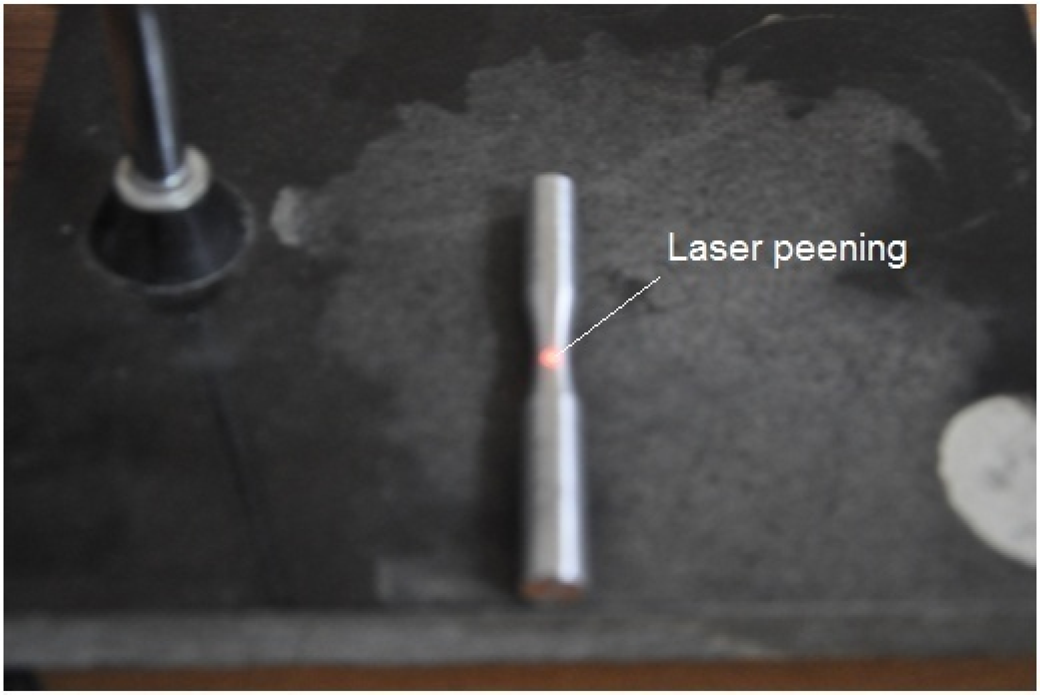

Fig. (4); Fatigue specimen under laser spot peening

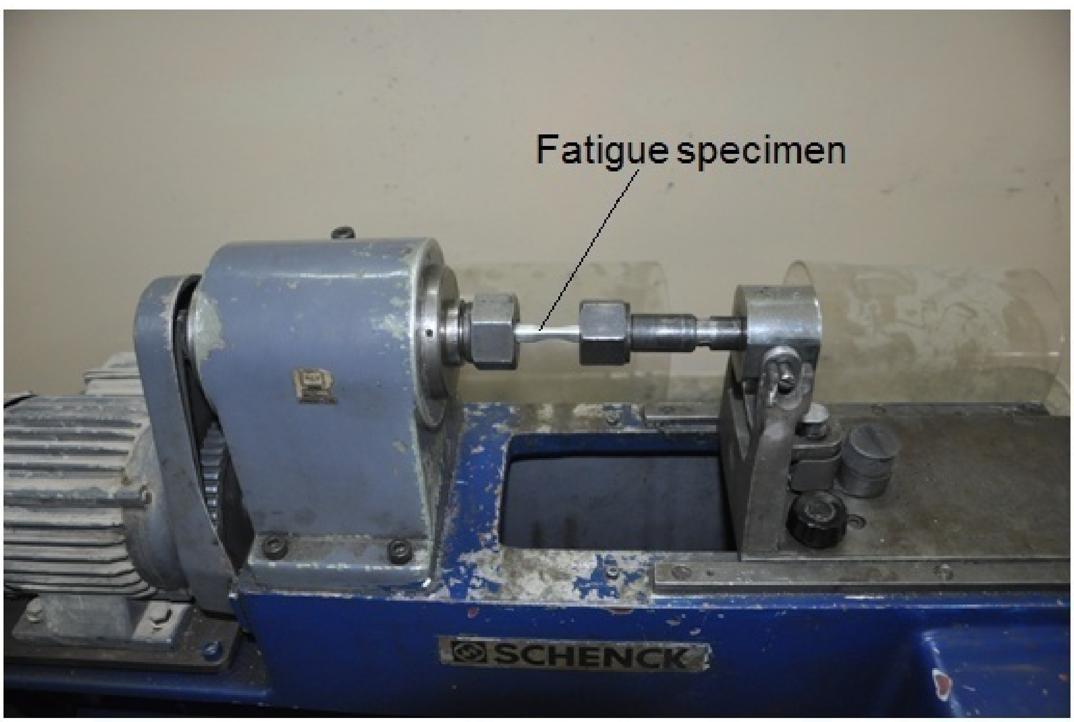

Fig. (5) ;Fatigue specimen installed on the device

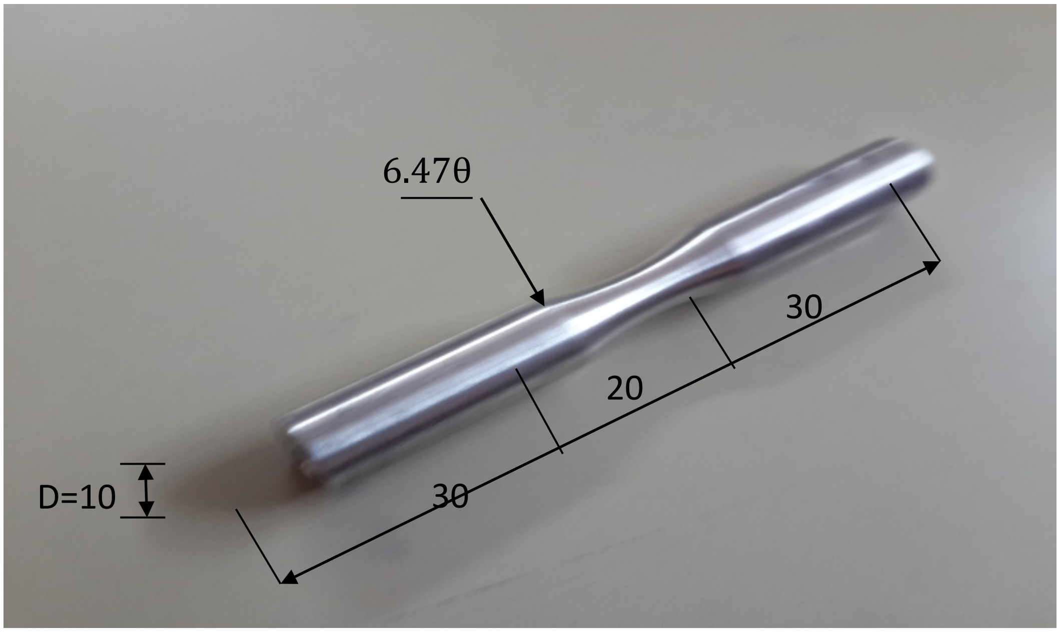

Fig.(6); Dimensions of fatigue test specimen according to DIN 50113.

(All dimensions in mm)

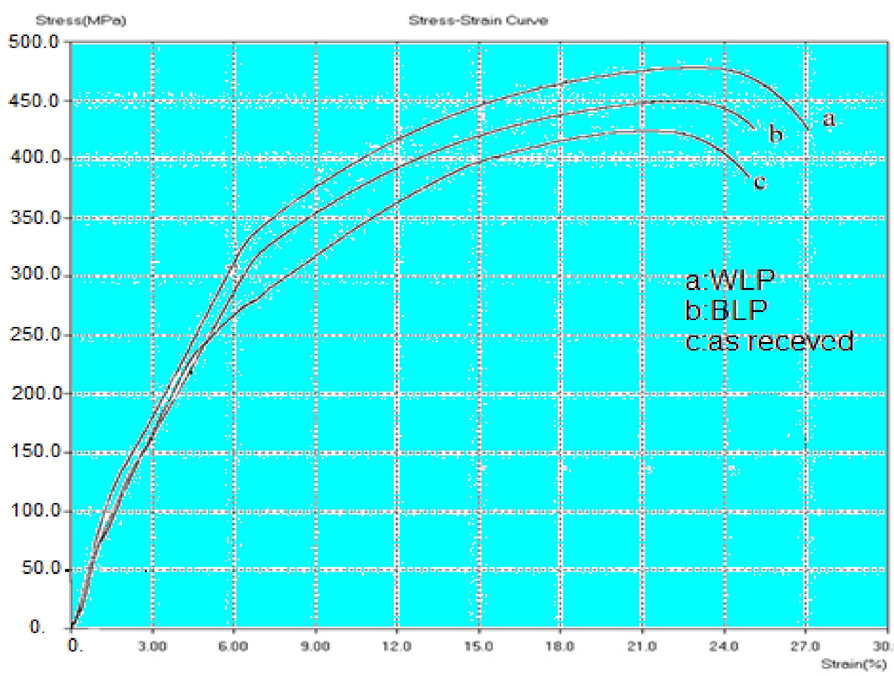

Fig. (7); Stress-strain diagram for tested specimens before and after four cases of laser hardening peening

Fig.(8); Fatigue specimens before and after fatigue testing

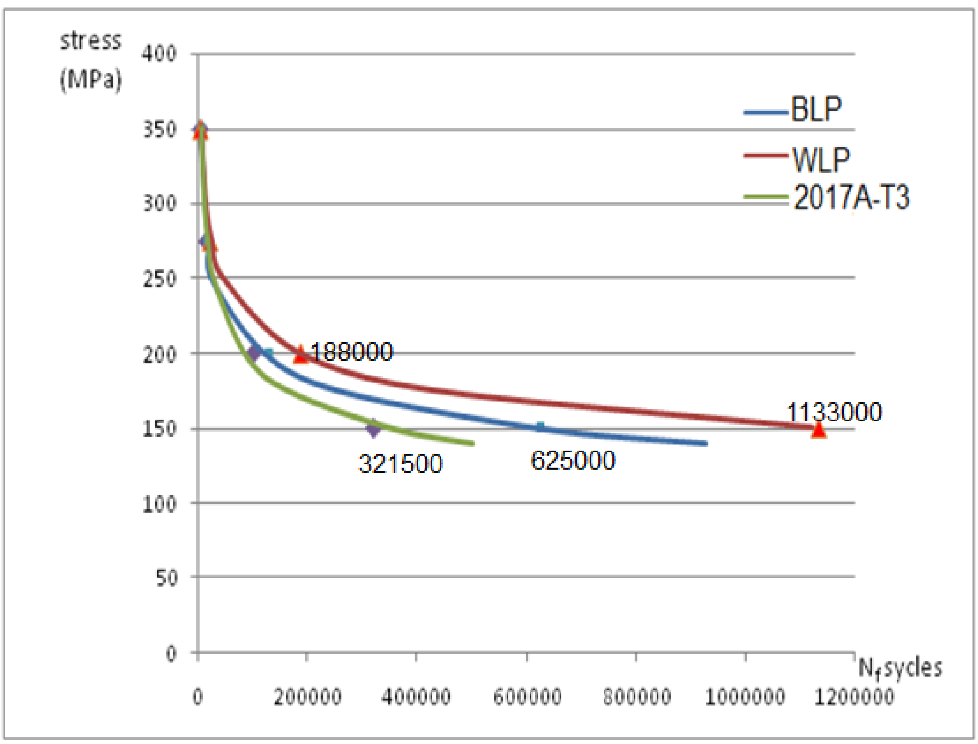

Fig.(9) Constant S-N curves behavior for different laser peening

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