SUST Journal of Engineering and Computer Sciences (JECS), Vol. 17, No. 2, 2016

7049 AL-Alloy Fatigue Behavior under Black Paint Laser Peening

Hussian J. Alalkawi, Madlool Awad Saeed, Ali Yousuf Khenyab

School of Mechanical Engineering, Sudan University of Science and Technology, Khartoum, Sudan
Alalkawi2012@yahoo.com

Received:15/06/2014
Accepted:28/08/2014

ABSTRACT- Black Paint Laser (bPL) peening technique is currently applied to engineering components due to their improvements of fatigue behavior and economic advantages. In the current work, the experimental examinations of bPL peening, which aims to understanding the fatigue behavior of bPL surface treated bars was carried out. The application of bPL was associated with significant extension of fatigue life and strength. This extension is due to compressive residual stresses (CRS) generating from peening process. A series of fully rotating bending fatigue tests was conducted at room temperature using 7049 Aluminum alloy. Improvements in fatigue life and strength for constant and cumulative fatigue were demonstrated. Finally, the fatigue strength of 7049 Aluminum alloy at 10^7 cycles increased by 53% and cumulative fatigue life improved by factors of 1.55 and 1.787 for Low-high sequence and high-low sequence due to bPL treatment respectively.

Keywords: *Aluminum alloy, black Paint Laser (bPL), fatigue strength, residual stress cumulative fatigue life, Laser shock peening (LSP), fatigue crack growth (FCG).*

المستخلص – إن تقنية معالجة سطوح المعادن بواسطة أشعة الليزر وبعد طلائها بطبقة من طلاء أسود تعتبر من الطرق الرائدة الحديثة والمستخدمة مع المواد الهندسية ، حيث يتم تحسين قابليتها علي تحمل الكلال (التعب) وبالتالي الحصول علي مزايا اقتصادية .في هذا البحث تم تصميم وأجراء التجارب اللازمة علي عمدان من سبيكة الألمونيوم نوع 7049 . كانت النتائج مشجعه وواضحة بزيادة قابليتها علي التحمل ومقاومة التعب وزيادة عمر الأشتغال ، أن هذه الزيادة أو التحسين نتيجة لتوليد إجهادات ضغط متبقية (CRS)علي السطح والتي تولدت بتأثير التعرض لاشعة الليزر . تم إجراء التجارب علي عينات من عمدان الألمونيوم مطلية بطبقة رقيقة من الطلاء الأسود وتعريضها الي أحمال مختلفة خلال دورانها . النتائج المحددة التي تم الحصول عليها هي أن مقاومة التعب عند 10^7 دورة زادت بمقدار53 % ونسبة زيادة عمر التعب التراكمي كانت بمقدار1.55 و 1.787 عند الزيادة أو النقصان المضطرد للدورات وعلي التوالي .

Introduction

Laser Shot peening (LSP) is considered as one of the most surface improvement method due to its ability to induce surface compressive residual stress, surface hardness and microstructure [1].

LSP may leave an improved surface, which would reduce the occurrences of surface lapping, folds, and other undesirable feature that occur with shot peening (SP). The improved surface condition should, therefore, result in improved resistance to crack growth [2]. In practice two different (LP) processes are known: first uses protective coating in order to protect the material surface from melting. This case done with high energy laser pulses. The coating is usually formed with a black paint or aluminum foil prior to laser process. The second is called laser peening without coating. This process works with lower energies pulses [3].

The objective of this paper is to examine the effect of laser peening on the fatigue behavior and cumulative damage using 7049 AL. alloy under the black paint laser peening process.

Literature review

Surface modification technologies have been widely employed in industry to reduce costs and avoid the requirements for expensive materials. Fatigue is one of the primary reasons for the failure of structural components. The life (duration) of a fatigue crack has two parts, initiation and propagation. In high cycle fatigue (HCF), with a polished part and no stress raisers,so about 90% of the life is spent in initiation stage [4].

Nowadays, a fatigue crack growth (FCG) behavior of titanium alloys is of great importance in the safety of critical components in engineering applications due to its wide use. Some alternative new peening techniques have emerged, such as laser peening (LSP), ultrasonic peening and micro-shot peening. Among these peening technologies, LSP is a competitive surface treatment technique with deeper and higher compressive residual stresses as well as lower surface roughness. Compared with SP, LP has stronger effects on reducing FCG rate of titanium alloys [5].

The effects of LSP coverage rate on residual stress distribution on the surface of AL- alloy, and the direction of LSP coverage is both parallel and perpendicular to crack growth direction. The compressive residual stress CRS induced by LSP can effectively decrease FCG rate and increase FCG lives of compact tension (CT) samples [6].

The effect of repeated impacts on mechanical properties and fatigue fracture morphologies of 6061-T6 aluminum subjected to laser peening (LSP) was studied. Compared with the untreated samples, nano-hardness and fatigue lives of the samples subjected to 1:3 LP impacts had increased by 18.1–59.1% and 7.3–99.4%, respectively. Residual stress presented compressive state on the superficial layer of the samples after LSP, and the value increased with the increase of the impact number [7].

Laser shock processing, also known as laser peening, can produce a compressive residual stress layer more than 1 mm deep in commercially available aluminum alloys, and has been shown to significantly improve fatigue performances. Moreover, laser peening is used commonly to harden the surface and improve the mechanical properties of some structural metal components such as commercially available carbon steels, stainless steels, cast irons, aluminum alloys, titanium alloys and nickel base super-alloys [8]. LSP can improve the residual compressive stress and microhardness effectively. With one LSP impact, Residual compressive stress and microhardness are 520.0 MPa and 398.5 HV0.5 respectively. They increase with the LSP impact, but the increment for each impact decrease with the LSP impact.Owing to comprehensive action of high amplitude residual compressive stress and surface nanostructure, the fatigue limit of (standard vibration specimen) is improved from 438.6 MPa to 526.7 MPa, or about 20.1% increased [9].

Laser shot peening generates deeper compressive stresses compared with other surface enhancement techniques like shot peening, making it appealing to the industry. Figure 1 shows the mechanics behind residual stress which generate by laser peening. When the material is peened under loading, the surface in contact is plastically deformed. The surrounding bulk material, which is elastically deformed, tries to get back to its initial state generating compressive stresses in the surface region, while tensile stresses are created in the subsurface to attain static equilibrium in the material [10].

The effects of residual stresses distribution on fatigue and fretting fatigue of sp and LP in alloy Ti–6Al–4V samples is studied. The results indicated that LP could induce greater fatigue resistance than traditional SP [11]. The effects of parallel multiple laseried/material interactions on the stress/strain distributions during LSP of AISI 52100 steel is studied.

When increasing the laser intensity increases both the stress magnitude and affected depth. The use of smaller laser spot sizes decreases the largest magnitude of residual stress and also decreases the depth affected by LSP.

Larger spot sizes have less energy attenuation and cause more plastic deformation [12]. The influence of processing parameters on the laser-induced shock waves in metal components are discussed and analyzed by Montross et al [13]. Application of laser peening is addressed.

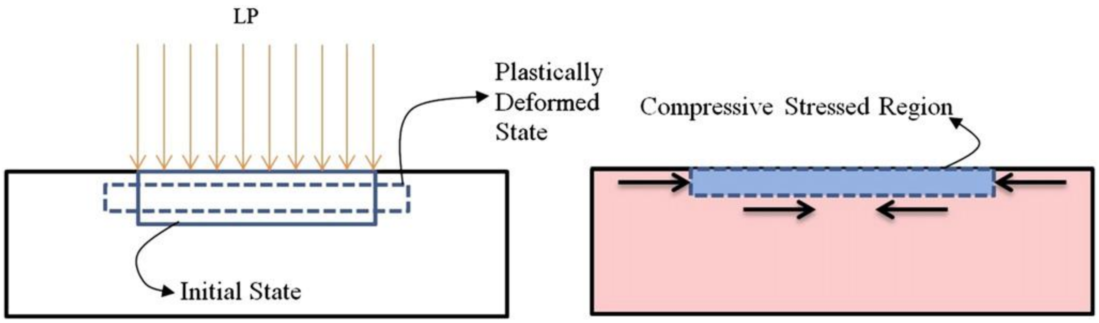

Figure 1. Mechanics of residual stress generation in laser peening [10].

Results to date indicate that laser peening has great potential as a means of improving the mechanical performance of components.

M. Achintha et al [14] used finite element model to describe that predict the residual stress fields associated with laser shock peening (LSP) applied to aerospace grade aluminum alloys. It is shown that interactions between the LSP process and geometric features are the key to understanding the subsequent fatigue strength. Particularly relevant for engineering application, is the fact that not all instances of LSP application provided an improvement in fatigue performance. Although relatively deep surface compressive residual stresses are generated which can resist fatigue crack initiation in these regions, a balancing tensile stress will always exist and its location must be carefully considered.

Yinqun Hua.et al. [15] was able to improve the hot corrosion resistance of TC11 titanium alloy by laser shock processing. Specimens were treated by laser shock processing on the whole surface. The hot corrosion resistance beneath Na2SO4containing 20 wt. % NaCl salt deposits at 650◦C, 800◦C and 900◦C in air was investigated. The effects of LSP impacts on surface microstructure, residual stress, and microstructure after hot corrosion were investigated by transmission electron microscope, X-ray diffraction technology, and scanning electron microscope. Results show that laser shock processing can induce (−295) MPa compressive residual stresses. The microstructure after LSP was characterized by a high amount of twins and highly tangled and dense dislocation arrangements.

We even observed nano-crystallization. More protective oxidation films were remained on the surface of laser shocked specimens after hot corrosion, and it mainly consists of TiO_2, Al_2O_3, MoO_3, etc. The average corrosion rate of TC11 titanium alloy treated by laser shock processing is more than 50% lower than that of the untreated alloy.

J. Fornell, et al [16], has investigated the effects of surface laser treatment (SLT) on the structure, mechanical properties and wet ability of Cu47.5Zr47.5Al5 metallic glass alloy. SLT has been carried out at three different intensities with the aim of inducing variable surface damage and tuneable changes in the resulting properties. X-ray diffraction characterization and scanning electron microscopy observations reveal that the alloy laser treated at 28.5 A. remains amorphous while the alloy treated at 29 A becomes partially crystalline (CuZr B2 phase).

When the alloy is treated at 30 A, it is mainly composed of copper and zirconium oxides. Nano indentation tests, carried out on-top of the as-cast and laser-treated surfaces, reveal that SLT at 28.5 A. causes an increase in hardness, which can be attributed to annihilation of free volume (i.e. structural relaxation). Conversely, hardness values of the alloy laser-treated at 29 A are almost the same as those of the as-cast alloy. This could be ascribed to the counterbalance effect between the softer nature of the CuZr B2 phase and the harder nature of the remaining relaxed amorphous phase. Larger hardness values are observed for the alloy laser treated at 30 A as a result of oxide phase formation.

Material and Methods

The material tested was a **7049** aluminum alloy supplied as round bar of 12 mm. The composition in wt% is reported in Table 1. The mechanical properties of the alloy used can be illustrated in Table 2. The fatigue tests were performed by fatigue test rig as shown in Figure 2,and using Hour-glass type specimen, which is shown in Figure 3. AQ-Switched ND: YAG laser with wavelength of 1.065µm,is used and pulse duration of 7ns power density of 300mJ was obtained for pulse energy 300mJ by maintaining laser beam spot size on the specimen as 8mm in diameter. More details of laser test rig can be found in Ref. [17] and figure 4. Prior to laser peening 12 specimens are painted by black paint and then peened by laser waves Figure 5.

Table 1: Experimental and standard chemical composition of 7094 Al-alloy, wt%

Material	Zn	Ti	Si	Cu	Fe	Cr	Mg	Mn	Al
Standard	0.25 max.	0.2 max.	0.8 max.	3.5-4.5	0.7 max.	0.1 max.	0.4-1	0.4- 0.8	Balance
experimental	0.22	0.08	0.15	3.8	0.25	0.06	0.72	0.57	Balance

Table 2: Mechanical properties of 7049 alloy

Property	σ_u (MPa)	σ_y	E (GPa)	μ	EI%	Fatigue strength (MPa)	Shear modulus (GPa)	Shear strength (MPa)	(HB)
experimental	515	312	73	0.32	19	287	27	277	131
Standard	520	317	74	0.32	20	290	27	280	132

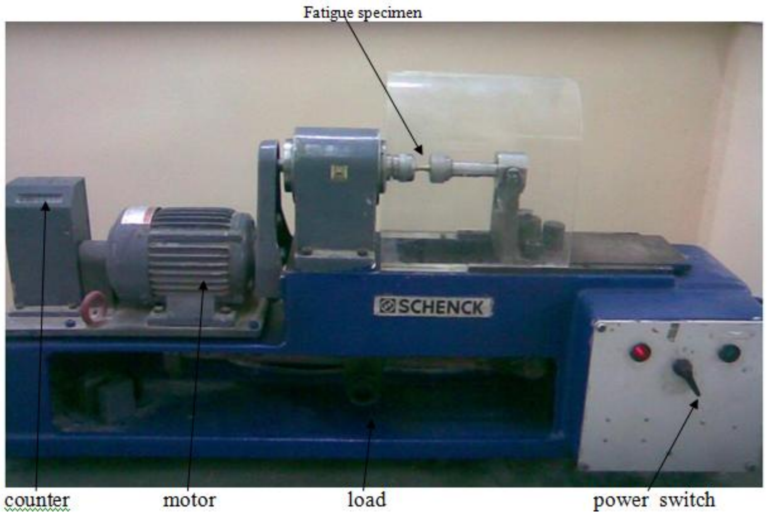

Figure 2: The fatique testing machine

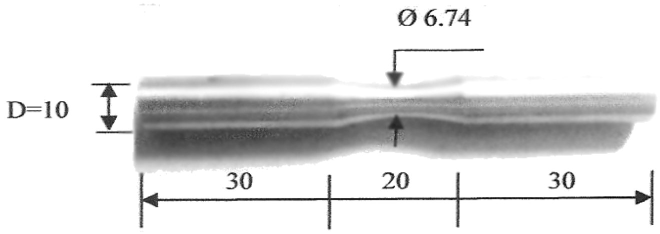

Figure 3: Hour-glass type specimen (All dimensions in mm)

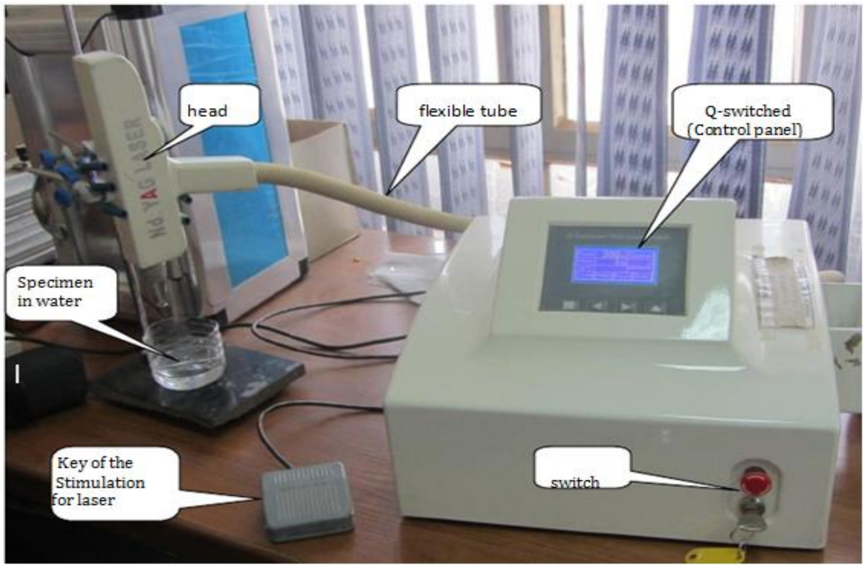

Figure 4: Details of laser peening test rig in University of Technology (Laser and Electroptical Engineering Department)

Figure 5: specimen which painted by black paint and then peened.

Table 3: Fatigue test results with and without laser peening

Dry Fatigue			**LSP**	
Specimens No.	**Applied Stress(σ_f) MPa**	**Cycles Nf**	**Specimens No.**	**Cycles Nf**
1,2,3	400	2000,2200,2500	13,14,15	3000,3400,4000
4,5,6	300	6000,7000,8000	16,17,18	9000,11000,8800
7,8,9	250	33000,31800,32600	19,20,21	119000,122000,105000
10,11,12	200	63000,57500,66000	22,23,24	270000,221600,234000

Results and Discussions

To assess the effect of laser peening on the fatigue life of 7049 AL-alloy, a constant amplitude fatigue tests were conducted on unpeened specimens and then on black paint peened specimens as illustrated in Table 3. The results of the measurements can be plotted in Figure 6.

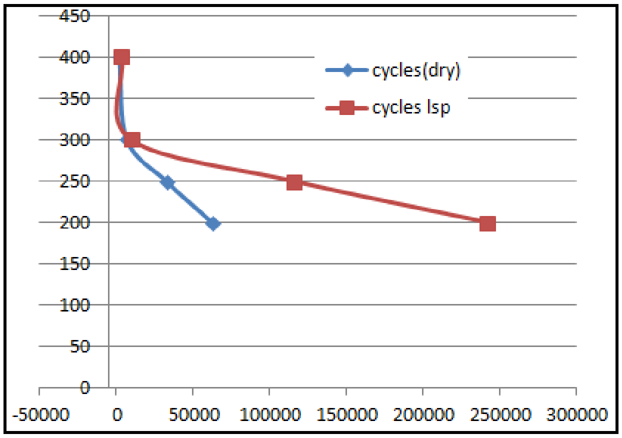

Figure 6: S-N Curves behavior of 7049 Al alloy, which is S-stress, N- number of cycles

The solid line of Figure 6 fits the equations obtained from the experimental data. Examination of this diagram reveals that there is a significant improvement in fatigue life, which depends on how to apply the black paint laser peening (bPL) and stress level. At high stress levels (above 300MPa) i.e. Low cycle fatigue, there is no effect of (bPL) on fatigue strength and life. But at High cycle fatigue region (HCF) below the stress level 300 MPa , there is more than two fold life extension associated with (bPL).This result is well agreed with Ref [18] who used aluminum alloy 2024-T3 with white polyurethane paint.

The behavior of LCF and HCF

It is know that Low cycles fatigue (LCF) deals with stress cycles less than 10^4 and above this limit the region may be called HCF. Table 4, and Figure 7 gives the fatigue strength of the two regimes.

Table 4: Fatigue strength of LCF, HCF

LCF Upeened			HCF Unpeend		
10^2	10^3	10^4	10^5	10^6	10^7
Fatigue Strength (MPa)			Fatigue Strength (MPa)		
719.5	464.5	300	193.66	125	80.73
Laser black paint			Laser black paint		
625	452	326.5	236	171	124

Laser techniques are currently applied in a series of engineering processes due to their technological and economic advantages. It is clear that the paint laser peening (PLP) improve the fatigue strength and fatigue life of 7049 AL-alloy. The SIF%

(strength improvement factor) can be obtained from the formula:

$$SIF = \frac{(\sigma plp - \sigma unp)}{\sigma unp} * 100 \qquad (1)$$

where **plp** is paint laser peening, and **unp** is unpeened. The results of the SIF% are given in Table 5.

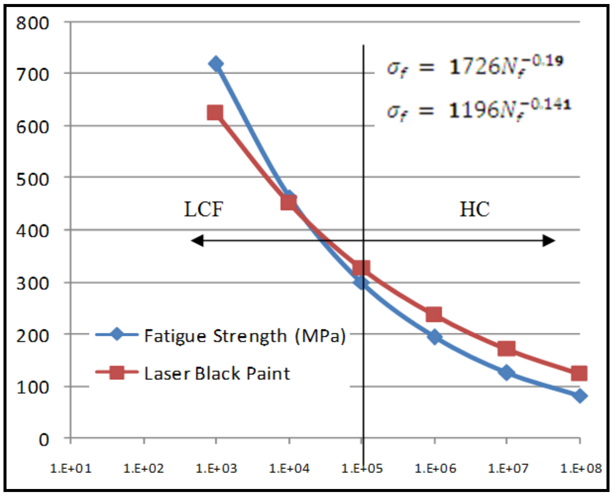

Figure 7: Fatigue strength of LCF, HCF with stress cycles.

It is observed from Table 4 that when increasing the testing life tends to increasing the SIF% or in another words reducing the applied stress gives increasing in SIF%.

Table 5: SIF% results due to paint laser peening at HCF region

10^4	10^5	10^6	10^7
8.8%	22%	36.8%	53.6%

The maximum improvement in fatigue strength occurred at 10^7 cycles, as shown in Table 6.

Table 6: Fatigue endurance limit improvement due to bpL

Fatigue strength (Dry) (MPa)	Fatigue strength bpL (MPa)	SIF%.
81	124	53

Table 7 compression **residual stresses due to bPL Peening for HCF**

Life (cycles)	10^4	10^5	10^6	10^7	avg
CRS (MPa)	-26.5	-42,34	-46	-43,3	-39.5

The observed extension in fatigue life and strength after the (LSP) treatment is the development of Compressive Residual Stress (CRS) at and sub the specimen surface [19].

Table 7: Compression residual stresses due to bPL Peening for HCF

Life (cycles)	10^4	10^5	10^6	10^7	avg
CRS (MPa)	-26.5	-42,34	-46	-43,3	-39.5

The residual stresses can then be estimated by using the approximate method:

$$\sigma rse = \sigma unp - \sigma pLp \qquad (2)$$

σrse: residual stresses

Table 7 gives the approximate values of compression residual stresses (CRS) created at the surface due to bpL peening

The computed values of compressive residual stresses (equation (2)) are listed in Table 7 for a given fatigue life. It is clear that the highest compressive residual stress is at 10^6 cycles Then by 10^7 cycles, and the average is 39.5 MPa. The computed results are quite similar to the results in Ref. [18]. They concluded that the average CRS obtained by using Paint removal method is 45 MPa for CO_2 laser and 20 MPa for Excimer laser experimentally .The increase of CRS tend to extend fatigue life.

Cumulative fatigue results analysis

Table 8 gives the cumulative fatigue results under two blocks loading with and without bPL using 12 specimens, six at dry and the other six are treated with bPL peening .

Table 8: Cumulative Fatigue results at two different conditions of treatments

Loading sequence	Without bPL N_f (Cycles)	With bPL N_f (Cycles)
200-300 (L-H)	18000,12000,7000 (15667 Aver.)	28000,21000,24000 (24333 Aver.)
300-200 (H-L)	11000,13000,9000 (11000 Aver.)	22000,19000,18000 (19667 Aver.)

The effect of bPL on extension of cumulative fatigue life for both L-H and H-L Loading sequences as in Figure 8.

The results on Figure (8) present the significant effect of CRS on cumulative fatigue life of 7049 Al alloy .An improvement fatigue life by a factor of about 1.55 at L-H and 1.787 at H-L. These factors are created due to structural changes caused by bPL treatment i.e. increase of the compressive residual stresses (CRS) tend to extend cumulative fatigue life.

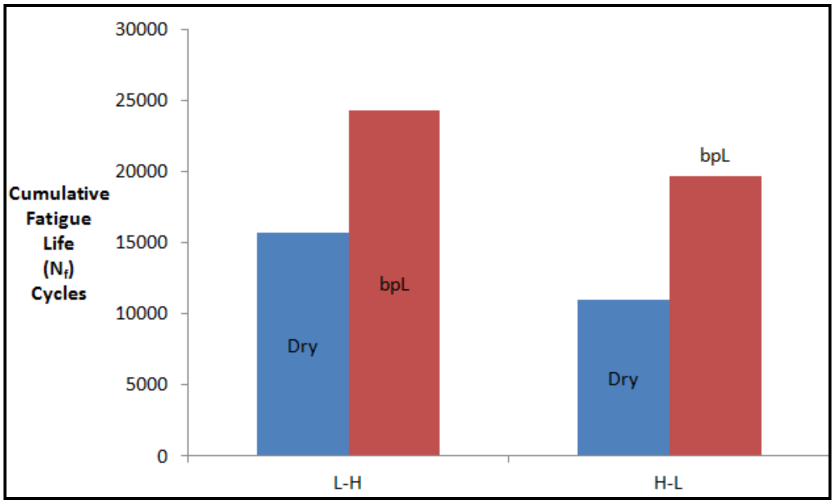

Figure 8: Effect of bPL treatment on cumulative fatigue life

At low stress (HCF), the domain controlling fatigue life is the crack initiation phase rather than crack propagation one. The CRS work to non-propagate short crack and the total life is increased. While at high stress level, crack initiation can be neglected and the controlling phase is the crack growth propagation (long cracks) [20].

Conclusions

The effect of bPL surface treatment present on the fatigue behavior of Al alloy 7049 was assessed. Black paint Laser peening (bPL) increased the fatigue strength of 7049 Al alloy by 53%. For constant fatigue life of HCF, so when increasing the testing life increasing the fatigue strength. The average CRS generated at the surface was 39.5 MPa due to bPL treatment. For cumulative fatigue results, the average fatigue life of L-H loading sequences increasing by a factor of 1.55 due to bPL process. While this factor was 1.787 for loading sequence H-L.

References

[1] S. sathyajith, S. kalainathan, S. Swaroop, (2013) "Laser peening without coating on aluminum alloy Al-6061-T6 using low entics ergy Nd:YAG laser" optics and laser technology 45,489-394.

[2] Jon E. Rankin, Michael R. Hill, L loyd A. Hackel, (2003) "The effects of process variation on residual stress in laser peening 7049-T3 Aluminum alloy" Material science and Engineering A349,279-291.

[3] Uros Trdan, Juan A. Porro. Jose L. ocana, Janez Grum, (2012) "Laser shock peening without absorbent coating (LSPWC) effect on 3D surface topography and mechanical properties of 6082- T651Al- alloy" Surface and coatings Technology 208, 109-116.

[4] P. Ganesh, R. Sundar, H. Kumar, (2013) "Studies on fatigue life enhancement of pre-fatigued spring steel specimens using laser shock peening." Raja Ramanna Centre for Advanced Technology, P.O. CAT, Indore 452 013, India.

[5] J.Z. Zhou, S. Huang n, L. D.Zuo, (2013) " Effects of laser peening on residual stresses and fatigue crack growth properties of Ti–6Al–4V titanium alloy" School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, PR China.

[6] S. Huang , J.Z. Zhou , J. Sheng, (2013) " Effects of laser energy on fatigue crack growth properties of 6061-T6 aluminum alloy subjected to multiple laser peening" School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, PR China.

[7] J.Z Zhou, S. Huang, J. Sheng, (2013) "Effect of repeated impacts on mechanical properties and fatigue morphologies of 6061-T6 aluminum subject to laser peening." School of Mechanical Engineering Jiangsu University, Zhenjiang 212013, PR China.

[8] Charles S. Montross , Tao Wei, (2006)" Laser shock processing and its effects on microstructure an properties of metal alloys: a review," Center of Expertise in Damage Mechanics, NSW2006, Australia

[9] Xiangfan Nie, Weifeng H, (2013)" Experiment investigation of laser shock peening on TC6 titanium alloy to improve high cycle fatigue performance. Science and Technology on Plasma Dynamics Lab .China.

[10] Ramana V. Grandhi, (2013) "Effects of curved geometry on residual stress in laser peening," Department of Mechanical and Materials Engineering, Wright State University, Dayton, OH 45435, USA.

[11] A King, A Steuwer, C Woodward, PJ. Withers, (2006) "Effects of fatigue and fretting on residual

stresses introduced by laser shock peening" Mater Sci Eng, A, 435-436, pp. 12–18, UK.

[12] A.W. Warren, Y.B. Guo, S.C. Chen, (2007)"Massive parallel laser shock peening :Simulation, analysis, and validation." The University of Alabama, Tuscaloosa, AL 35487, United States.

[13] Charles S. Montross, Tao Wei, Lin Ye, (2002), "Laser shock processing and its effects on microstructure and properties of metal alloys: a review." University of Sydney, Sydney, NSW 2006, Australia.

[14] M. Achintha, D. Nowell, D. Fufari , E.E. Sackett, (2013)"Fatigue behavior of geometric features subjected to laser shock peening: Experiments and modeling " Engineering and the Environment, University of Southampton, Southampton UK.

[15] Yinqun Hua, Yuchuan Baib, Yunxia Ye, "Hot corrosion behavior of TC11 titanium alloy treated bylaser shock processing, (2013)"School of Material Science and Engineering, Jiangsu University, Zhenjiang, Jiangsu, China.

[16] J. Fornell, E. Pellicer, E. Garcia-Lecinab, (2013)"Structural and mechanical modifications induced on Cu47.5Zr47.5Al5 metallic glass by surface laser treatments", Departament de Fsica, Universitat Auțnoma de Barcelona,. Bellaterra, Spain.

[17] Samer S.murdhi, (2013). "Fatigue behavior under shot peening and laser peening stainless steel turbine shaft "A thesis submitted to the material engineering department ,AL –Mustansiriya University , Degree of master of science.

[18] Pantelakis SP. G., Haidemenopoulos G. n., (1996) "Effect of novel paint removed processes on the Fatigue behavior of Al alloy 2024 " Surface and the Technology, 106.

[19] Daniel G., Claudia P, Rachana D.B,Jasper P.Sisa P.,Bathusile M ,Tebogo M.,Enrico T. , (2014) "Laser shock Peening on a 6065-T4 Al. alloy airframe application “Advanced Materials Research, vol891-892.

[20] Miller K. J., Alalkawi Mohammed H. J.,de los Rios E.R., (1986) "Fatigue damage accumulation above and below the fatigue limit “European Group on Fracture publication, No.l, EGFI, London.