Journal of Solid and Fluid Mechanics (JSFM), 14(5): 1-5, 2025

Shahrood University of Technology

Journal of Solid and Fluid Mechanics (JSFM)

DOI: 10.22044/jsfm.2024.14595.3871

Manufacturing Engineering of Iran

Investigation of the Simultaneous Effect of Laser Shock Peening and Graphene Oxide Coating on Residual Stress and Fatigue Corrosion Properties of IN792 Alloy

A.Afsarimoghaddam[1], S. Y. Ahmadi broghani[2*], Y. Yaghoubinezhad[3] , M. khanzadeh[4]

[1] Ph.D. Student, Mechanical Engineering Department, University of Birjand, birjand, Iran

[2] Prof. of Mechanical Engineering, University of Birjand, birjand, Iran

[3] Assoc. Prof. of Materials Engineering, Birjand University of Technology, birjand, Iran

[4] Assist. Prof., Departement of Physics, Vali-e-Asr University of Rafsanjan, Rafsanjan, Iran

*Corresponding author: syahmadi@birjand.ac.ir

Received: 06/18/2024 Revised: 08/27/2024 Accepted: 10/09/2024

Abstract

Laser shock peening is a mechanical surface treatment that is caused by laser beam radiation on the surface of the metal. This processing causes plastic deformation, and compressive residual stresses under the surface of metal. In addition, applying nanostructure coatings is one of the new methods to increase the resistance of components under corrosive environment and high temperature. The purpose of this article is to investigate laser shock peening on residual stress and fatigue corrosion of Inconel 792 in $75\%\ Na_2SO_4 + 15\%\ NaCl + 10\%\ V_2O_5$ environment. For this purpose, a number of samples were subjected to laser shock peening and another group was coated with graphene oxide before laser processing. Then, all the samples were subjected to corrosive environment at high temperature, and then the fatigue test was performed. The result of this research showed that the laser shock peening operation increased the fatigue life of this alloy for 2.4 times.

Keywords: Laser Shock Peening; Graphene Oxide Coating; Residual Stress; Fatigue Corrosion

1. Introduction

Nickel-based superalloys are used in gas power plants due to their high mechanical properties and corrosion resistance [1, 2]. In certain environments, these alloys are prone to surface pit formation, which can initiate and propagate fatigue cracks under cyclic loading. This reduction compromises the alloy’s fatigue corrosion resistance [3].

In another study, after laser peening, improvements in microhardness and residual stress were observed due to the induced plastic deformation. Furthermore, with an increase in the number of laser impacts, both effective hardness depth and residual stress increased. Results showed that the fatigue life of samples subjected to three laser impacts increased by as much as 244%. [4].

In a study, fatigue tests with strain ranges from 0.4 to 1.2 percent were performed on the samples. Investigations revealed that in laser shock peened samples, crack initiation was reduced, the spacing of fatigue lines was shorter, and smaller micro-pits were formed. Additionally, the plastic deformation, very fine grains, twinning, and dislocations created due to this operation can prevent the initiation and propagation of cracks, thereby increasing the fatigue life of Inconel 625 [5].

In past studies, The effects of laser peening on the fatigue corrosion resistance of metallic materials have been rarely examined, especially in comparison to conventional surface treatments; especially, the effects of residual stresses combined with microstructure during this process for the Inconel 792 superalloy have not been investigated so far. Therefore, research into the corrosion behavior of metallic materials subjected to laser shock peening is valuable. Moreover, the coating of superalloy with graphene nanostructured coatings and the combined effect with a surface treatment has not been studied so far.

2. Method of Experimentation

2.1. Material Selection

The tensile and fatigue samples were prepared from a cast bulk of Inconel 792. XRF analysis was conducted to determine the chemical composition of the elements in this material.

2.2. Determining Mechanical Properties

To determine the mechanical properties of the material, flat tensile samples were prepared and tensile testing was performed using a Zwick 60-ton machine.

2.3. Coating Process

Coatings on the samples were created using an electrochemical method. To achieve a uniform coating with an acceptable thickness, 10 layering steps were performed on the samples.

2.4. Laser Shock Peening Operation

Typically, a Q-Switched Nd:YAG laser (1064 nm) is used with high energy (J 1-8) and short pulse duration (ns 6-20), which passes through a transparent medium (water or glass) to remove a thin coating (aluminum tape or commercial black paint) from the surface of the material [6]. When the laser beam irradiate to metallic surfaces, the heated area vaporizes in a very short time (a few nanoseconds) to reach temperatures exceeding 10000; then, it converts into plasma through ionization. The plasma continues to absorb laser energy until the end of the laser pulse duration. The pressure from the plasma is transferred to the material through shock waves. To increase shock pressure, the metal surface is usually covered with an opaque material such as black paint or aluminum tape, while a transparent material like distilled water or glass is placed against the laser beam [7].

2.5. Fatigue Corrosion Test

To simulate the power plant environment and induce corrosion, the corrosive material with a chemical composition $75\%\ Na_2SO_4 + 15\%\ NaCl + 10\%\ V_2O_5$ has been sprayed on all samples [8]. Before applying the corrosive coating, the samples were preheated at 200℃, and then each sample's surface was covered with approximately 3 to 4 grams per square centimeter of the corrosive material. Subsequently, they were placed in an oven at a temperature of 600℃ for 48 hours.

Fatigue testing was carried out according to the standard on three groups of samples: 1) Polished raw samples, 2) Coated and laser-treated samples, and 3) Laser-treated samples. This test was conducted at the Razi Research Center under tension and compression at a frequency of 10 Hertz at room temperature. Samples were subjected to loading until failure with 50% of the ultimate stress, and the number of cycles until fracture was recorded.

3- Results and Discussion:

3.1. Tensile and Microhardness Test Results

The tensile test was conducted at a rate of 1 mm per minute. Yield stress is 700 MPa and Young's modulus is 180 GPa. The microhardness of the material after laser shock peening changed from 263 to 315 and 300 for samples from groups 2 and 3 respectively. This result indicate a 20 percent increase in surface microhardness after laser treatment. Other studies have also shown that this operation significantly affects microhardness [9 and 10].

3.2. Residual Stress

To evaluate the residual stress, Xpert HighScore Plus software was used.

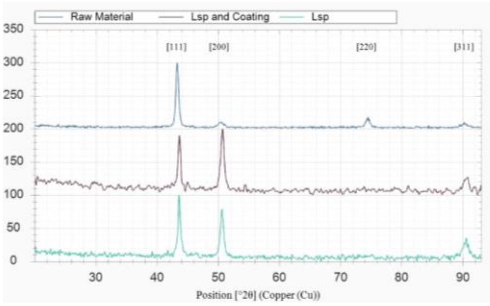


Figure 1. X-ray diffraction test results of three different samples, top: raw material, coated, and laser shock peened samples

Figure 1 indicates no new peaks being formed in the XRD graph as a result of this operation, indicating that no phase transitions or new phases have formed in the material. Only the intensity of the peaks has significantly decreased, indicating the refinement of grain sizes. The residual stress at the surface of the sample under two operations (laser shock peening and coating) was recorded at -270 MPa, while for the sample subjected to laser shock peening it was -290 MPa.

As a result of laser shock operations, residual compressive stresses are generated due to the impact on the sample's surface. The Xpert HighScore Plus software was used to analyze the obtained pattern and identify the peaks. The height, peak width, FWHM, crystal size, and strain were calculated. Based on the Williamson-Hall plot and using relations 1 and 2, the residual stresses in the samples were calculated. In these two relations, ε is the strain in the desired plane, σ is the stress in the plane, E and υ are material constants, ϕ and ψ are the angles of the planes, d is the distance between the parallel crystalline planes, and d_0 is the interplanar distance in an unstressed sample [11] .

$$\varepsilon_{\phi\psi} = \frac{1+\nu}{E}(\sigma_1 Cos^2\phi + \sigma_2 Sin\phi) * \sin^2\psi - \frac{\nu}{E}(\sigma_1 + \sigma_2) \qquad (1)$$

$$\sigma_\phi = \frac{E}{(1+\nu)Sin^2\psi}(\frac{d_\psi - d_n}{d_n}) \qquad (2)$$

Using equation 3 (Scherer's relation), the average crystal size can be calculated [12] and the grain size can be obtained using estimates where D is the crystal size, λ is the wavelength, K is the shape factor, and β is the peak width. and θ is the location of the peak. Using the Scherer equation calculator in Xpert software, by entering the FWHM values and also the angular position of the desired diffraction line, the crystal size and lattice strain are calculated . The size of the crystals obtained from the XRD test that the laser shock peening operation has reduced the size of the crystals.

$$D = \frac{K\lambda}{\beta Cos\theta} \quad (3)$$

3.3. Fatigue corrosion analysis

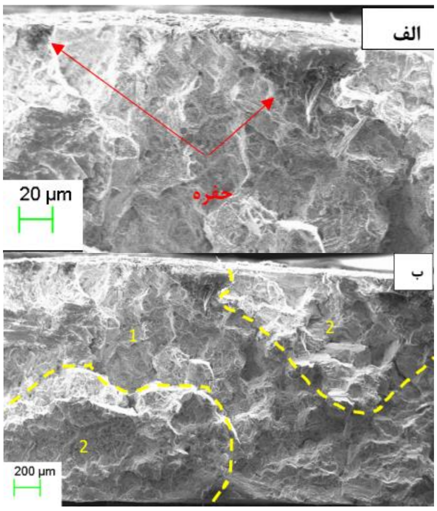
Fatigue tests were performed on Inconel 792 samples after corrosion, before and after laser shock peening. Table 1 shows the fatigue test results.

Table 1. Fatigue test results

3) Laser shock peening sample	2) Coating and laser shock peening sample	1)Rraw sample without treatment	Type of sample
36900	36163	15000	Number of cycles to fracture

3.4. Microstructural analysis

After the fatigue test, the cross-section of fracture surfaces were tested with Scanning Electron Microscope (SEM). Figure 2 shows these images for the raw and unprocessed sample.

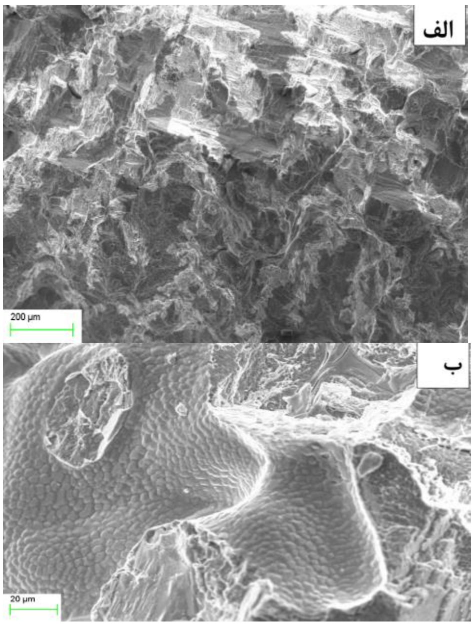


A

B

Figure 2. SEM of the fracture surface of the sample without operation after the fatigue test

After the fatigue and fracture tests of the samples were completed, the fracture cross-section was examined using a Scanning Electron Microscope (SEM) for fractography. Figure 2 shows these images for the raw sample without any treatment. Figure 2 illustrates the fracture surface of the sample corroded with a salt coating for 48 hours at 600 degrees Celsius without any post-fatigue fracture processing. Figure 2A shows the initiation site of the crack along the margins of the fatigue fracture surfaces. These areas are pits formed on the surface due to corrosion. The origin of fatigue crack initiation was from these points on the surface, which ultimately led to final fracture under cyclic loading. Figure 2B presents a macro image with higher magnification of the fracture surface and the regions formed on it. The regions of fatigue crack growth are evident from the beach marks visible on the fracture surface. Cyclic stress application creates fatigue conditions in the material. Corrosion leads to the formation of pits and cavities on the material's surface, which facilitate the growth of fatigue cracks [12]. The wavy lines indicate the mechanism of fatigue failure. The surface of the samples first undergoes corrosion; this corrosion aids in the initiation and growth of fatigue cracks, and eventually, due to the propagation of the fatigue crack, the sample fails under the fatigue mechanism. A series of parallel fatigue lines are observed in laser peened samples. As shown in Figure 3A, the fracture surface is almost free of microcracks. Grain boundaries act as a barrier to crack propagation [13]. Increased grain boundary formation due to laser shock peening accounts for the extended fatigue life to failure in the laser-peened sample compared to the untreated sample. The SEM results align well with the XRD test results regarding the reduction in grain size during this process, as discussed in the previous section. Laser shock peening has managed to close microcracks by inducing plastic deformation in the material's surface. The SEM image of the fracture surface of the sample after coating and laser shock peening also confirms the absence of microcracks and the reduction in grain size due to this surface treatment (3A). As shown in Figure 3A, the zigzag crack propagation path makes crack growth more difficult; for this reason, the samples subjected to laser peening and coating have undergone more cycles until failure.



A

B

Figure 3. SEM image of the sample after coating and laser shock peening

3.5. Electrochemical Corrosion Analysis

The polarization corrosion test was conducted for the coated and laser-treated samples in a 3.5% NaCl solution. Based on the results obtained from the potentiodynamic polarization curves in Figure 4, it is observed that the presence of graphene in the coating acts as a protective layer for the material against corrosion.

The corrosion rate of the sample under laser peening operations is reduced compared to the raw material due to higher corrosion potential and lower corrosion current density. The improvement in corrosion resistance is attributed to the reduction of surface defects and the increase in mechanical performance resulting from laser shock peening. Additionally, this mechanical treatment reduces surface defects such as pores and cracks, thereby delaying corrosion [14].

When laser shock peening is applied to Inconel, it induces compressive strains on the surface of the material. The residual compressive stresses generated as a result can affect the corrosion behavior of the materials. In this operation, the residual compressive stresses from shock waves contribute to the corrosion resistance of the materials. Corrosion processes often begin with the formation and propagation of cracks on the surface of materials; this mechanical operation prevents crack propagation through surface compression. This helps to prevent the penetration of corrosive agents and the spread of corrosion damage [15].

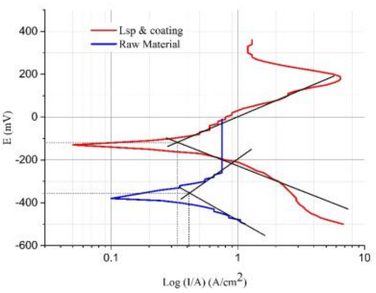


Figure 4. Comparison of the polarization curve of the raw sample and the coated and laser sample

4 - Conclusion

Failure resulting from the combination of fatigue loading and corrosion is one of the reasons for the degradation of gas turbine components. The creation of favorable residual compressive stress plays a significant role in improving the life of turbine blades. This research aims to present a novel method for enhancing the fatigue life of components under cyclic loading in corrosive environments. The results of this research are as follows:

1- Laser shock peening operations create residual compressive stress on the material's surface due to the propagation of shock waves within the material.

2- Laser shock peening operations reduce the grain size of the material by locking dislocations.

3- The creation of residual compressive stress on the surface through laser shock peening significantly increases the fatigue life of the material.

4- The formation of a graphene oxide coating enhances the corrosion resistance of the superalloy.

5- One of the reasons for the reduction of residual stress in the coated sample compared to the uncoated sample after laser shock peening is that the coating layer was applied before the laser process. During the laser shock peening, it acts as a buffer layer, preventing the laser wave from fully penetrating into the main sample.

6- Laser shock peening and coating enhance the fatigue life 2.4 times.

7- The corrosion current and corrosion potential in the treated sample compared to the raw material changed by 24% and 218%, respectively.

References

[1] Brooks, C. R. (1982). Heat treatment, structure and properties of nonferrous alloys. (No Title).

[2] Sims, C. T., Stoloff, N. S., & Hagel, W. C. (Eds.). (1987). superalloys II (Vol. 8). New York: Wiley.

[3] Neidel, A., & Riesenbeck, S. (2012). Pitting Corrosion Induced Fatigue Fracture on a Gas Turbine Compressor Blade. *Practical Metallography*, 49(1), 35-48.

[4] Wang, C., Shen, X. J., An, Z. B., Zhou, L. C., & Chai, Y. (2016). Effects of laser shock processing on microstructure and mechanical properties of K403 nickel-alloy. *Materials & Design*, 89, 582-588.

[5] Sun, Y., Wu, H., Du, H., & Yao, Z. (2022). Investigation of Strain Fatigue Behavior for Inconel 625 with Laser Shock Peening. *Materials*, 15(20), 7269.

[6] Telang, A., Gill, A. S., Teysseyre, S., Mannava, S. R., Qian, D., & Vasudevan, V. K. (2015). Effects of laser shock peening on SCC behavior of Alloy 600 in tetrathionate solution. *Corrosion Science*, 90, 434-444.

[7] TELANG, A., GILL, A. S., RAMAKRISHNAN, G., & VASUDEVAN, V. K. (2018). Effect of Different Ablative Overlays on Residual Stresses Introduced in IN718 SPF by Laser Shock Peening. *International Journal of Peening Science & Technology*, 1(1).

[8] Pradhan, D., Mahobia, G. S., Chattopadhyay, K., & Singh, V. (2018). Effect of pre hot corrosion on high cycle fatigue behavior of the superalloy IN718 at 600 C. *International Journal of Fatigue*, 114, 120-129.

[9] Rozmus-Górnikowska, M., Kusiński, J., & Cieniek, Ł. (2020). Effect of laser shock peening on the microstructure and properties of the inconel 625 surface layer. *Journal of Materials Engineering and Performance*, 29, 1544-1549.

[10] Bae, S., Kim, Y., Jung, J., Shin, K., Suh, C. M., & Jeong, S. (2024). Effects of laser shock peening on Inconel 738LC to improve mechanical and fatigue characteristics. *Optics & Laser Technology*, 171, 110290.

[11] Hilly, M. E. (1971). Residual stress measurement by X-ray diffraction. *SAE Information Report*, 784.

[12] Mahobia, G. S., Paulose, N., Mannan, S. L., Sudhakar, R. G., Chattopadhyay, K., Srinivas, N. S., & Singh, V. (2014). Effect of hot corrosion on low cycle fatigue behavior of superalloy IN718. *International Journal of Fatigue*, 59, 272-281.

[13] Ross, J. R. (2018). Contemporary Catalysis: Fundamentals and Current Applications. *Elsevier*.
[14] Huang, S., Liu, J., Sheng, J., Meng, X., Hu, X., Zhu, M., ... & Zhou, J. (2022). High-temperature fatigue crack growth characteristics of IN718 Ni-based alloy treated by laser peening. *Engineering Fracture Mechanics*, 276, 108922.
[15] Yoo, Y. R., Choi, S. H., & Kim, Y. S. (2023). Effect of laser peening on the corrosion properties of 304L stainless steel. *Materials*, 16(2), 804.