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LASER SHOCK PEENING OF N-155 SUPERALLOY AFTER LONGTIME SERVICE

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Preliminary notes
Iron base superalloy N-155 samples have been cut from the turbine blade which had been exposed to elevated pressure and temperature during its long-time service. The samples have been irradiated with pulsed laser beam, observed with scanning electron microscopy (SEM) and analysed by energo-dispersive spectrometry (EDS). The range of implemented beam parameters for which two types of treatments – mechanical and thermo-mechanical – occurred, has been determined. Vickers micro hardness tests have shown the increase in micro hardness after laser treatment.

Keywords: *EDS, laser, mechanical treatment, microstructure, SEM, superalloy*

Mehanička obrada laserom superlegure N-155 nakon dugotrajnog rada

Prethodno priopćenje
Uzorci superlegure željeza N-155 isječeni su iz lopatice turbine nakon dugotrajnog rada na povišenim temperaturama i tlakovima. Uzorci su izloženi impulsima lasera različitih parametara, promatrani skenirajućim elektronskim mikroskopom (SEM) i analizirani energodisperzivnom spektrometrijom (EDS). U ovisnosti o parametrima lasera, interakcija laserskog snopa i materijala je u nekim slučajevima promatrana kao mehanička, a u drugim kao termomehanička obrada. Mikrotvrdoće su mjerene po Vikersu. U ovom radu, analizirane su mikrostrukture nastale nakon različitih frekvencija impulsa i zatim uspoređene.

Ključne riječi*: EDS, laser, mehanička obrada, mikrostruktura, SEM, superlegura*

1 Introduction

N-155 superalloy is an alloy with good ductility, strength, excellent oxidation, and corrosion resistance, and can be readily fabricated and machined. It is used in numerous aircraft applications such as tail cones and tailpipes, exhaust manifolds, combustion chambers, afterburners, turbine blades and buckets, and bolts.

Many superalloys are generally subjected to cyclic loading at elevated temperature service. Surface morphology plays an important role in the performance of machine parts that experience cyclic loading. Under fatigue loading, cracks always nucleate from the free surface [1].

Lasers have been used for precise materials processing in micro and nano manufacturing operations due to their non-contact nature and high intensity [2]. The processes occurring during the interaction between the laser beam and surfaces of alloy systems [3] are multifold, influencing various features of the target material (thermal, mechanical, electrical and optical characteristics, surface and subsurface structure…).

The principle of laser shock peening (LSP) is to generate high-pressure shock waves at the surface of the workpiece, by using a high intensity laser beam and suitable overlays covering the surface [4].

The magnitude of formed compressive residual stress is maximal at the surface and decreases deeper in the material. The transient shock waves can also induce two effects, microstructure changes near the surface and forming of high-density dislocations. The combination of the effects contributes to the amelioration of the mechanical properties near the surface. The compressive residual stresses improve the resistance to corrosion fatigue. The advantage of the LSP is that the affected volume is deeper, as compared to the conventional shot peening.

The LSP improves fatigue, corrosion and wearing resistances of metals through mechanical effect produced by shock waves. It is well suited for precisely controlled treatment of localized fatigue critical areas, such as holes, notches, fillets and welds [4].

The investigation is carried out with the aim to improve mechanical properties or recover the material after long time service as laser shock peening improves fatigue, corrosion and wearing resistance. By laser treatment of material we tried to improve microstructure of crept material and in that way its life. For the N-155 super alloy, it has been shown [5 ÷ 7] that, depending on the implemented laser parameters, the processes developed in the material are numerous and linked to the heating of the narrow area of the material, melting and evaporation. Moreover, several other processes arise due to the influence of the heat wave: thermal plastic deformation of the material, the change of the grain shape and volume, slide strips, initial pores and cracks [7, 8].

2 Experiment

The experiment was carried out on iron base superalloy samples that had been cut from turbine blades after 10 000 h of exploitation. The dimensions of samples were 20 × 10 × 1,2 mm, and their chemical composition is listed in Tab. 1; it should be noted that the oxygen is absent from the superalloy. The experiment setup is presented in Fig. 1.

For the LSP, the surface of the specimen is pre-coated with a thin layer of sprayed material highly absorptive at the operating wavelength of the laser beam [3] and is soaked in or covered with transparent material.

In this paper, the surface of the samples is sprayed with a black paint (as an absorptive/protective layer), the samples are placed in the container filled with distilled water (a translucent layer) and exposed to pulsed laser beam (Nd^{3+}:YAG, wavelength 532 nm, pulse energy 37 mJ, and duration 10 ns). The protective overlay is used for two reasons: (1) to absorb the incident thermal energy, expand and transfer the shock wave to the target surface and (2) to protect the target from the heat influence of the incident beam. The implementation of the transparent layer increases the plasma pressure by a trapping-like effect on the plasma expansion.

Table 1 Chemical composition of superalloy N-155

element	Ni	Cr	Mo	Mn	Si	
% wt	20,0	21,0	3,0	1,5	0,5	
element	Fe	C	Al	Co	W	Nb
% wt	30,0	0,15	0,15	20,0	1,2	2,0

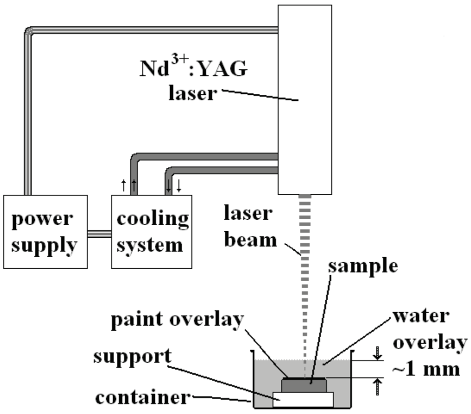

Figure 1 The experimental setup

The material is treated with nearly square-shaped profile of the laser beam, as there is no focus point of release waves. The residual stress drop will not be as remarkable as that treated by a round laser spot. For a circular shape, there is a lack of residual stresses at the centre of the treated zone after laser interaction. It may be attributed to the simultaneous focusing of the waves emitted from the edges of the area under impact [4]. To avoid this defect, the circular symmetry should be eliminated, for example by using rectangular beam [8].

The samples are exposed to various numbers of laser pulses with different repetition frequencies (Tab. 2).

Table 2 The number of pulses and different pulse frequencies used in the experiment

Repetition frequency, Hz	1	2	4
Number of pulses	20	16	12

The microstructure is observed by scanning electron microscope – model JEOL JSM-5800, and analysed by energo-dispersive spectrometry (EDS). The micro-hardness measurement is performed by Vickers using the apparatus – model ZWIK– Edman Weltzar and under load of 0,5 N.

3 Results and discussion

In this work, the analysis of the experiment with complex-structured N-155 superalloy is presented. The main characteristics of the workpiece from which the samples were cut off is that it was exposed to creeping process during its regular working life without functional damaging. During the creeping process, nano- and micro-structure changes regularly occur, which is influential to macro-structure [9]. It is also expected for new structural changes to occur during the additional interaction with laser beam in small, restricted areas. Therefore, the X-ray diffraction analysis would then be a useful tool for the discussion on melting processes. Moreover, the estimation of the reflections, which tell us about the activation of particular crystal planes depending on the creeping process effects and frequency differences, would be useful for the determination of thermal effects.

The microstructure of the N-155 superalloy workpiece sample is presented in Fig. 2. Several areas of the inhomogeneity are visible in the microstructure, the areas with micro-pores of approx. 9 nm in size. These areas appeared in the form of bright circles with fine-grain structure (Fig. 3) [5 ÷ 7].

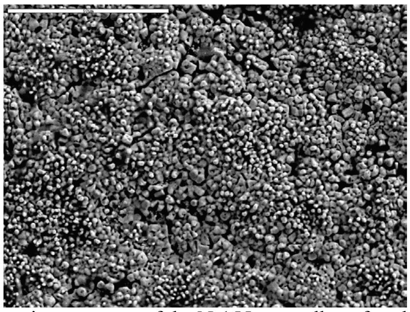

Figure 2 The microstructure of the N-155 superalloy after the creeping process (1000×); the white bar in the upper left corner indicates 50 μm.

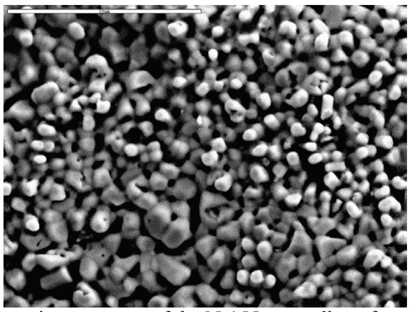

Figure 3 The microstructure of the N-155 superalloy after the creeping process (1000×); the white bar in the upper left corner indicates 20 μm.

According to Tabs. 2 and 3, it is very likely that the oxidation occurred during the creeping process. Forming of Cr_2O_3 also affirms this, with keeping in mind that chromium has high melting temperature and high oxygen affinity. Besides this, increased content of C suggests Cr-carbide forming as well.

Table 3 EDS results for Fig. 2

element	O	C	Al	Si	Cr	Mn
% wt.	7,9	2,1	1,38	0,66	55,40	0,22
element	Fe	Co	Ni	Nb	Mo	W
% wt.	22,49	10,87	5,23	1,51	2,26	

Figs. 4 and 5 show the microstructure after laser treatment of longtime exposed N-155 alloy. The interaction with laser pulses caused the structure homogenization.

Tab. 4 presents the EDS results of the microstructure from Fig. 4, while Tab. 5 presents the EDS results of the areas depicted with blue rectangles in Fig. 5. Increased content of chromium suggests further forming of chromium carbides. The analysis of the EDS results leads to conclusion that the laser treatment of the crept iron based samples increases the presence of Cr carbides while reducing the presence of oxides.

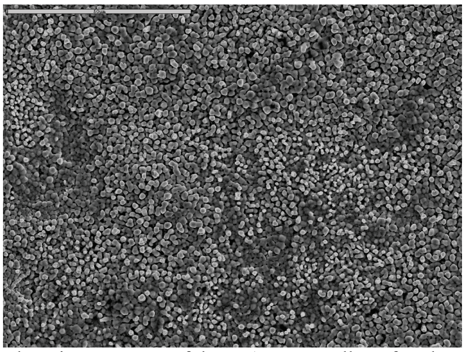

Figure 4 The microstructure of the N-155 superalloy after the process of creeping and the laser treatment (37 mJ, 987 mJ/cm^2, 10 ns, 1 Hz, 1000×); the white bar in the upper left corner indicates 50 μm.

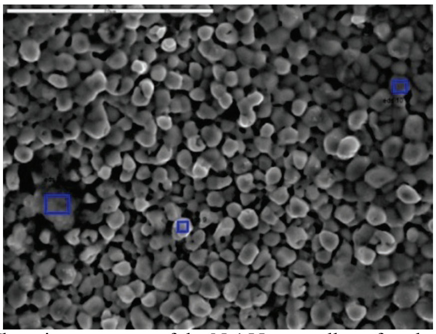

Figure 5 The microstructure of the N-155 superalloy after the process of creeping and the laser treatment (37 mJ, 987 mJ/cm^2, 10 ns, 1 Hz, 3000×); the white bar in the upper left corner indicates 20 μm.

Table 4 EDS results for Fig. 4

element	O	C	Al	Si	Cr	Mn
% wt.	2,1	3,03	0,86	0,48	58,25	0,23
element	Fe	Co	Ni	Nb	Mo	W
% wt.	17,21	7,56	5,23	1,62	2,38	1,05

Table 5 EDS results of the areas 8, 9 and 10 from Fig. 5

	Si	S	Cr	Fe	Co	Ni
area 8	2,06	0,65	62,06	22,57	9,03	3,63
area 9	0,34	0,95	62,97	22,20	9,24	4,26
area 10	0,30	0,98	58,16	27,08	10,47	3,00

The samples are treated with pulsed beams of various repetition frequencies and different number of pulses, as shown in Tab. 2. It has been noticed that, at 1 Hz of repetition frequency, only the effects of the mechanical treatment occurred, while on higher repetition frequencies (2 and 4 Hz) both mechanical and thermo-mechanical effects took place. This suggests 1 Hz to be the threshold repetition for the occurrence of thermal effects. There is no clear boundary between only mechanical and only thermal processes. The range of parameters combination (fluence, repetition rate, the area of interaction) for which both of the effects take place is wide. At 1 Hz, there was enough time for the material to cool down before the next pulse impinged the zone of the interaction, while at higher frequencies the accumulation of the energy between two pulses led to melting processes. However, in spite of the occurrence of the melting at higher repetition rates, the mechanical effects remained at the areas of the interaction zone separately from the areas where thermo-mechanical effects occurred. This is due to several reasons. The energy was unevenly distributed over the surface of the interaction zone, resulting in local variations of the fluence (Fig. 6), the inhomogeneity of the thickness of the absorption layer over the interaction area and – possibly – the inhomogeneity of the material itself.

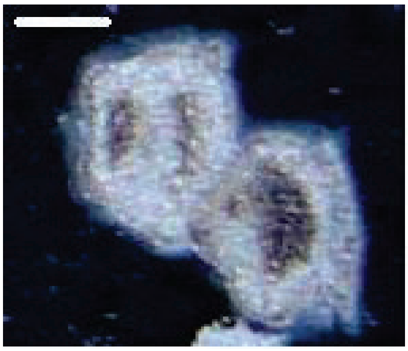

Figure 6 The view of the damage, indicating the uneven distribution of the beam energy over the interaction zone; the white bar in the upper left corner denotes 1 mm.

The microstructures of the N-155 superalloy samples after the process of creeping and the laser treatment with 2 and 4 Hz repetition frequencies are shown in Figs. 7 and 8. Melted areas at the surface, which represent the homogenous structure, are visible; it is assumed that the surface solidification occurred and the plastic wave, which commonly creates residual stresses in the material [10 ÷ 12], selectively strengthening the surface layers of controlled dimensions, has been generated.

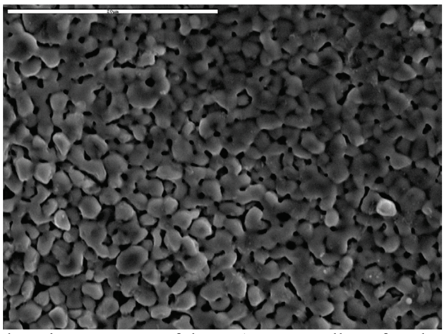

Figure 7 The microstructure of the N-155 superalloy after the process of creeping and the laser treatment (37 mJ, 987 mJ/cm^2, 10 ns, 2 Hz, 3000×); the white bar in the upper left corner indicates 20 μm.

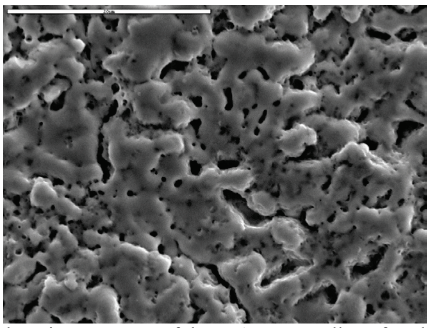

Figure 8 The microstructure of the N-155 superalloy after the processs of creeping and the laser treatment (37 mJ, 987 mJ/cm^2, 10 ns, 4 Hz, 3000×); the white bar in the upper left corner indicates 20 μm.

Besides numerous different processes simultaneously occurring in the material, the formation of melted areas during the interactions of 2 and 4 Hz (Figs. 7 and 8, respectively) is followed by a strong thermo-plastic deformation of the material.

In Fig. 9, the comparative results of the microhardness testing of the samples are presented. BM stands for the "base material", i.e. crept samples not subjected to the laser beam. 1 Hz, 2 Hz and 4 Hz stand for the pulse repetition rates used during the interaction with the beam, i.e. laser-treated crept samples. These results confirm the microhardness increase after the laser beam interaction with the material. Different pulse repetition rates do not have noticeable influence to the microhardness of the material.

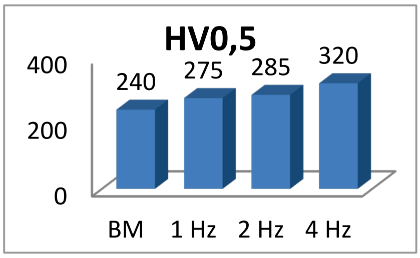

Figure 9 Results of microhardness tests for crept material (base material, BM) and for crept material treated by pulsed beam with variable repetition rates (1 Hz, 2 Hz and 4 Hz).

According to the literature [13, 14], it could be assumed that the changes occurred in the bulk of the material.

4 Conclusion

The oxidation commonly occurs in the process of creeping during the regular working life of the specimen. The interaction of the ns laser beam caused the increase in both Cr and Si contents. The laser beam treatment of the crept iron-based samples increased the content of Cr carbides and reduced the forming of Cr oxides. Some issues connected to other materials described in a previous work [15] – the number of pulses leading to melting – here are briefly notified. On lower repetition rates, only mechanical treatment (the LSP) has been noticed, due to the sufficiency of time for the material to cool down. On 2 Hz and 4 Hz of repetitions, the formation of melted areas took place, and a strong thermo-plastic deformation of the material occurred. The laser beam interaction increased the microhardness of investigated material.

Acknowledgments

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