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Laser heat treatment effect on fatigue of hinged cantilever beams

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Abstract. The paper considers the effect of laser hardening treatment of steels on the fatigue strength of materials. The statement of efficiency of laser processing for formation of hard surface layer of processed surface which protects from wear is substantiated in relation to a hinge design in agricultural machines placed on a cantilever fastened beam which is a hinge axis. The phenomenon of reduction of fatigue characteristics of structural steels after laser treatment is investigated. Influence of fatigue loading on beam durability is analyzed. On the basis of experimental data analysis, the conclusion is formulated that the surface defects in the form of wells which are formed under the influence of laser pulse play an important role during the pulse laser treatment. Particular attention is paid to the role of residual stresses generated by the thermal effects of the laser. On the basis of this research, it is recommended that laser hardening treatment should be carried out, the pulse energy of which does not lead to surface melting.

1 Introduction

Cantilevered beam constructions with movable bearing units are widely used in various industries, e.g. in additive manufacturing apparatuses, in agricultural machinery for the attachment of pulleys of power transmission mechanisms by flexible links. Cantilever beams are often the axes of the bearings mounted on them. In critical applications, the shafts are made from high-strength stainless steel, more often carbon structural steels. Laser heat treatment is used to increase wear resistance of surfaces, but the increase in wear resistance of beams can lead to reduction of fatigue strength of beam material. It is shown in [1] that laser heat treatment technology can increase the hardness of parts through laser hardening process but may exhibit limited fatigue wear resistance. The authors believe that the laser treatment process could replace the conventional thermal cementation process. A laser surface hardening fatigue study of flat stainless steel samples was carried out in [2]. The microstructure of the hardened layer in the fusion zone was investigated. Experiments were conducted with a laser beam power of 1200 W, a welding speed of 200 mm/min and a focal distance of 10 mm, which improved the mechanical properties of steel. In the paper [3] the low-cycle fatigue of 316L steel was investigated with selective laser melting. It is shown that steel 316L obtained by selective melting has stable cyclic softening and higher fatigue life, has higher strength, yield strength 1.9 times higher than that of conventional steel 316L. In

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[4] the fatigue characteristics of martensitic stainless steel produced by using jetting technology with different levels of porosity and under two different ageing conditions and with the alloy characteristics produced by the conventional method are compared. It is found that fatigue strength is increased by reducing porosity. The fatigue strength of steels after laser hardening has received much attention. In [5] the fatigue properties of the ageing steel produced by laser cladding were studied. Efforts have been made to improve the wear resistance and fatigue properties of steel using the method of surface modification by fine-dispersed hardening under induction heating with controlled atmosphere. Laser impact hardening [6] is a method of improving the surface by creating favourable residual compressive stresses, increasing the resistance to propagation of cracks. This type of laser hardening treatment is shown to effectively improve fatigue resistance and crack propagation characteristics of AISI D2 steel. The paper [7] deals with the study of fatigue resistance improvement by laser impact surface treatment, which is a surface modification technique using high-energy laser without absorption coating. Treatment creates favourable compressive residual stresses with a hardened surface layer but causes intergranular corrosion, which does not increase service life due to low fatigue. In [8], the effect of laser impact hardening on the surface properties and tensile behaviour of ASTM A 588 grade D low alloy steel was studied. It was found that laser technology h improves mechanical surface properties without a significant deterioration in surface roughness. Crack accumulation was significantly reduced, resulting in an increase in fatigue life: approximately twice as long as untreated samples. Paper [9] describes the results of uniaxial tension and fatigue tests with controlled stress on stainless steel 2205 of 4 mm thickness. The microstructural characteristics of the compounds were investigated by optical microscopy and electron backscatter diffraction. Experiments were carried out to characterise the mechanical properties of samples containing laser beam welded joints. Much research has been done in the field of materials analysis after laser treatment and evolution of fatigue cracks. In [10] an analytical model is presented to predict the distribution of residual stresses induced by the laser treatment process. The material softening properties induced by laser heating and its influence on distributed stresses and mechanical stresses are considered. To achieve this, a flux stress model is used, which takes into account the combined effects of laser heating and plastic deformation. The correspondence between predicted and measured results confirms that the proposed model mostly reliably describes the stress-strain formation process. In [11] the evolution of the residual stress formation mechanism is investigated, the performed analysis contains the accumulated plastic strain, the stress tensor and the plastic strain. It is found that laser action can change the yield strength. In [12] the fatigue strength of AISI 4140 steel with different levels of porosity manufactured by laser-powder surface was studied. A detailed study of microstructural phases, defect distribution, fatigue characteristics, fractography and residual stresses was carried out. The size of the defect can be varied without deteriorating the fatigue strength. Discrete laser surface hardening by pulsed laser treatment produces [13] many distinct zones of high surface hardness and wear resistance. There is also a soft self-hardening zone in the near-surface layer, which is unavoidable and detrimental to the machined part. The evolution of the microstructure was investigated using different physical methods. Changes in phase composition, dislocation density, number of twins in the laser treated surface layer and different hardening mechanisms between the laser hardened zone and the substrate zone have been established. In [14], the effect of laser dressing on the fatigue characteristics of load-bearing angle cross joints made of S960 steel was considered. Experimental fatigue tests and geometry and residual stresses measurements were carried out together with finite element analysis and various statistical calculation processes. In [15] the fatigue crack growth rate and fracture toughness of laser-clad, additively fabricated stainless steel samples were studied. The influence of notch orientation on crack growth and fracture toughness was investigated. It was found that the dependence

of the crack growth rate on orientation was insignificant. Analysis of the performed works has shown that after laser treatment of joint axes the regularities of crack growth process are mainly studied, and the statistics of fatigue test results are not sufficient for acceptance of technological parameters of laser treatment.

The aim of the work is to establish parameters of laser treatment of steels providing formation of surface hardened layer of high hardness and wear resistance taking into account reduction of endurance limits up to 20%, which in many cases can be recognized as acceptable.

2 Materials

For the tests were made samples of steel 12X18H9 (GOST 5582-75), the chemical composition of steel C (up to 0.12), Si (up to 0.8), Mn (up to 2), Ni (8-10), S (0.02), P (up to 0.035), Cr (17-19); structural carbon steel 20 and steel 35 (GOST 1050). The samples had a flat shape and rectangular cross-section (3 x 20) mm.

3 Equipment and methods

The samples (Fig. 1) of rectangular cross-section sheet metal were tested on the MUP-150 with constant amplitude of displacement under pure bending in one plane and frequency of 1500 loads per minute.

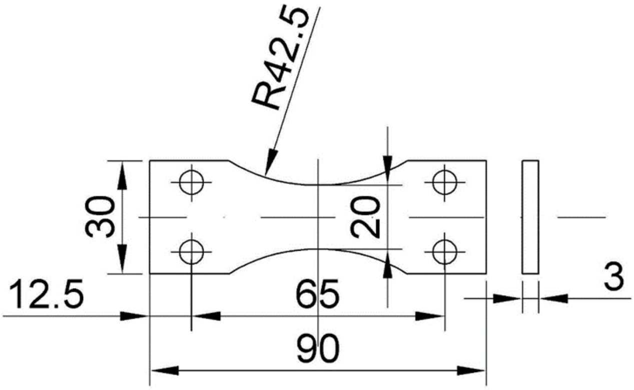

Fig. 1. Sample.

The friction surface pulse laser hardening influence research methodology on characteristics of resistance to fatigue consisted in the following. Fatigue curves of samples made from the original metal were plotted. Then, at levels of stresses above the fatigue limit of metal with initial state of surface tested samples, treated at different energy of pulse laser radiation of 0.2; 2.0; 3.0 J.

4 Results

The low-cycle fatigue curve of 12X18H9 steel was plotted according to results of tests of 14 smooth samples at 4 strain levels, and to plot the fatigue curve of steel 20, 8 samples at 4 strain levels were tested. X18H9 steel samples were tested at one plastic strain rate per cycle (δ = 1.3%) at 20°C. The results of tests are presented in Table 1.

Table 1. Results of fatigue tests of laser-treated samples of X18H9 steel.

Sample no.	**Type of treatment**	**Hysteresis loop width**	**Number of cycles to failure**	**Design number of cycles to failure**
1 2	Machining along the formwork	1.307 1.285	568 650	808 835
3 4	Ring machining	1.288 1.324	789 639	832 788

Test results showed that the greatest reduction in strength was achieved with high intensity annular machining, as well as machining along the formative (in both cases deep grooves remain in the samples). The tests on these types of samples produced a network of cracks parallel to the working cross-section, which led to failure, most often not even in the nominal working cross-section of the corseted sample. The decrease in the number of cycles to failure: reached at the base of 800 cycles. Test data of low-intensity ring samples fit practically in the dispersion range of experimental values of smooth control samples. Reduction of fatigue strength at low densities of laser radiation is connected with existence of residual tensile stresses on the surface, and at high densities - with formation of comparatively big wells, which are stress concentrators. Tests on steel 20 samples were carried out at three steps of plastic deformation per cycle at 20°C. The test results are presented in Table 2.

Table 2. Fatigue test results of laser-treated steel 20 samples.

Sample no.	**Type of treatment**	**Hysteresis loop width**	**Number of cycles to failure**	**Design number of cycles to failure**
1 14 20	Machining along the formwork	1.091 0.770 1.513	570 1800 300	904 1722 494
4 23 10	Low-intensity ring machining	1.567 1.199 0.949	350 802 1470	463 759 1170
22 8 19	High-intensity ring machining	1.467 1.494 0.948	300 475 650	523 506 1172

The greatest reduction in strength of laser-treated samples of 12X18H9 steel was achieved during high-frequency ring treatment and machining along the formwork. With plastic strain rate per cycle less than 10%, the cyclic strength of low-intensity ring-treated samples and samples machined along the formative were practically the same as those of smooth control samples. All types of samples fail at their nominal working cross section (Fig. 2).

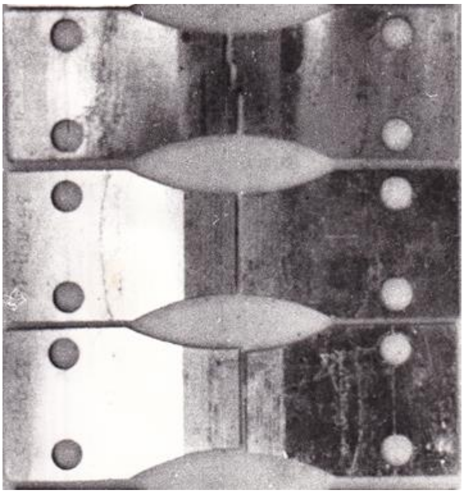

Fig. 2. Fractured samples.

Thus, as a result of fatigue tests carried out on of irradiated samples of steel 20 and X18H9 in a range of plastic strain measurements per cycle in the range of 0.7 - 1.6%, a considerable decrease in cyclic strength was obtained in case of high intensity ring laser treatment and processing along the formative, after which the deep circular and longitudinal grooves remained on the samples. The photograph in Fig. 3 shows a view of the fractured samples along the well groove, showing the contours of the well halves.

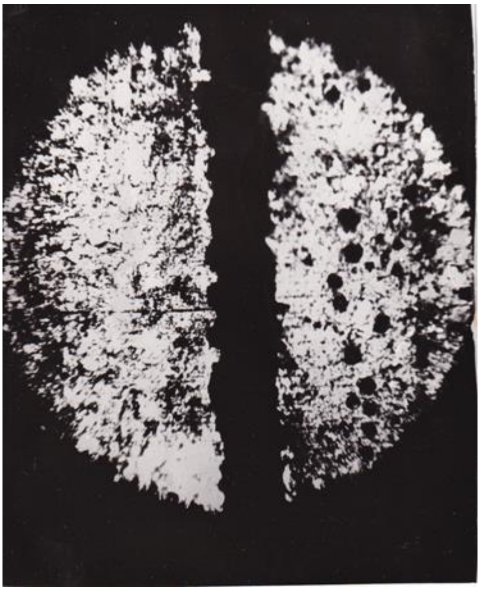

Fig. 3. Photograph of a sample fracture (x 100).

The samples were tested under cyclic mechanical loads. All experiments were carried out under symmetrical loading cycles at room temperature conditions on a base of 107 cycles. Flat samples with constant amplitude of displacement in pure bending in one plane with frequency of 1500 loadings per min. It has been found that, at the same stress level, the fatigue life of the samples decreases with increasing radiation energy. The fatigue curves are shown in Fig. 4.

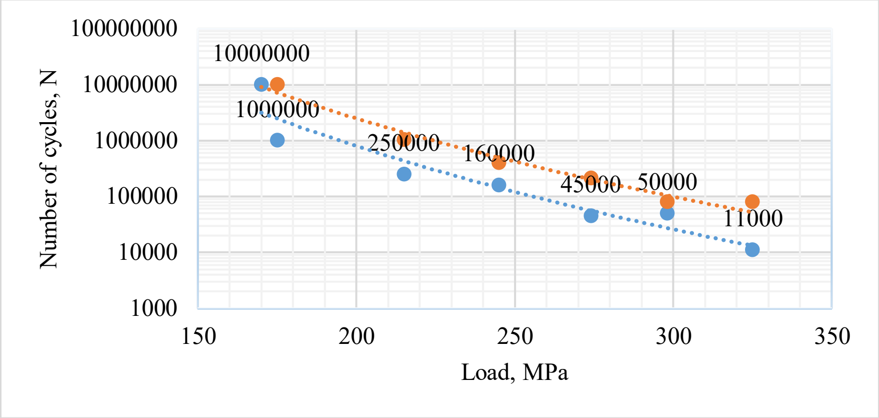

Fig. 4. Dependence of number of cycles to failure on load: blue - laser treated samples; red - original metal samples.

The decrease of fatigue resistance at different durability of laser-treated samples in comparison with the initial state in % is presented in Table 4.

Table 4. Reduction of fatigue life of laser treated steel samples 35 cross-section 39 x 20 mm.

Number of cycles	$4*10^4$	10^5	$4*10^5$	10^6	10^7
Reduction of fatigue, %	11.8	12.8	15.3	17.5	10.2

The surface micro-hardness of steel sample 35 in its initial state was H_{50} = 186 kgf/mm^2. After laser treatment at a pulse energy of 0.2 J, the micro-hardness of the surface increased within H_{50} = 285 – 300 kgf/mm^2. A comparison of these measurements shows that the micro-hardness in the laser treatment area in this mode is 1.5 times higher than in the original surface condition area.

5 Conclusions

Laser hardening of steels forms a surface hardened layer of high hardness and wear resistance. The application of laser pulse treatment has obtained a decrease in the endurance limits of up to 20%, which is explained by the formation of stress concentrators on the surface in the form of defect-holes, as well as by tensile stresses in the surface layer. The practical applicability of laser treatment will be determined by the effect of increased hardness and wear resistance. Reductions in endurance limits of up to 20 % can be accepted in specific cases, if there will be a significant increase in wear resistance.

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