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Influence of laser processing of the low alloy medium carbon structural steel on the development of the fatigue crack

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ABSTRACT

The paper contains the results of the structural analysis, hardness tests and fatigue tests conducted for the medium carbon structural steel with low content of Cr and Ni after its processing with CO_2 laser beam. Pre-cracks were made in the round compact tension (RCT) specimen used for fatigue test. Next, four paths, parallel to each other, were melted on both sides of the samples using a laser beam. The paths were perpendicular to the direction of the axis of the cut notch. The first melted path ran at a distance of about 2.5 mm from the pre crack tip. Fatigue test results were compared with the sample which was not subjected to laser treatment. The fatigue tests showed that the sample with no laser treatment fractured after 270,000 cycles and the laser treated sample was able to withstand 7.2 million cycles for the same load and during this time the crack length increased only 0.4 mm. Hardness tests to estimate the residual internal stresses in the melted zone, in the heat affected zone (HAZ) and in the native material were carried out using nanoindenter. It was shown that compressive residual stress, in native material, close to HAZ in half-length of the melted path, just before the front of the crack, was 1165 MPa. These residual stresses contribute to the stopping of the development of the fatigue crack. It was also shown that the longitudinal manganese sulfide inclusions reduce crack development rate probably by blunting the crack blade.

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1. Introduction

Lasers have been used in many fields since their invention. Lasers have also found applications in surface engineering. Cases of various materials can be modified by using a laser beam to give them other chemical, physical and mechanical properties. Laser treatment can improve, for example, the tribological properties [1–5], corrosion resistance of the surface layers [6–10] or significantly increase the surface hardness [11–14]. Using a laser beam, thermal stresses are generated in the surface layer during its heating [15]. For some materials, heating may also cause phase changes in the solid state which can further generate structural stress. Then the residual stresses are the sum of thermal and structural stresses. Residual stresses can significantly affect the fatigue resistance of the processed material. If residual stresses are tensile, the fatigue strength decreases significantly. In the case of compressive stress, fatigue strength increases significantly since then it reduces the tensile stresses before the face of the fatigue crack. For example Wei and Ling [16] presented a three dimensional model to predict the development, magnitude and distribution of residual stress field induced by laser shock processing (LSP). They reached the conclusion that the overlap between two laser surface locations improves the magnitude and the affected depth of the residual stress. Morales et al also reported [17] that from the practical point of view, the LSP technology allows the effective induction of residual stresses fields in metallic materials. Cvetkovski et al showed in [18] that the development of residual stresses in medium carbon steels during their laser treatment depends on heating rate, temperature and mainly two material properties, thermal expansion/contraction and yield strength. In turn, Zhang et al studied the effect of two-sided laser heating of the aluminum 7050-T6 alloy on its fatigue resistance [19]. According to them, the laser treatment is very beneficial because crack initiation is delayed greatly, which plays a leading role in prolonging the fatigue life of specimen. Additionally crack propagation rate slows down which is attributed to superficial compressive residual stress induced by laser. Altus and Konstantino, in their work [20], enhanced fatigue resistance of Titanium 6Al–4 V alloy using 1.8 kW continuous wave (CW) — CO_2 Laser. They attempted to find the optimal conditions of laser treatment which will improve the material resistance to fatigue failure, and explore the mechanisms involved. They identified two basic mechanisms. One is related to healing mechanism (HM), and the other is connected to microstructure mechanism (MM). Healing was found to be effective for surface temperatures above 400 °C. They reached a conclusion that the changes of microstructure adversely affect fatigue resistance except for temperatures lower than 600 °C and specific laser conditions. They also found a positive correlation between hardness and fatigue life. Bień also reported [21] the

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Table 1
Chemical composition of investigated steel.

Chemical composition wt%							
C	Mn	Si	P	S	Cu	Cr	Ni
0.30	1.15	1.10	0.030	0.025	0.25	1.05	1.65

Table 2
Laser parameters used for melting of the sample.

Parameter	Value
Laser type	CO_2
Laser mode	Pulse
Laser power [W]	$P = 840$
Radius spot laser (the conversion) [mm]	$r = 1.6$
The speed of the laser beam [mm/s]	$v = 3.5$
Shielding gas (low-pressure)	Argon
The distance of the sample from the plane of the beam focusing lens [mm]	118
Focal length of the lens ["]	3.8

beneficial effects of selective laser re-melting of the steel on fatigue crack propagation. According to her research, the modification of the steel microstructure due to the laser beam re-melting increases fatigue strength of the processed materials.

This paper presents the possibility of stopping a fatigue crack by melting the material before its front, using a laser beam. Matching parameters of the laser beam and the appropriate arrangement of the *re*-melted paths, large compressive stresses able to stop the fatigue crack can occur before the face of the crack.

The aim of this paper is to check whether using laser beam is capable of generating high enough compressive residual stresses in the areas before the face of the crack (near the heat affected zone but still outside of the zone) able to stop the fatigue cracks in the treated steel.

2. Experimental procedure

2.1. Investigated material

Low-alloy steel with a content of 0.30% C was used for research. Chemical composition of testing steel is presented in Table 1. This steel is designed for quenching and tempering and it is designated for the most loaded parts of machines and engines, which require a very good plastic properties. This grade of steel is used, inter alia, in the aircraft industry. Round compact tensile (RCT) specimen for fatigue testing was made from steel after softening. Next six samples were hardened by quenching (heating up to 850 °C and cooling in oil) and then they were tempered in 300 °C. After tempering, the samples were cooled in oil. After heat treatment, the mechanical properties of the steel are as follows: tensile strength 1620 MPa, yield strength 1510 MPa, elongation 10%, reduction of area of the specimen 45%, toughness 48 J.

2.2. Laser beam treatment

Five RCT samples were treated by laser beam after making pre-cracks in samples. The width W and the thickness B of the cylindrical shape RCT sample was 37 mm and 7 mm respectively. The surface roughness (Ra) of the samples was 0.32 μm. Pre-cracks have a length of $a = 12.5$ mm (see Fig. 1) from the axis of the holes in the sample. One sample was left untreated. This sample was used as a reference.

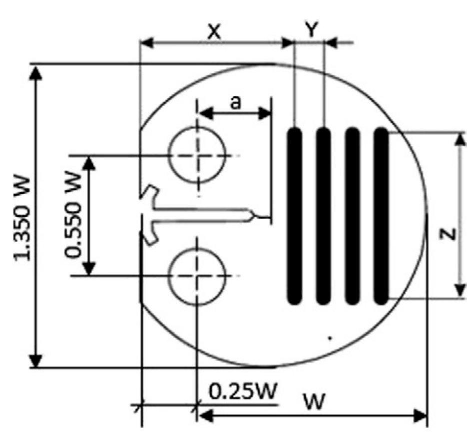

Fig. 1. RCT sample used for fatigue testing with marked melted paths. W — specimen width, X — distance from melted path to the front of the sample, Y — distance between melted paths, Z — length of melted path, a — length of the pre-crack.

Then on both sides of the samples, four paths parallel to each other were melted using laser beam. The distance from each path (Y) was 5 mm and tracks were perpendicular to the direction of the axis of the cut notch (see Fig. 1). The first track runs at a distance of about 2.5 mm from the pre crack tip ($X = 24$ mm). The length of each path was approximately 40 mm (Z). The width of each melted path ranged from 1.2 to 1.5 mm and the width of HAZ ranged from 0.7 to 0.95 mm. Laser treatment was performed starting from the track closest to the tip crack (P1). Then, another path was melted without waiting for the sample to cool down. Subsequent paths were performed on the other side of the samples in the same order. Laser treated sample was located on a metal plate for faster cooling. The samples were treated by various parameters of the laser beam. This paper presents the results of the sample which showed the best resistance to fatigue crack growth. The laser processing parameters for this sample are presented in Table 2. Samples were coated by colloidal graphite before laser treatment in order to reduce the light reflection of the treated surfaces. The surface roughness of the samples in the melted paths was much >0.32 μm and it was not measured. Increased roughness of the surface after the laser treatment was not an obstacle in stopping the fatigue crack.

2.3. Fatigue test

After laser processing, the resistance to fatigue crack propagation of laser treated sample was studied. The results were compared with the effects of fatigue tests carried out using the same parameters on the samples without the laser treatment. The results are the contents of the patent approved in 2012 [22]. The content of the patent describes the obtained effect without analyzing its reasons. Tests of crack propagation rate were performed on the testing machine MTS 8502 in the Air Force Institute of Technology in Warsaw. The maximum magnitude of the force was $F = 3500$ N. The frequency of the load was 10 Hz with an asymmetry coefficient of the cycle $R = 0.2$. The temperature during the test was between 20 and 25 °C and air humidity 40% to 60%. The samples used in the fatigue tests were shaped as shown in Fig. 1 and had the following dimensions $W = 37$ mm and thickness $B = 7$ mm.

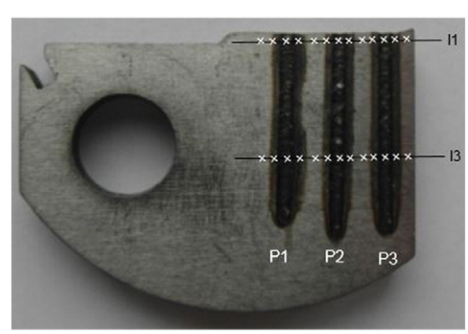

Fig. 2. View of the broken RCT specimen with the marked lines l1 and l3 along which the hardness measurements were performed. Marked crosses indicate the place of hardness measurement.

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