Influence of laser-induced microstructure notches on the configuration of residual stresses in a steel plate

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Abstract. Among technological problems related to manufacturing materials with controlled and localized properties, the effect of a microstructure notch is still unsatisfactorily recognized. Laser modification of selected areas of material structures is one of the most promising technologies in the field. The work presents selected variants of generating the intended microstructure changes in the near-surface areas of steel plates by means of a laser beam. A field of residual stress was generated in the examined steel as a result of phase transformations accompanying the laser treatment. Both the microstructure changes and configuration of residual stresses were identified by means of the optical microscopy, and X-ray diffraction technique. The results, additionally related to crystallographic texture, allowed to characterize the microstructure modifications and to interpret a potential change of mechanical properties. It was found, that the level of the stresses and its range can vary essentially with parameters of the laser treatment, which gives one a chance to control the behaviour of a material in the conditions of mechanical loading, by exploitation of a structure element.

1. Introduction

A generally understood decay of constructional elements can be defined as a process of multi-aspectual degradation of material structure. Progress of the degradation process depends on the nature of destructive factors and on the resistance of a material. From the point of view of the efficiency of a construction and the safety its exploitation, the possibility of controlling the profile of decay zone spreading in a material constitutes a interesting question. One way of achieving a control of that sort is to introduce a definite disorder of material microstructure which makes it possible to control both the size of the destruction area, and the propagation route of a destructive process. Among many methods of generating microstructural notches, the laser melting/hardening of a surface is one of the most effective methods, which is due to a comparatively large range of possible variants and close control over the location of generated notches [1,2]. This work presents a texture and stress profile of the microstructure of steel with a microstructural notch made by controlled laser treatment.

2. Experimental procedure

Structural steel 45H (0.45%C, 0.65%Mn, 0.27%Si, 0.95%Cr) with maximum content of P and the content of S within the range of 0.025-0.035% was used in the experiments. The sample in the form of plates (ca. 55 × 10 × 4 mm³) was cut off a steel-rod perpendicular and parallel regarding the rolling direction (RD). Before cutting the samples, laser remelting in the form of straight paths was performed.
on a selected surface of the rod. As a result of thermal treatment (hardening at 1050°C and then annealing at 510°C), the investigated steel reached the hardness of 350 HV and the yield stress of 1200 MPa. In laser processing were used: high-power fibrous laser HPFLSPI 200C and high-power diode laser HPDL ROFIN SINAR DL 200. The direction of remelted paths was parallel or perpendicular to the rolling direction (RD). Both a diode and fiber-type laser with various combinations of power and velocity travel were applied. The treatment was carried out in nitrogen or argon protective atmosphere. The research area of each sample was prepared in the form of metallographic specimens, where cross-sections of laser-remelted paths were revealed. Electron and optical microscopy were applied to characterize the microstructure and morphology of laser-modified areas. Residual stresses and crystallographic texture in selected sub-areas surrounding laser-treated volumes of material were analyzed by X-ray diffraction techniques. Topography of changes in the above characteristics of microstructure of the samples in question was obtained (figure 1).

The presented investigations concern four chosen samples with paths remelted by means of lasers configured for various parameters of treatment. The samples are denoted as DA22_1, DN22_1, WA22_3, and WN22_3. The notation reads: type of laser (D – diode-type, W – fibrous-type), protective atmosphere (N – nitrogen, A – argon), temperature of hardening (2 corresponds to 1050°C) as well as the direction of laser paths (2 - perpendicular to RD). The last digit in a sample symbol indicates the number of the path (definite power and relative velocity of the laser head). Experimental data for texture and stress analyses were registered in the areas (measurement points) marked in figure 1.

3. Results and discussion

3.1. Microstructure

The pictures obtained by means of optical microscopy were used to identify the size of the heat-affected zone (HAZ), the distribution of martensite and ferrite in modified areas of steel. The results show that the size of the HAZ, remelting area and hardened volume increased almost threefold when the diode laser was used, as compared to the treatment with the fibrous laser.

Figure 2. Cross-sections of samples with selected laser paths performed by the diode and fibrous laser. Nearby each of the cross-section, a related longitudinal-break counterpart registered by means of electron microscopy is presented. The optical and electron microscopy pictures have been made in the IMIM PAN in Krakow and in the WITPiS in Sulejowek, respectively.
Optical and electron microscope pictures of the cross-sections of laser paths reveal a strong inhomogeneous microstructure of the modified areas of the steel samples (figure 2). Apart from the intentionally introduced disturbances of the microstructure, distinct zones of gas pores are observed. The reaction of the examined steel to localized laser beam was also reflected in the shape of the microstructure irregularities (elongated sub-areas) in the path region. Depending on the parameters of the laser treatment, a specific morphologic pattern of the path can be observed. Visible differences between the tracks result from differences in the power and velocity of laser travel. Individual laser paths are characterized by considerable heterogeneity produced during the melting process followed by subsequent crystallization (difference in size and shape of dendrites). A distinct diversity in the size of the HAZ accompanying each of the paths is visible in its surroundings. The morphology and configuration of individual phases with a defined preferred orientation of crystallites and the post-processing morphological objects (dendrites, pores) create a kind of microstructure notch in the sample space which generates a field of residual stresses in laser-modified steel.

3.2. Crystallographic texture
Texture analysis of investigated samples reveals the preferred orientation of crystallities related to the cross-section of laser paths. The coordinate system (ND, TD, RD) assumed in texture analysis is related to the one assumed for stress analysis and presented in figure 2: ND \( \equiv \sigma_{11} \), TD \( \equiv \sigma_{22} \), RD \( \equiv \sigma_{33} \). Experimental (110), (100) and (211) pole figures of ferritic-martensitic phase were registered for the round-shape surface areas with the diameter of 1.0 mm, covering the remelted region and partially HAZ. The X-ray diffraction technique was applied by the Schulz’s method of back-reflection [4]. Based on the experimental pole figures, an orientation distribution function (ODF) was calculated by discrete the arbitrarily defined cells method [5], which allows one to reproduce complete pole figures and inverse pole figures of the normal direction (ND) for the ferrite-martensite phase. LaboTex software was used in texture analysis [6]. As it can be observed in the inverse pole figures of ND for selected paths presented in figure 6, the texture of the material bulk treated by the diode laser differs from the material treated by the fiber laser. Apart from orientations of ND dominating in all of the considered paths and situated in the range of \(<216> \times <116>\) directions, an additional, relatively strong component close to \(<321>\) orientation was identified in the case of the diode laser. Another important result concerning the RD direction informs about its dominant space orientation near \(<100>\) in the case of diode-laser paths and close to \(<410>\) orientation in the case of fiber-laser ones. The third direction (TD) connected to the investigated sample surface (cross-section of the laser paths) does not show any stronger diversification depending on the kind of laser and parameters of treatment.

Figure 3. Inverse pole figures of normal direction (ND) for selected laser paths performed by the diode laser: DA11 and DA12, and by fibrous one; WA11 and WA12

3.3. Residual stresses
The distribution of residual stresses (\(\sigma_{22}\) component in figure 2) in the central zone of the laser paths and in its surroundings was analyzed by the X-ray sin\(^2\)\(\psi\) method [7]. The diffraction profiles were measured by means of Rigaku MSF X-ray Stress Analyzer. Young’s modulus \(E = 223,3\) GPa and Poisson coefficient \(\nu = 0.28\) have been assumed in the calculations. The results are shown in figure 4. The revealed distributions of the residual stresses depend essentially on the parameters of the
performed laser treatment. The highest compressive stresses were generated by the fiber laser in nitrogen atmosphere and the lowest ones by the diode laser in the same protective atmosphere. Along with compressive stresses, tensile stresses also were changed. The highest compressive stresses (ca. – 250 MPa) were identified in sample DA12 for path No. 1, at the distance of about 1.0 mm from the central point of the cross-section (figure 4). In sample DA11 (path No. 1) for the same distance, tensile stresses (up to 60 MPa) were identified. The larger the distance from the central point (~3.0 mm), the greater the tensile stresses become in both samples treated by the diode laser. The distribution of the tensile stresses in sample DA12 passes much more softly into the distribution of compressive ones, as compared to sample DA11. In the case of the fiber laser (sample WA11 and WA12), an analogous tendency in the distribution and level of the stresses is observed, regarding mutual orientation of the paths direction and rolling direction of matrix material before laser treatment. Essential difference in the stress distribution are observed for samples DA11_1 and WA11_3. Among the analyzed variants of the laser treatment, the most diverse stresses (from compressive $\sigma_{22} = 200 \pm 140$ MPa to tensile $\sigma_{22} = 310 \pm 240$ MPa) were identified in the case of paths generated by fibre laser in argon atmosphere and for laser paths perpendicular to RD.

![Figure 4](image.png)

**Figure 4.** Distribution of values of the $\sigma_{22}$ component of stress field in the area of the cross-section of the diode laser path No.1 and of the fibrous laser path No.3.

4. Conclusions

Based on the performed analyses of texture, stress analyses and microscopic observation, the laser modified areas of investigated steel can be qualified as a poly-phase microstructural notch. The morphology of remelted areas surrounded by the heat affected zones create specific conditions for maintaining a specific field of residual stresses in the modified material. In the case of the fiber laser treatment, the modified microstructure is characterized by greater dimensions and exhibits more homogeneous and weakly shaped texture, as compared to the case of diode laser treatment. The configuration of the stress field (its $\sigma_{22}$ component) is essentially influenced by the parameters of the laser treatment. The investigated variants of laser modification make it possible to identify the areas of potential weakness in the material in response to external mechanical loading. It is also possible to foresee the road of crack propagation in examined steel plates after applied laser modification.

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