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LASER SHOCK PROCESSING OF AN AUSTENITIC STAINLESS STEEL

LASEROWO ODKSZTAŁCAJĄCA OBRÓBKA POWIERCHNIOWA STALI AUSTENITYCZNEJ X5CrNi18-10

The aim of this work was to examine the effect of laser shock processing (LSP) on the morphology, microstructure and surface layer properties of an X5CrNi18-10 austenitic stainless steel. The laser shock processing was accomplished by a high-power Q-switched Nd:YAG laser, operating in a 1.064 μm wavelength range, with laser power density of 1 GW/cm^2 and pulse duration of 18 ns. The microstructure and phase composition of the laser treated surface layer of the material were analyzed by light, scanning and transmission electron microscopy as well as by X-ray diffractometry. The X-ray diffractometer was also use to determine the value and level of residual stresses in the treated surface layer.

It has been found that the laser shock processing causes significant plastic deformation and generate compressive stresses in the treated surface layer.

Keywords: laser shock processing, surface treatment, microstructure, surface roughness, compressive residual stresses, austenitic stainless steel

W pracy przedstawiono wpływ laserowej obróbki odkształcającej na morfologię, mikrostrukturę i własności warstwy wierzchniej stali austenitycznej X5CrNi18-10. Laserowe odkształcanie przeprowadzono za pomocą lasera impulsowego ReNOVALaser Nd:YAG z modulacją Q, przy gęstości mocy 1 GW/cm^2 i czasie trwania impulsu 18 ns. Do oceny wpływu laserowego odkształcenia na mikrostrukturę i skład fazowy warstwy wierzchniej wykorzystano mikroskopię optyczną, elektronową skaningową i transmisyjną jak również rentgenowską analizę fazową. Pomiar naprężeń w warstwie wierzchniej przeprowadzono za pomocą dyfraktometru rentgenowskiego.

Wykazano, że laserowa obróbka odkształcająca powoduje odkształcenie plastyczne i wprowadza naprężenia ściskające do warstwy wierzchniej badanej stali austenitycznej.

1. Introduction

Laser shock processing (LSP) is a promising surface treatment technique, in which metallic target is irradiated with a short, intensive laser pulses in order to induce plastic deformation and surface strengthening by the shock wave generated when high-pressure plasma rapidly expands over the material surface [1]. By now, the theoretical aspects of LSP are well elaborated and widely presented in many publications, where physical processes of laser driven shock wave generation, models of pressure generation and mechanics of a laser shock interaction with matter are described [2,3]. In recent years, the studies on LSP have focused on parameters of laser beam-matter interactions, which depend on the physical and mechanical properties of materials as well as laser power density and duration of laser pulse [4,5]. In order to increase the efficiency of the LSP process, the treated samples are usually coated with a black paint, serving as a laser-energy absorbing layer, which, in turn, is covered with a transparent layer (samples are frequently immersed in water) (Fig. 1a). When the laser beam is directed onto the surface, it passes through the transparent layer and strikes the black coating, which is heated and instantaneously vaporized, due to absorption of laser beam energy. In the next step, the plasma plume is generated due to vapor ionization and heating by absorption of the remaining laser beam radiation. The rapidly expanding plasma is trapped between the sample and the transparent layer (water) and creates high surface pressure. The pressure generates a shock wave which propagates into the material (Fig. 1b) and leads to its plastic deformation. Simultaneously, a very thin surface zone is rapidly heated, due to heat transfer from the hot plasma to the treated material. The plastic deformation induced by the shock wave generate compressive residual stress in the sample surface [6,7].

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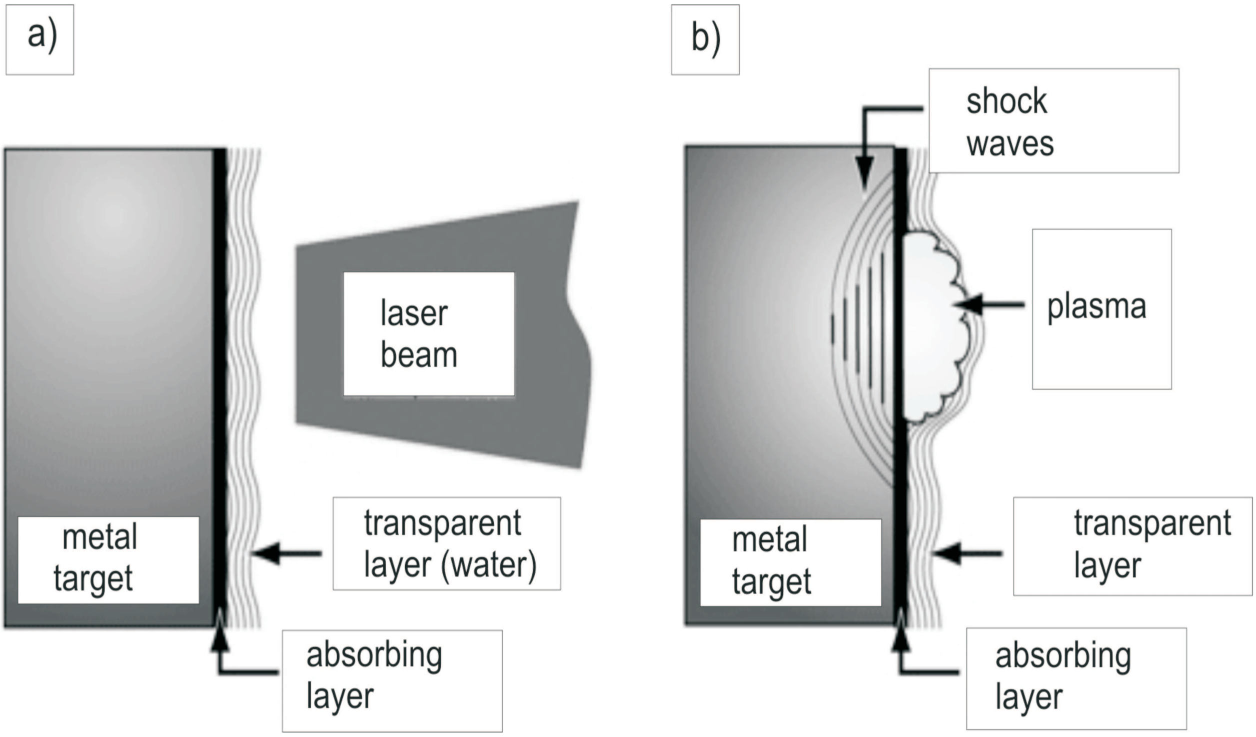

Fig. 1. Schematic representation of the laser shock processing (a) metal target with absorbing and water layers (b) shock wave generation by laser beam

The aim of this work was to examine the effect of the laser shock processing on morphology, microstructure and surface layer properties of an X5CrNi18-10 austenitic stainless steel.

2. Material and experimental procedures

The material used in this study was an X5CrNi18-10 austenitic stainless steel containing 18% Cr and 10% Ni. Samples for the LSP processing have been annealed at 1160°C for 1 hour and then mechanically ground and polished. Before the laser treatment, the sample surfaces were coated with the 50 μm thick black paint, playing a role of the laser energy absorbing layer. The sample was subsequently immerged in water (serving as an inert layer) 3 mm beneath its level.

The laser used in this study was a Q switched Nd:YAG laser, operating in the 1.064 μm wavelength range and a pulse duration of 18 ns. The laser power density was 1 GW/cm^2. The laser treatment was conducted in air. During the LSP only the central part of the rectangular sample has been treated, as shown in Fig. 2 (with series of overlapping spots – 2 subsequent laser shots to the same place). The diameter of the laser beam on the sample surface was about 2 mm. After the LSP, the remaining black paint was removed from the treated surface with acetone.

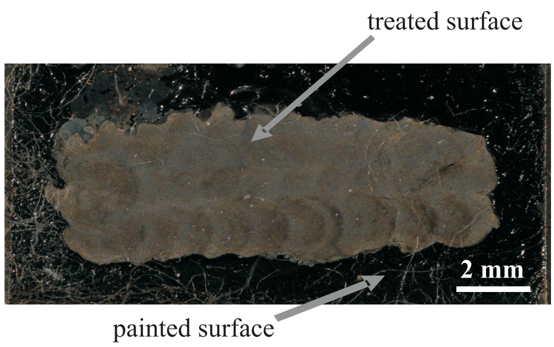

Fig. 2. Light microscopy image of the treated sample

The microstructure of the annealed and laser treated samples, were investigated by means of light and scanning electron microscopy (SEM). Both, the surface and the cross-sections of the treated samples were examined. The chemical composition of treated surface was determined by means of Energy Dispersive Spectrometry (EDS) attached to the SEM. In order to identify the existing phases in the surface layer of the laser treated material the X-ray diffraction (XRD) analysis using CoK$_\alpha$ radiation has been applied. Also, using the XRD technique, the residual stresses in the treated surface of the stainless steel were measured. Measurements were performed by a grazing angle ($\sin^2\psi$) technique of the laser treated surface layer. Finally, detailed microstructural investigations of modified surface layer have been performed by means of transmission electron microscopy (TEM). To prepare thin foils for TEM investigations 0.5 mm thick slices were cut out perpendicular to the treated surface. Then, a stack has been made by gluing together two slices: treated surface-to-treated surface. When the glue dried out, the 2 mm × 2 mm × 6 mm cuboids were cut out from the stack and fixed with the Gatan glue inside a 3 mm brass tube. Next, after drying, the tube was sectioned with a diamond saw to get 0.3 mm thick discs. The discs were mechanically ground down to the thickness of about 80 μm. Before the final ion-beam thinning, the discs were first dimpled so the final thickness in the center of the sample was about 30 μm. For the ion milling the PIPS Gatan apparatus working at 4 keV and low attack angles has been applied to get perforation in the sample.

3. Results and discussion

Microstructure of the investigated austenitic stainless steel after annealing at 1160°C for 1 hour is shown in Fig. 3. Only one phase (austenite) was distinguished by light microscopy. The average grain size determined from micrographs was about 70-100 μm.

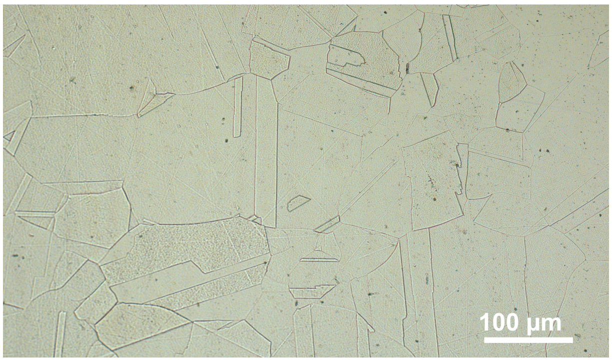

Fig. 3. Microstructure of austenitic stainless steel before the laser treatment (light microscopy)

Morphological changes at the treated sample surface are presented in Fig. 4. SEM investigations showed that the laser shot processing brought about the ablation and melting of the thin surface layer of the treated material. As a consequence of the accumulated pulse energy the surface layer exhibited high porosity and the presence of resolidified droplets and ablation craters. Cracks were not observed in the surface layer. The results of the EDS analysis showed the presence of Fe, Cr, Ni, C as well as O in the examined surface layer (Fig. 4). The presence of oxygen indicates a possibility of surface oxidation during laser processing, while the carbon peak comes likely from the burned black paint.

The measurements of the surface roughness showed that the Nd:YAG laser treatment of the stainless steel brings about an increase in the surface

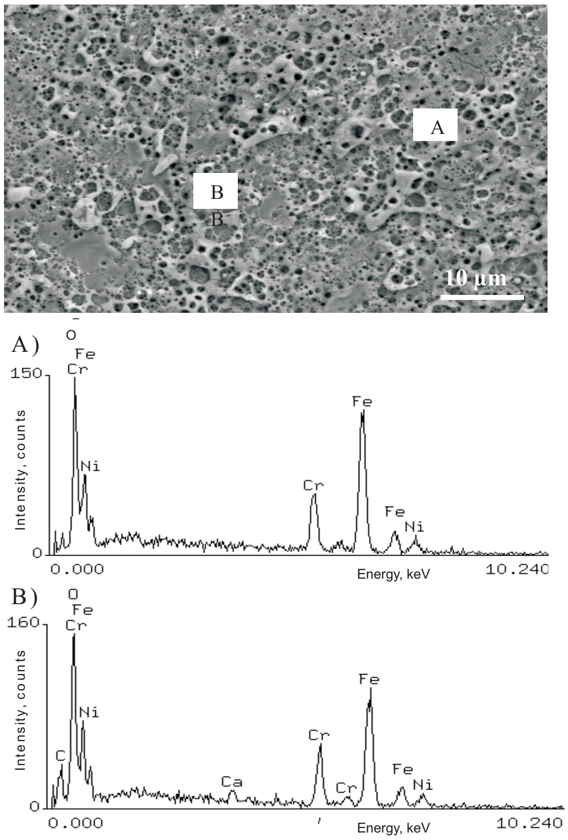

Fig. 4. Topography of austenitic steel after LSP, 2 shots (SEM SE), the EDS spectra show presence of oxygen, iron, chromium and nickel at the treated surface

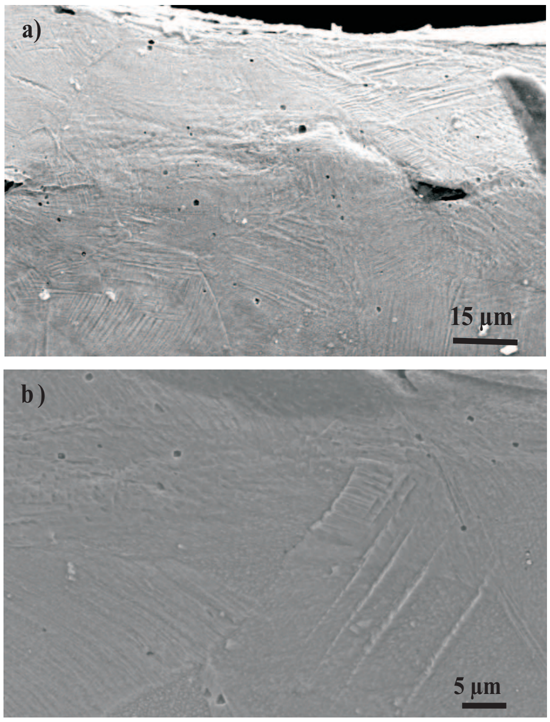

Fig. 5. Slip bands on the cross section of the treated surface; SEM, a) low magnification, b) high magnification

roughness. The Ra (arithmetic average of the absolute values of all points of the profile) increased from 0.1 μm before the treatment to 0.58 μm after the LSP. It is believed that the reason for the increase of roughness of the surface is ablation and melting.

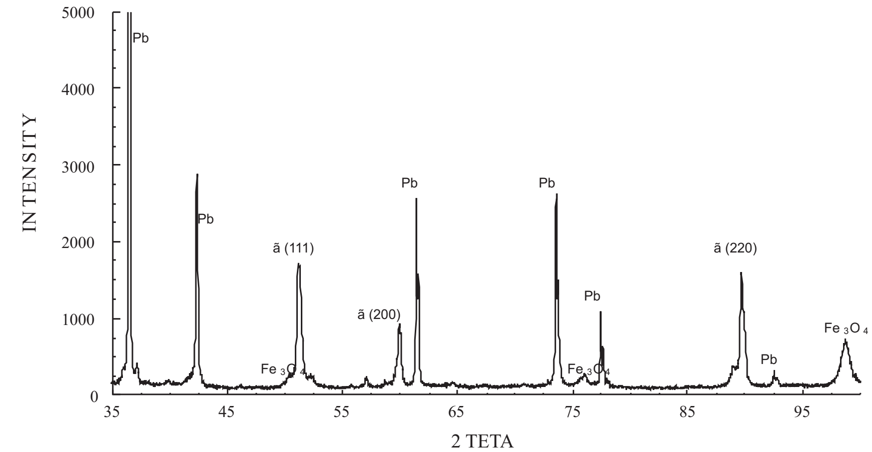

Fig. 6. XRD pattern of austenitic stainless steel after LSP (C_oK_α radiation)

SEM images of the sample cross sections showed that clusters of slip bands were formed during the treatment in the near surface region (Fig. 5). Such a feature is usually observed in austenite after plastic deformation and is often associated with the formation of deformation twins and stacking faults.

The X-ray diffraction pattern from the treated surface is presented in Fig. 6. It was found that the surface layer of the steel after the LSP was composed mainly of austenite. Also weak peaks of Fe_3O_4 oxides were recognized on the XRD pattern. Strong Pb peaks appeared on the XRD pattern because before the XRD measurements, the sample was covered with a thin mask of Pb in order to limit the sampling area. Due to the combination of thermal (ablation and melting) and mechanical effects, the laser shock processing generates tensile residual stress in the near surface region and compressive one below. The residual stress in the treated surface measured at a depth of 3.7 μm (thermal effect) was a tensile in nature (+262 MPa) while that measured at the depth of 23.8 μm was compressive one (-460 MPa). Thus, a stress gradient is evidenced on the first 24 μm, starting from the + 262 MPa surface stress, to the -460 MPa value at 23.8 μm below the surface. This result clearly indicates that the laser shot processing generates the compressive residual stress on the surface of the austenitic stainless steel. Similar effect was observed in 316L stainless steel by Peyre [8].

Microstructure of thin foils from the surface layer is presented in Fig. 7 and 8. The micrographs show very high density of dislocations and deformation twins.

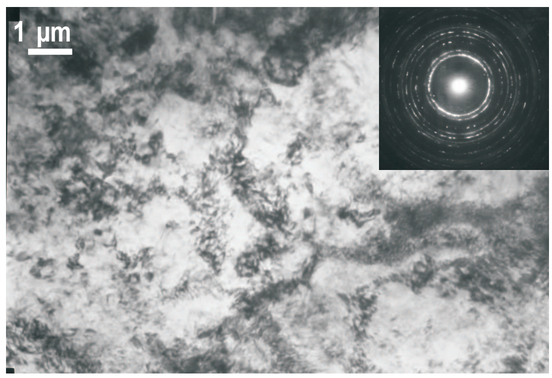

Fig. 7. High density of dislocations in the LSP treated austenitic stainless steel with corresponding diffraction pattern

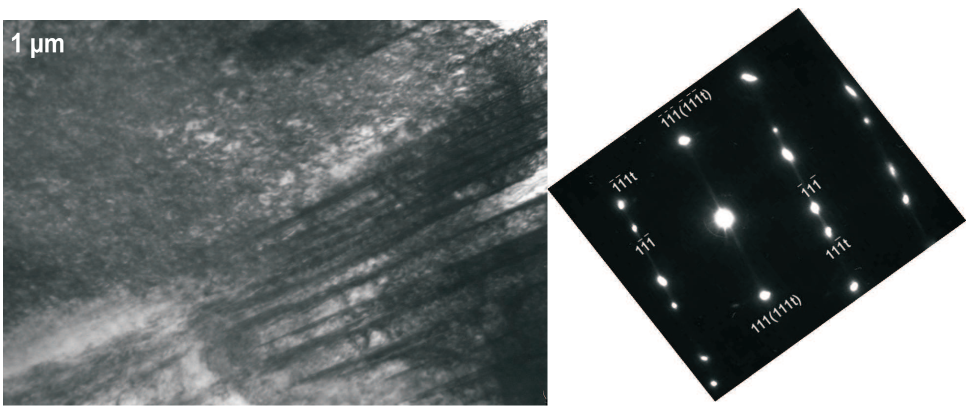

Fig. 8. Deformation twins in the LSP treated austenitic stainless steel with corresponding diffraction pattern

4. Conclusions

Laser Shock Processing is now recognized as a new technique which demonstrates its unique ability for processing of thin surface layers of different materials. For the X5CrNi18-10 austenitic stainless steel the present research permitted to draw following conclusions:

- It was found that the laser shock processing performed under the conditions of 1 GW/cm^2 laser power density and pulse duration of 18 ns caused an ablation and melting of the thin surface layer of the treated material
- SEM images of the treated sample cross section showed that clusters of slip bands were formed during treatment in the near surface area
- It was found that the laser shock processing causes plastic deformation by slip or twinning and generate the compressive residual stress on the surface of the austenitic stainless steel

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