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Physical Aspects of Surface Layer Changes After Laser Ablation Process

R. Gołębski*, P. Boral and P. Paszta

Czestochowa University of Technology, 42-201 Częstochowa, Poland

Doi: 10.12693/APhysPolA.147.214 *e-mail: rafal.golebski@pcz.pl

Laser surface melting is a process that significantly changes the structure and properties of the surface of engineering materials such as stainless steel and hot-rolled 1100MC structural steel. As a result of the impact of the laser beam on the surface, a fine-crystalline layer is formed, characterized by a clear orientation. This process does not affect the chemical composition of the material, which allows for maintaining the original chemical properties while improving other physical parameters of the layer. The melted surface shows increased hardness, which results in better abrasion resistance, which is crucial in engineering applications. These changes are the result of optimizing the laser surface melting process parameters, such as laser power and feed rate, which allows for precise control of the resulting surface structure and its physical properties. The article presents an analysis of changes in the structure and properties of the surface layer of engineering materials under the influence of laser melting. The authors analyzed the effect of laser surface melting process parameters on changes in the values of surface structure parameters and its hardness.

topics: laser ablation, microhardness, surface layer, surface functional parameters

1. Introduction

The impact of a laser beam on the surfaces of different materials can have various effects depending on the laser parameters, such as its power, wavelength, exposure time, and processing technique. The laser can be used for the local hardening of steel, changing its physical properties, increasing microhardness and resistance to wear and corrosion of the surface, while the core remains soft. Laser surface hardening has many advantages over other methods, such as flexibility, low deformation due to high power density, and accuracy [1, 2]. High precision of the laser action leads to local melting and crystallization of the material, which affects the microstructure and can change the mechanical properties in different areas of the processed part.

Under the influence of the laser, coatings such as Cr_3C_2–NiCr can also be applied, and surface layers can be modified using the laser alloying method, improving the mechanical properties of sintered stainless steel [3]. The ablation process allows for the removal of thin layers of material without disturbing the basic structure of the steel. The laser can be used to remove contaminants from the steel surface, such as rust, paint, or deposits, without damaging the material itself, or to melt the previously applied coating, improving the mechanical properties of the treated surface [4].

There are many publications on the effect of laser action on the microstructure of steel [5–10] and the nature of the formation of mechanical properties of processed surface layers of various materials. The action of laser on the steel surface can bring various benefits depending on the application, including high precision, minimal deformation, the possibility of surface hardening, removal of impurities, or modification of the material structure. The use of appropriate laser parameters is crucial to achieve the desired effect without undesirable side effects, such as excessive oxidation or too large a change in mechanical properties. The presented studies analyzed the effect of laser surface melting (LSM) process parameters on changes in the values of surface structure parameters and its hardness. The studies were conducted for hot-rolled structural steel.

2. Research

Sample processing was carried out on a fiber laser cutting machine with a maximum power of 1500 W, which was equipped with a head with a cutting nozzle with a diameter of 2.5 mm. Nitrogen at a pressure of 2 bar was used as a shielding gas, and the laser power was declared in the range of 150–250 W. The beam displacement speed was 10 mm/s. Samples on which the tests were carried out were in the form of 4 mm thick sheets of hot-rolled structural

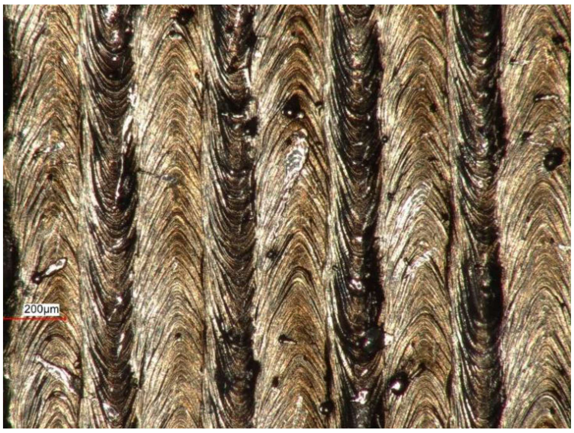

Fig. 1. Surface view of a 1.8877-DIN steel sample, magnification ×200, after laser processing with a power of 250 W, at a beam speed of 10 mm/s, in a nitrogen shield at a pressure of 2 bar.

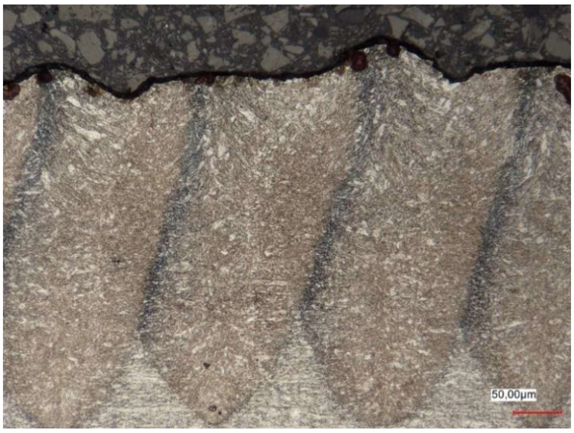

Fig. 2. Cross-section of a 1.8877-DIN steel sample, magnified ×500, after laser processing with a power of 250 W, at a beam speed of 10 mm/s, in a nitrogen shield at a pressure of 2 bar.

steel Strenx 1100MC (1.8877-DIN), intended for cold forming, with crushed grain and a minimum yield strength of 1100 MPa. Their chemical composition was as follows: max 0.15% C, max 0.5% Si, max 1.8% Mn, max 0.02% P, max 0.005% S, min 0.015% Al. When analyzing the initial samples, it was possible to notice that the surface after laser treatment with a power below 150 W had little effect on the structure and mechanical properties of the surface layer. However, when using a laser with power above 250 W, large meltings occurred on the surface. In further studies, ablation with a power of 200 W and 250 W was used.

The microhardness test was performed on a UHL VMH-002VD microhardness tester. The surface structure tests were performed on a Taylor Hobson New Form Talysurf 2D/3D 120 profilometer, which is equipped with a head with an interferometric transducer with a resolution of 0.6 nm. The measurements were performed using a measuring tip in the form of a diamond needle in the shape of a cone, with a radius of 2 μm and a cone angle of 90°. In all tests, the measurement was performed on a surface of 6×5 mm^2. The surface topography analysis was performed using the TalyMap Platinium 5.1 software from Taylor Hobson.

In the process, it was very important to determine the value of the amplitude roughness parameter in relation to the entire tested area. The analysis included the parameter Sa defining the arithmetic mean of the height of all surface points measured in relation to the reference plane in the analyzed area subjected to the action of the laser beam. Roughness measurements indicate that laser ablation of the surface causes a deterioration of smoothness in relation to the initial surface $Sa = 1.78$ μm. The greatest influence on the geometric structure of the surface has the laser power, i.e., the higher the power, the higher the roughness parameters. At 150 W, the roughness parameter $Sa = 2.05$ μm, at 200 W, the roughness parameter $Sa = 3.24$ μm, while when using 250 W, the roughness parameter Sa increases to 12.3 μm.

The photo (Fig. 1) shows a surface with clearly visible, alternatingly oriented remelts, which reflect the path of the laser beam. These remelts have a characteristic "arc" shape resulting from the dynamic energy distribution during the laser movement. Regular patterns may indicate a well-controlled ablation process with uniform beam advancement. The grooves and depressions can act as micro-reservoirs for lubricant, which improves tribological properties in mechanical applications. The performed process not only modifies the surface mechanically, but also improves its functional properties. It shows potential for applications in demanding environments where both mechanical and tribological properties of the material are important.

The depth of the laser's influence depends primarily on its power. In the case of a 250 W laser, the changes in grain structure reach 0.3 mm (Fig. 2). On the surface of the material (Fig. 2), there is a clearly visible melted zone, which was created as a result of intensive laser action. This zone is characterized by a fine-grained, dendritic structure, which is typical for metals crystallizing from a liquid state under conditions of rapid cooling. The dendrites have a characteristic arrangement of "branches", which is the effect of crystal growth in the direction of the maximum temperature gradient. Fine grains suggest a very high crystallization rate, which is caused by intensive heat removal from the melted area to the cooler core material. Residual segregations of alloying elements (e.g., chromium and molybdenum) may occur in the structure, but their size is minimal, which is the result of limited diffusion time at high temperature.

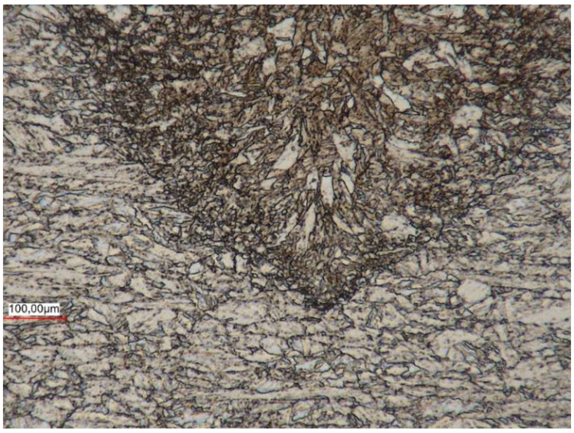

Fig. 3. Cross-section of a 1.8877-DIN steel sample, magnification ×2000, after laser processing with a power of 200 W, at a beam speed of 10 mm/s, in a nitrogen shield at a pressure of 2 bar.

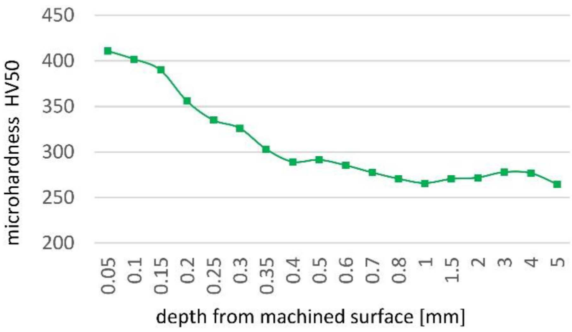

Fig. 4. HV50 microhardness in the cross-section of a 1.8877-DIN steel sample after laser processing with a power of 200 W, at a beam speed of 10 mm/s, in a nitrogen shield at a pressure of 2 bar.

The core of the material, located below the heat-affected zone, retained the original microstructure of the steel, which consists mainly of ferrite and pearlite. A clear contrast is visible between the microstructure of the core, the remelted layer, and the heat-affected zone (Fig. 3). This shows that the thermal gradient was steep enough to avoid structural changes in this part of the sample. The observed changes significantly improve the hardness, wear resistance, and potential corrosion resistance of the surface layer. However, the presence of thermal stresses and brittle phases such as martensite can limit fatigue strength and promote the formation of microcracks. To further optimize the physical properties of the surface layer, additional heat treatments such as tempering can be considered to reduce internal stresses and improve the ductility of the material.

Figure 4 shows the microhardness distributions in the surface layer of samples taken from 1.8877-DIN steel after laser processing with a power of 200 W, at a head speed of 10 mm/s, in a nitrogen shield with a pressure of 2 bar. As a result of laser processing,

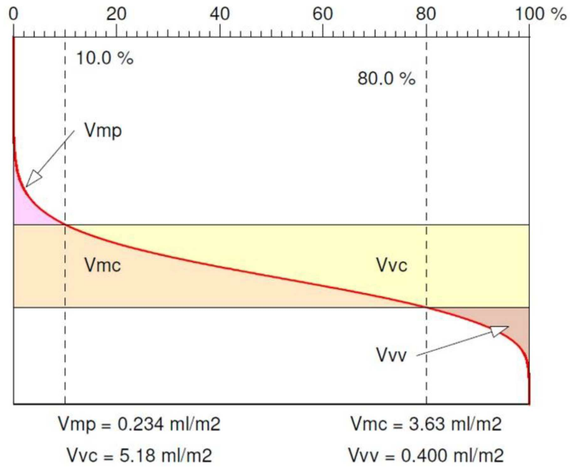

Fig. 5. Abbott–Firestone curve (bearing area curve) surface volumetric functional parameters for a sample after laser treatment with a power of 200 W, at a beam velocity of 10 mm/s, in a nitrogen shield at a pressure of 2 bar.

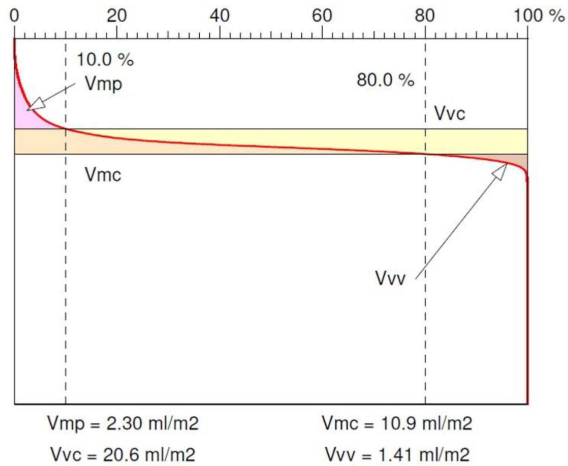

Fig. 6. Abbott–Firestone curve (bearing area curve) surface volumetric functional parameters for a sample after laser treatment with a power of 250 W, at a beam velocity of 10 mm/s, in a nitrogen shield at a pressure of 2 bar.

the hardness of the near-surface layers increased by 100–150 HV50 compared to areas that were not subjected to laser processing. The hardness of the near-surface layers (at a depth of ≈ 0.1 mm) is 405 HV50. The observed hardness profile may have a positive effect on wear resistance, but its effect on other properties, such as brittleness or fatigue strength, should be taken into account.

Taking into account the functional parameters related to volume, calculated based on the material share, the following parameters were obtained for the surface after laser treatment with a power of 200 W: the peak volume of the surface material Vmp equal to 0.234 [ml/m2], the core volume of the surface material Vmc equal to 3.63 [ml/m2], the volume of the surface space of the hollow core Vvc equal to 5.18 [ml/m2], and the surface cavity volume Vvv equal to 0.4 [ml/m2] (Fig. 5). However, the parameters obtained for the surface after laser treatment with a power of 250 W are much higher (Fig. 6).

Analysis of the graph in Fig. 6 surface volumetric functional parameters in terms of the core volume parameter (Vmc) shows that the sample surface after ablation with a 250 W laser beam in relation to the applied beam power of 200 W (Fig. 5) is characterized by a higher value, which indicates that this surface can be more stable and durable in applications exposed to high mechanical loads. Also, a high value of the Vvc surface volume of the material voids indicates the physical ability to store a lubricant. In summary, the use of higher laser power (250 W) increases the functionality of the surface by improving both its mechanical stability and tribological properties (friction and lubrication). This is particularly important for applications requiring high reliability. Laser processing by changing its parameters allows for the control of the surface functional parameters depending on the desired material application.

3. Conclusions

- Laser ablation significantly affects the changes in the properties of the surface layer of steel, causing numerous physical changes as a result of high temperature, the melting process, and extremely rapid cooling. The analysis allows for the formulation of key conclusions regarding the effect of this process on the material surface namely that the main feature of the surface layer is the formation of a fine-crystalline dendritic structure in the melted zone. A high cooling rate prevents full thermodynamic equilibrium, which results in limited grain growth. Fine dendrites are the result of rapid crystallization from the molten state towards the temperature gradient. This structure increases the hardness of the surface layer, which can be beneficial in applications requiring resistance to abrasion and surface loads.
- As a result of rapid cooling in the melted zone and the heat-affected zone, metastable phases such as martensite or bainite are formed. These phases are characterized by high hardness and brittleness. In the heat-affected zone, hardening martensite can be a source of local stresses, and its presence requires special attention in the context of fatigue strength. The presence of such phases improves the surface resistance to abrasion.
- From a physical perspective, laser ablation changes the mechanical properties of the surface layer, increasing its hardness due to the fine-grained structure and metastable phases. It causes a decrease in ductility due to the presence of martensite and internal stresses and improves abrasion resistance, which is important in applications requiring high surface strength.

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