

Optimization of the Parameters of Local Laser Treatment for the Creation of Reinforcing Ribs in Thin Metal Sheets

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1. Introduction

Steel is the fourth most commonly used metal in the world. Its production plays a significant role in the global economy and production amount is an indicator of the strength of national economy. In 2018, the total world crude steel production amounted to 1,692 million tons [1]. In order to diversify the use of thin-sheet metal products in industry, it is necessary to solve certain problems. At given load, the deformation should not exceed certain limited values imposed by the structural design requirements [2].

Current methods to increase the stiffness of thin-sheet metals are mainly design methods based on the relationship between a construction geometry and its stiffness. For example, creation of ribs or thick areas will increase the stiffness, but also leads to an increase in size, shape, and weight of the product [3].

The development of new metal processing technologies enables to control and improve the microstructure and properties of metals. Laser treatment is one of such modern techniques: local laser-induced heating allows creating zones with structure, hardness and overall mechanical properties differing with the rest of the metallic structure [4].

Knowing the properties of the laser-treated zones, as well as the distribution and values of the elastic deformations that occur in the whole structure under a given load, it is possible to affect the rigidity of the structure significantly.

Thus, using laser treatment, it is possible to locally generate phases transformation within metals. This treatment changes the structure and properties of the materials, for instance increase the stiffness.

2. Aim of the study

The main goal of this study was to evaluate the effect of laser treatment on the microstructure of thin-sheet metals and to determine the optimal parameters of laser treatment providing minimal external deformations and maximal increase in stiffness of the material. Another goal was to assess how the different laser treatment parameters influence the microstructure and mechanical properties of the material.

3. Object of the study

Structural and carbon steels are most often used for construction elements where high tensile and flexural

strengths and resistance to other types of stresses are required. Tensile or tear tests as well as bending and hardness measurements are the most common methods used to characterize the mechanical properties of metallic materials. The techniques characterize the rigidity, strength, and stability of structural elements, especially of thin-walled structures. A thin sheet of steel C22E (20x180mm and thickness $h=2\text{mm}$) was subjected to the laser treatment.

Steel 20 (1.1151, C22E) is a hypoeutectoid high-quality carbon steel, widely used in the manufacture of various metal products (beams, cross-arms, levers, shafts) and other parts of low strength (Table 1, 2). The mechanical properties and structure of this heat-hardened steel may vary depending on the heat treatment method and the delivery condition.

Table 1

Chemical composition % of steel C22E (1.1151) according EN 10083-2

C	Si	Mn	P	S	Cr+Mo+Ni
0.17 - 0.24	max 0.4	0.4 - 0.7	max 0.03	max 0.03	max 0.63

The sample was subjected to tempering to remove the internal stresses. To ensure a uniform absorption of laser radiation, one of the surfaces of the steel sheet was exposed to additional mechanical preparation: abrasive blasting using PowerPlus tool and quartz sand SAKRET with grain size 0.1-0.5 mm. After this treatment surface roughness R_a was not more than $5\text{ }\mu\text{m}$. Then this metal sheet was subjected to local laser treatment with varying parameters. Even a short treatment of a steel sheet with pulse laser beam (impulse time 0.1 – 1 sec) heats the surface to temperatures inducing the steel austenitizing or melting. The resulting temperature gradients cause subsequent rapid cooling of the surface at a speed of $10^3 - 10^4\text{ }^\circ\text{C/s}$ due to heat dissipation to the surrounding metal. This promotes the formation of quenching zones; which microstructure can be determined using the CCT diagrams.

The laser-treated zone in the steel sheet is usually characterized by a large structural heterogeneity and consists of several layers of varying depths. The number of layers of different properties and structure, as well as their depth, size, microstructure and hardness depend on the parameters of the laser treatment, as well as on the chemical composition and initial microstructure of the material. Usually, the treated zone of hypoeutectoid steel consists of a

near-surface region with a more uniform microstructure and underlying layers with non-uniform microstructures. [5]

The main parameters that influence the formation and characteristics of these zones are the laser power, spot size and speed of the laser beam focused in the steel surface.

Table 2

Mechanical properties of steel C22E (1.1151); EN 10083-2

Heat treatment	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, %	Hardness, HB
	Min	Min	Min	Max
Rolled		490	7	207
Annealing or tempering 600 °C	230	390	21	163
Normalizing 900 °C	240	430	24	101-143
Quenching 880 °C	340	590	18	370
Quenching 880 °C+ tempering 600 °C	340	500-650	20	143-179

At high treatment speeds, martensite with microhardness up to 6000 MPa can form at the surface and near-surface area instead of pearlite. The heterogeneity of the underlying microstructure increases with depth and may consist in phases such as martensite, troostite, which then becomes troostite-ferrite, and then ferritic microstructure (at the interface with the original steel microstructure). At higher laser speeds, the zone of homogeneous martensite is absent, and the troostite-ferrite structure around individual martensite segments can be formed at the surface, causing a decrease in hardness. At lower treatment speeds with continuous laser, martensite is prevalent and the local microhardness reaches 4300-5000 MPa. [6] Therefore, it is more desirable to treat hypoeutectoid steels at lower laser speeds, typically less than 8.0 mm/s. [7].

4. Methods of the experiments and used equipment

Surface laser treatment was performed with 3-axis Laser Welding Machine BMM400 (Table 3). Pulsed Nd:YAG lasers with wavelength of 1064 nm and various power are currently among the most common industrial lasers for different operations: processing, welding, cutting of steel. The following parameters of laser treatment were changed within certain limits: pulse energy, pulse duration, pulse frequency, spot size and table moving speed.

Table 3

Technical data of BMM CNC laser-welding machine

Technical parameters	Range
Laser working substance	Nd:YAG
Maximum single-pulse energy, J	150
Maximum peak power, kW	14
Laser wavelength, nm	1064
Spot size (diameter), mm	0.1-3.0
Average laser power, W	400
Pulse duration, ms	0.5-10
Pulse frequency, Hz	0-20

The influence of each of these laser treatment parameters on the geometry and microstructure of the treated layer was evaluated experimentally. For this, 40 test passes were made on the C20 sheet using various laser modes. Then, microsections of samples were prepared for microscopic examination. A metallographic analysis of the microstructure of the laser-treated zone was performed using Nikon Eclipse MA200 optical microscope with a Lumenera Infinity 2 video camera. Changes of mechanical properties of the laser-treated samples were evaluated by measurement

of the microhardness using a Zwick/Roell ZHμ microhardness tester with a Vickers four-sided square-based diamond pyramid. Sheet of C22E after heat treatment has a hardness of 149 HV according to the GOST 4041-71.

5. Method of calculation and optimization of laser treatment parameters

Calculation and optimization of the required parameters of laser treatment were performed considering the characteristics of the existing laser equipment and properties of the steel. The laser power must be sufficient to melt the minimal metal layer and induce local phase transformation within the thin-sheet steel sample. Nd:YAG laser works in pulse regime, then this laser can produce a peak power that is greater than its average power [8]. For example, a 400 W pulsed Nd:YAG laser can produce a peak power of up to 14 kW over few milliseconds. Melting of most part of metals is performed at low energy density in the range of 10^4 – 10^5 W/cm² (typically around $0.5 \cdot 10^5$ W/cm²).

As is well known, most of the steel and metal matrix composites properties, including their structural strength, follow the additivity rule, being linearly dependent on the percentage quantity or volume of individual components of the mixture. In this case, the strength of dual-phase steels can be calculated according to the rules of mixtures:

$$\sigma_c = \sigma_m V_m + \sigma_r V_r, \quad (1)$$

where: σ_m - average tensile strength of matrix; σ_r - average tensile strength of the reinforcement phase; V_m , V_r - the volume fraction of matrix and reinforcement phase.

According to this rule, the efficiency of the laser treatment and the final strength of the laser-treated surface depends on the treatment area and the depth of melting. In this case, the depth of penetration should be minimal in order to avoid of excessive embrittlement, cracking, and deformation of the treated material.

The critical power density for material melting and evaporation by a laser in pulse mode can be calculated according to Eq. (2) [8–12]:

$$P_d = \frac{\rho(T_m - T_0)ch}{At_p}, \quad (2)$$

where: P_d - critical power density, W/m²; A - absorptivity $A = (1 - R)$; R - reflection coefficient; c - specific heat, J/(kg

$^{\circ}\text{K}$); T_o – initial (room) temperature, $^{\circ}\text{K}$; T_m – material melting temperature, $^{\circ}\text{K}$; t_p – duration of laser pulse, s; h – depth of penetration, m.

The physical properties of carbon steel for calculations are presented in Table 4 below.

Table 4

Physical characteristics of steel [12]

Melting temperature, T_m , $^{\circ}\text{K}$	Initial (room) temperature, T_o , $^{\circ}\text{K}$	Absorptivity, A	Reflection coefficient, R	Density, ρ , kg/m^3	Specific heat, c , $\text{J/(kg }^{\circ}\text{K)}$
1733	295	0.09	0.91	7800	462

Based on the relationship between melt depth and pulse duration in Eq. (2), it is possible to calculate the main parameter of laser treatment – the required critical power. During technological tests, other laser treatment parameters (speed and spot size, pulse frequency) were varied (within a range of the technical characteristics of the available equipment) in order to determine the most effective mode of the laser treatment of the sample and to identify the correlations between individual treatment parameters and the level of hardening.

6. Research results and their analysis

The calculated values of laser critical power are presented in Fig. 1 as a function of the pulse length and the depth of the laser penetration into the material.

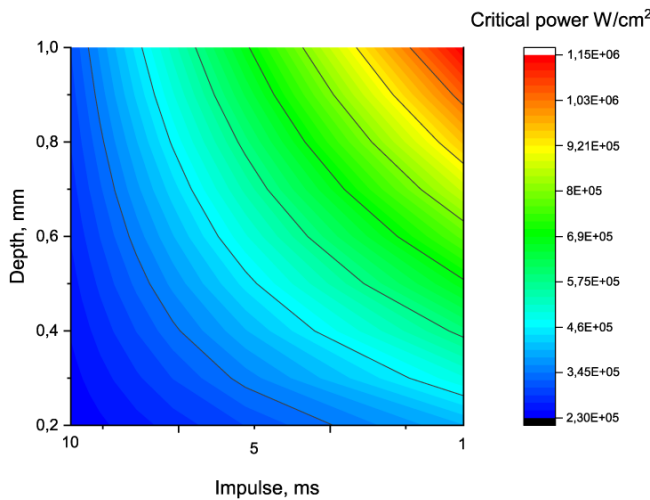
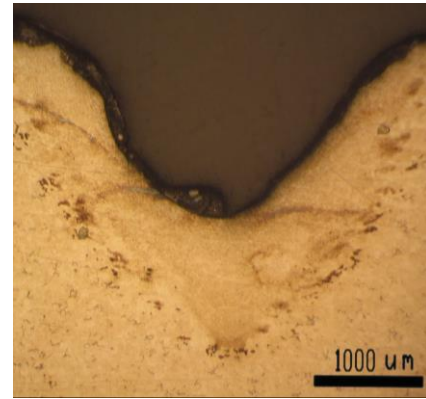


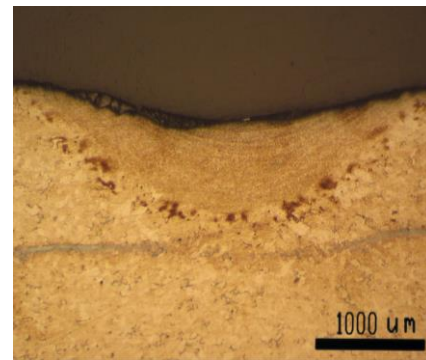
Fig. 1 Calculation of the laser critical power

Microscopy examination results of the samples treated by local laser treatment showed the following correlation between laser treatment parameters and experimental depth and width of laser penetration (Table 5). Some of the low laser speed modes resulted the cutting of the material, which adversely affects the quality and appearance of the product. Modes with low current and frequency are not able to melt the material and significantly affect the material rigidity. Some examples of treated zones are presented in Fig. 2. Based on our results, it is possible to conclude, that the optimal critical power of $\varnothing 3$ mm laser beam for the generation of inner reinforcing ribs ranges between $2.5 \cdot 10^5$ and $4.5 \cdot 10^5$ W/cm^2 , while speed of the beam ought to be set between 20 and 50 mm/min. Reduced speed of the laser beam

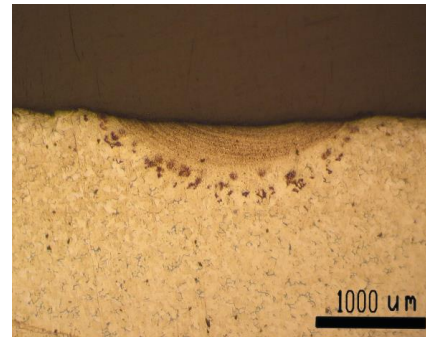
(less than 20 mm/min) leads to metal cutting due to the high critical power applied to the material, while increased speed of movement (more than 50 mm/min) decreases the penetration depth by half.



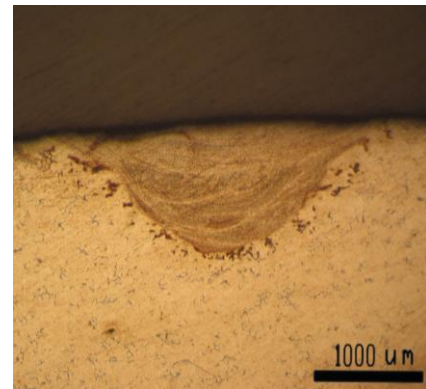
a



b



c



d

Fig. 2 The view of laser treated zones. a – critical power $8.27 \cdot 10^5$ W/cm^2 ; b - critical power $3.9 \cdot 10^5$ W/cm^2 ; c - critical power $1.11 \cdot 10^5$ W/cm^2 ; d - critical power $3.59 \cdot 10^5$ W/cm^2

Table 5

The correlation between the laser treatment parameters and the geometry of the melted zone

Depth, mm	Cutting	Speed v , mm/min	f , Hz	Single pulse energy, J	Spot size, mm	Peak power, kW	Overlap coefficient P_{er}	Calculated critical power P_{d1} , W/cm ²	Real critical power P_{d2} , W/cm ²
0.718	Present	120	20	11.8	2	2.36	99.5	$7 \cdot 10^5$	$8.27 \cdot 10^5$
0.559	Present	240					99		$6.44 \cdot 10^5$
0.329	Present	480					98		$3.79 \cdot 10^5$
0.292	Absent	960					96		$3.36 \cdot 10^5$
0.764	Present	120	20	11.8	3	2.36	99.6	$3.37 \cdot 10^5$	$8.8 \cdot 10^5$
0.501	Present	240					99.3		$5.77 \cdot 10^5$
0.339	Present	480					98.6		$3.90 \cdot 10^5$
0.274	Absent	960					97.3		$3.16 \cdot 10^5$
0.368	Absent	120	10	14.4	3	2.8	99.3	$4.11 \cdot 10^5$	$4.24 \cdot 10^5$
0.346	Absent	240					98.6		$3.98 \cdot 10^5$
0.336	Absent	480					97.3		$3.87 \cdot 10^5$
0.312	Absent	960					94.6		$3.59 \cdot 10^5$
0.209	Absent	120	10	7.2	3	1.4	99.3	$2 \cdot 10^5$	$2.41 \cdot 10^5$
0.181	Absent	240					98.6		$2.08 \cdot 10^5$
0.155	Absent	480					97.3		$1.78 \cdot 10^5$
0.096	Absent	960					94.6		$1.11 \cdot 10^5$

Microscopy analysis showed that low-carbon ferritic-pearlitic steel (Fig. 3) of 149 HV hardness after the laser treatment acquire a sorbite structure (Fig. 4): a ferrite-cementite mixture, where cementite has a rounded shape and 206 HV of hardness. Sorbite has higher tensile strength and hardness with a relatively high yield strength [13]. Vickers microhardness examination results showed that the metal hardness can be increased up to 38.26% depending on the laser treatment (206 HV) compared to the untreated zones (149 HV).

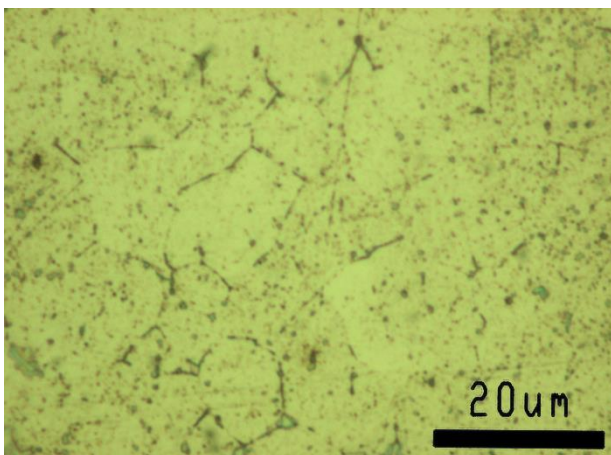


Fig. 3 Microstructure of low-carbon ferritic-pearlitic steel

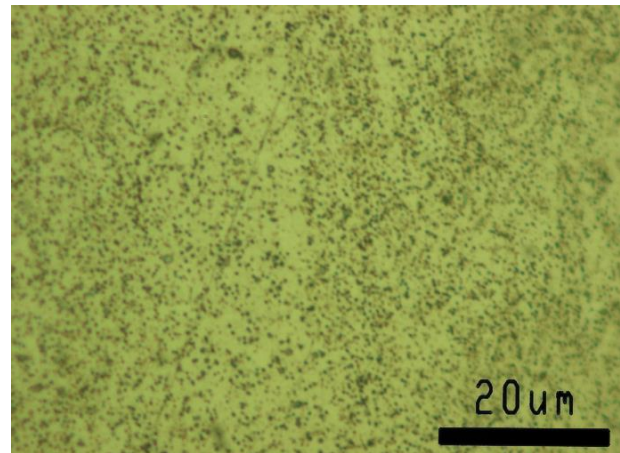


Fig. 4 Sorbite structure after laser treatment

7. Conclusions

1.The described method of local laser treatment allows the generation of reinforcing ribs in thin-sheet metal structures.

2.Optimal critical power for used sample of thin sheet C22E steel is in the range from $2.5 \cdot 10^5$ to $4.5 \cdot 10^5$ W/cm²

3.The optimal laser beam speed for used sample of thin sheet C22E steel is in the range 20-50 mm/min.

4.The laser treatment of used sample of thin sheet

C22E steel allows to increase the hardness in the treatment zone up to 39 %.

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OPTIMIZATION OF THE PARAMETERS OF LOCAL LASER-INDUCED HEATING FOR THE CREATION OF REINFORCING RIBS IN THIN METAL SHEETS

Summary

This article describes the results of mathematical and experimental studies aiming to determine the optimal parameters for generation of reinforcing ribs in thin metal sheets using local laser treatment. The effects of various parameters of local laser treatment on material stiffness were investigated. The influence of the major parameters of laser treatment on the microstructure, width, and depth of penetration of the laser is reported.

Keywords: reinforcing ribs, laser treatment, stiffness.