

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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**RESEARCH OF IMPROVEMENT OF NON-
ALLOY STEEL SURFACE HARDNESS AND
STIFFNESS BY LASER TREATMENT**

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Abstract

The dissertation deals with the development of new metal processing technologies that enable to control and improve the microstructure and properties of the metals. Laser treatment is one such modern technique. The dissertation aims to determine the laser processing effect on the surface of a thin sheet of non-alloy structural steel. The research aims to solve one of the critical problems in diversifying the use of thin-sheet steel products in the industry by developing laser-processing technology for the creation of structural strengthening ribs, which can significantly affect the overall strength and stiffness of metal parts.

The proposed solutions will help solve the problems of using thin-sheet metal products in the industry by increasing the stiffness with preserving the original design parameters (e.g., the product's size, shape, and weight). This will save production time and resources due to the reduced number of technological and maintenance operations compared to traditional methods of increasing the stiffness of thin-sheet metals, where designing methods are based on the relationship between a construction geometry and its stiffness.

The introductory chapter discusses the research aim and objectives. It also describes the research methodology, its scientific novelty, and the practical significance of the results. The introduction closes by presenting the author's publications and conference papers on the dissertation's topic and structure.

The first chapter reviews the existing methods of increasing the hardness and stiffness of thin-sheet steel products. It also overviews the microstructure and the possibility of increasing the mechanical strength and hardness of the non-alloy steel. At the end of the chapter, the conclusions of the literature review are formulated, and the essential tasks of the dissertation are specified.

The second chapter describes the materials and laboratory equipment used in the research work. This includes the methodology of microstructure analysis, mechanical properties testing, surface laser processing technology, calculating laser processing parameters, and modeling bending and tensile cases.

The third chapter presents the results of the analysis of surface layer microstructure and phase composition, mechanical properties, calculation and selection of laser processing parameters, modeling of bending and tensile of treated thin-sheet samples, analysis of the importance of laser processing depth, and direction of processing, geometry, and direction of processing, and location of reinforcement areas.

Six articles on the topic of the dissertation have been published, and the research results have been presented at nine scientific conferences in Lithuania and abroad.

Reziumė

Disertacijoje nagrinėjamos naujos metalo apdirbimo technologijos, leidžiančios kontroliuoti ir tobulinti metalų mikrostruktūrą bei savybes. Apdirbimas lazeriu yra vienas iš tokių modernių metodų. Disertacijos tikslas – nustatyti nelegiruotojo konstrukcinio plieno, turinčio mažą anglies kiekį, plonos plokštės paviršiaus apdorojimo lazeriu poveikį, lazerio apdorojimo parametrų įtaką plieno mikrostruktūrai, mechaninį stiprumą, ašinį ir lenkimo standumą, jėgos įlinkį. Tyrimu siekiama išspręsti vieną iš sarbių problemų, siekiant įvairinti plonasluoksnių plieno gaminių naudojimą pramonėje, kuriant lazerinio apdorojimo technologiją ir sukuriant konstrukcijų stiprinimo briaunas, kurios gali reikšmingai paveikti bendrą metalinių dalių stiprumą.

Siūlomi sprendimai padės išspręsti plonasluoksnių metalo lakštų gaminių naudojimo pramonėje problemas, didinant standumą ir standumą išsaugant originalius konstrukcinius parametrus (pvz., gaminio dydį, formą, svorį). Tai padės sutaupyti gamybos laiką ir ekonominius išteklius dėl mažesnio technologinių ir priežiūros operacijų skaičiaus, palyginti su tradiciniais plonasluoksnių metalų standumo didinimo metodais, kai projektavimo metodai grindžiami konstrukcijos geometrijos ir jos standumo ryšiu.

Įvardiniame skyriuje aptariamas tyrimo tikslas ir uždaviniai. Taip pat aprašoma tyrimo metodika, jo mokslinis naujumas, praktinė rezultatų reikšmė. Įvado pabaigoje pristatomos autoriaus publikacijos ir konferencijos pranešimai disertacijos tema ir disertacijos struktūra.

Pirmajame skyriuje apžvelgiami esami plonasluoksnių plieno gaminių kietumo ir standumo didinimo būdai. Taip pat apžvelgiama nelegiruotojo hipoeutektoidinio plieno mikrostruktūra ir galimybė padidinti mechaninį stiprumą ir kietumą. Skyriaus pabaigoje suformuluotos literatūros apžvalgos išvados, sukonkretinami esminiai disertacijos uždaviniai.

Antrajame skyriuje aprašomos tiriamajame darbe naudojamos medžiagos ir laboratorinė įranga. Tai apima mikrostruktūros analizės metodiką, mechaninių savybių testavimą, paviršiaus lazerinio apdorojimo technologiją, lazerinio apdorojimo parametrų skaičiavimą, lenkimo ir tempimo atvejų modeliavimą.

Trečiajame skyriuje pateikiami paviršinio sluoksnių mikrostruktūros ir fazinės sudėties analizės, mechaninių savybių, lazerinio apdorojimo parametrų skaičiavimo ir parinkimo, apdirbamų plonasluoksnių bandinių lenkimo ir tempimo modeliavimo, lazerinio apdorojimo gylio ir krypties svarbos analizės rezultatai. Apdorojimas, geometrija ir apdorojimo žingsnis bei sutvirtinimo zonų vieta.

Disertacijos tema paskelbti 6 moksliniai straipsniai. Tyrimo rezultatai pristatyti 9 mokslinėse konferencijose Lietuvoje ir užsienyje.

Notations

Symbols

A – absorptivity;
 c – specific heat;
 F_r – material property of reinforcement phase;
 h – thickness of the material or melted layer;
 H_m – material property of matrix;
 n – strain-hardening exponent;
 P_d – critical power density;
 ρ – density;
 R – reflection coefficient;
 T_e – heating temperature (material melting or evaporation temperature);
 T_0 – initial (room) temperature;
 t_p – duration of laser pulse;
 V_m – volume fraction of matrix phase;
 V_r – volume fraction of reinforcement phase;
 ε^e – elastic deformation;
 ε^p – plastic deformation;
 σ_B – tensile strength;
 $\sigma_{0.2}$ – yield strength.

Abbreviations

CALPHAD – calculation of phase diagrams;
CCD – charge-coupled device;
CCT – continuous cooling transformation;
CW – continuous-wave;
CEMS – conversion-electron Mössbauer spectroscopy;
DSPD – dynamic surface plastic deformation;
EDS – energy dispersive spectroscopy;
FCC – face-centered cubic lattice;
FEA – finite element analysis;
LTH – laser transformation hardening;
OES – optical emission spectroscopy;
PPD – pulsed plasma deposition;
SEM – scanning electron microscopy;
SSPD – static surface plastic deformation;
TTT – time-temperature transformation;
XRD – x-ray diffraction.

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Introduction

Problem formulation

Despite the availability of a wide range of durable and lightweight materials in various areas of industry and engineering, steel is currently one of the most used structural materials with increasing global production.

In 2021, the total world crude steel production was 1951 million tons. The World Steel Association (Worldsteel, WSA) predicts a rise in steel production by at least 3.6% in 2022 (“Global crude steel output increased by 4.6% in 2018” 2019). High alloy stainless steels and special steels constitute a separate market and production segment. Currently, the metal products market is undergoing tight competition and minimum profit. The introduction of innovative technical solutions to the world market significantly increases the margins and profit. In addition to sheet metal, as traditionally used for producing welded pipes or containers, a new specific branch of the metal industry has now been formed as the production of light thin-walled metal structures (Zhao & Al-Mahaidi, 2009; Li et al., 2022). As a raw material for manufacturing such thin-walled products, non-alloy structural steel with an average thickness of about 2 mm is mainly used. However, the application of structural non-alloy steel is limited due to insufficient mechanical strength and rigidity (Tylek & Kuchta, 2014a; 2014b). Therefore, to diversify the use of thin-sheet steel products in different fields of industry, it is

necessary to solve certain technological problems. At a given operating load, the maximum deformation should not exceed certain allowable values imposed by the structural design requirements (worldstainless.org). Current engineering methods to increase the stiffness of thin-sheet steels are mainly based on the relationship between a construction geometry and its stiffness (Liu, 2008; Jalilzadeh, 2019; Troina, 2020). For example, the creation of ribs or thick areas will increase the stiffness but also leads to an increase in the size, weight and complexity of the shape of the final product (Feschenko, 2016). The development of new steel processing technologies enables to control and improve the microstructure and properties of steel (Yin, 2021). By using laser processing, it is possible to locally generate phase transformation of constructional non-alloy steel structures with carbon content below 0.3% (Ghorabaei, 2021). The local laser-induced heating allows the creation of zones with structure, hardness, and overall mechanical properties differing from the rest of the metallic untreated structure (Elagina, 2009). Thus, this processing technology can help change the properties of steel products; for instance, it can increase the stiffness and hardness of the steel products.

Relevance of the dissertation

During the research presented in the dissertation, new knowledge was obtained about the specifics of local surface treatment of thin-walled metal products made of household non-alloy structural steel with a carbon concentration of up to 0.3%. A methodology for the processing and analysis of such thin-walled steel products has been compiled.

The established relationship between the adequate microstructure obtained after laser processing and the parameters of processing make it possible to affect the rigidity of such thin-walled steel products significantly and control the distribution and values of internal stresses and deformations that occur in the whole thin-sheet steel structure after the laser processing. This will significantly improve the existing production technology and improve the operational properties of such products. The results of the research work are important for solving existing technological problems in different industrial objects (for example, pressure equipment, vessels, storage tanks, transport, and shipbuilding), where thin-walled metal shells and structural components from non-alloy steels are necessary.

Research object

This study used locally laser-treated (with different designs of the laser-treated area) thin metal sheets from non-alloy high-quality steel 1.1151 (EN 10083-2:2006) and 1.0402 (EN 10250-2:2022) containing less than 0.3% carbon.

Aim of the dissertation

This work aimed to develop new local processing technology able to modify the local surface areas of thin-sheet non-alloy steel products to increase the operational properties (hardness and stiffness) of such steel products without changing their original design (e.g., size, shape, and weight) at the expense of using laser techniques.

Tasks of the dissertation

To achieve the aim of the dissertation, it is necessary to solve the following tasks:

1. To assess the influence of laser processing technique and parameters on the steel microstructure and mechanical properties and determine the optimal parameters of laser processing providing minimal deformations and maximal increase in surface hardness.
2. To evaluate the mechanical properties of the laser-treated layer and the efficiency of applying local laser processing with surface melting, to increase the mechanical strength and stiffness without the use of complex shape structures or heat treatment.
3. To model the bending and tensile loading conditions and analysis of the effectiveness of the application of laser processing with surface melting to strengthen thin sheet components.
4. To compare the experiment results and finite element modeling, evaluate and select the optimal processing area, orientation, and depth of laser processing to obtain maximum efficiency in resistance to exploitation loads.

Research methodology

Different analytical and experimental methods were used in this research work. Samples of thin-sheet non-alloy steels containing less than 0.3% carbon were laser treated. The microstructure was analyzed using SEM, EDS, color microscopy,

XRD, and Mössbauer spectroscopy. The properties of the laser-treated steel thin sheets were evaluated by different types of mechanical testing (i.e., bending, tensile, and microhardness). Experimental results were compared with thin-walled objects' deformation modeling results simulated using the finite element method.

The scientific novelty of the dissertation

The following new results of materials engineering science were obtained during the preparation of the current dissertation:

1. New data on the formation of a sorbite microstructure in non-alloy steel with a carbon content of less than 0.3% using local laser processing has been obtained.
2. The hypothesis regarding the possibility of strengthening thin-sheet elements from non-alloy steels was confirmed. It was established that using certain laser processing parameters of non-alloy steels with low carbon content, it is possible to obtain a sorbite microstructure of the treated surface. This microstructure is characterized by greater hardness, mechanical strength, and sufficient ductility compared to the original steel structure.
3. The obtained results and the proposed methodology can be used for further elaboration on the development issues of technology for improving thin-sheet structures by creating structural rigidity ribs in other types of steel.

The practical value of the research findings

The results of this work are important in solving the technological problems of the existing and developed thin-walled and lightweight steel structures, their production, and processing. These results allow for selecting and applying the most rational, technologically simple, and practically convenient laser processing technology of thin-walled steel structural elements to select and optimize processing parameters and predict the main performance of laser-treated surfaces and products.

Experimental studies confirm that it is technically possible to perform local laser processing of structural steels with a carbon content of less than 0.3% to create the hardest structure on the surface of thin-sheet steel products. The optimal combination of laser processing parameters for the creation of structural rigidity ribs has been proposed. The proposed optimal texture and deep local laser processing help to increase the resistance to workloads and the strength of

structural elements made of high-quality non-alloy steel with a carbon content of less than 0.3% as an alternative to the application of complex geometric shapes, additional strengthening elements, or heat treatment.

The application of the research results will allow Lithuanian and other European and foreign industrial enterprises to reduce the design complexity and production costs of manufactured thin-walled steel products.

Defended statement

1. The described local laser processing technology of steel surfaces due to transformation of initial steel structure to sorbite microstructure with enhanced mechanical properties allows for generating reinforcing ribs or areas in thin-sheet metal structures from 1.1151 (EN 10083-2:2006) and 1.0402 (EN 10250-2:2022) steels with carbon content below 0.3%, when optimal critical power for local laser processing of steel surface is in the range from $2.5 \cdot 10^5$ to $4.5 \cdot 10^5$ W/cm². The proposed methodology improves surface hardness by up to 50% and flexural stiffness by up to 10%.

Approval of the research findings

Six articles have been published on the topic of the dissertation: two in Clarivate Analytics Web of Science Core Collection with Science Citation Index (Kapustynskiy et al., 2020a, 2020b), one in Clarivate Analytics Web of Science with Conference Proceedings Citation Index (Kapustynskiy et al., 2020), two in the publications of other international databases (Kapustynskiy et al., 2022, 2021), and one in other peer-reviewed scientific conference proceedings (Kapustynskiy et al., 2019). The results of the research work have been presented at nine scientific conferences in Lithuania and abroad:

- International scientific conference *Mechanika 2019, 2022*, Kaunas, Lithuania.
- International conference on metallurgy and materials *Metal 2020, 2021, 2022*, Brno, Czech Republic.
- International conference – school *Advanced Materials and Technologies, 2019, 2020*, Palanga, Lithuania.
- 3rd Virtual Congress on Materials Science & Engineering *Materials Info 2021*, Oregon, USA.
- 6th Belarusian-Baltic Forum *Collaboration is a catalyst for innovative growth*, Minsk, Belarus.

Structure of the dissertation

The dissertation has the following structure: the introduction, three chapters, general conclusions, references and the author's publications on the dissertation's subject. The volume of the work is 118 pages. The dissertation includes 18 numbered formulas, 53 figures, and 34 tables. The dissertation cites 106 literature references.

Acknowledgement

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Review of the processing technologies, structure, and physical properties of non-alloy steels

The chapter deals with thin-walled steel structures, considering the peculiarities of the structure of non-alloy steels with a carbon content of up to 0.3%, possible structural changes, and achievable mechanical properties depending on heat treatment technology or other alternative surface treatment methods. Technical possibilities of application and the specifics of laser processing are also analyzed. The results of this chapter are published in the author's publications (Kapustynskyi et al., 2019; Kapustynskyi & Višniakov, 2020).

1.1. Overview of the features of thin-walled structures made of non-alloy steels

Scientific interest in laser processing technologies has been growing recently. Numerous publications consider the effects of laser processing of steel and other metals on the microstructure and properties of laser-treated surfaces and their application in practice for the production of various metal structures (Yu et al.,

2020; Černašėjus et al., 2020; Miraoui et al., 2013). Global production of thin-walled structural components made of such steel is steadily increasing. Therefore, the actuality of studying and obtaining important results on the potential for improving the mechanical and other performance of various thin-walled non-alloy steel structural components with carbon content below 0.3% is very relevant. In modern mechanical engineering, thin-walled structures are often used to provide high rigidity and strength with a relatively small weight (Peksen, 2018). Reducing the weight of steel structures and the amount of metal required by improving the strength, hardness, and stiffness of steel products is a major task in the metalworking sector (Dzwierzynska, 2021).

All shell-type structures are made of rolled steel. Depending on the purpose, design, and manufacturing features, shell structures can be divided into oversized containers, oversized cylindrical products, vessels operating under excessive pressure, pipelines, and bodies. Naturally, such classification of shell structures is largely conditional. Therefore, each industry has, as a rule, its different classifications of shell-type equipment. It should also be noted that various steel structures have components in their composition that are fragments of a wide variety of shell types (bottoms, pup joint/short pipe, hatches, fittings, etc.).

These structures have low rigidity, and the use of their entire strength range is often impossible due to unacceptably large deformations. Since most thin-walled structures are usually destroyed due to stability loss, critical loads are determined not by strength but by the modulus of elasticity.

In addition, some types of shell structures under operating conditions are subjected to low-cycle loading in the presence of increased pressure of an aggressive medium, and this pressure can change simultaneously with the loading cycle.

Since stability loss means an almost complete loss of the load-bearing capacity of the structural element, this phenomenon must be considered when designing new constructions. First, it is necessary to avoid this type of load at which stability loss is possible. Thin-walled steel structures are reinforced by flanging, reinforcing linings and stiffeners, blocking movements by cross-links, and applying rational arrangement of stiffness nodes to increase local stiffness, reduce stress concentration and increase cyclic strength.

It should be noted that the phenomenon of stability loss is most pronounced in lightweight, thin-walled compressed shells and walls. The calculation specifics of these structures' strengths gave rise to a special calculation scheme. The theory of soft shells is used when calculating thin-walled structures with small bending stiffness. According to this theory, the shell is considered momentary and unable to perceive compression forces. Therefore, thin-walled shell structures are lightweight constructions, mostly designed to carry only tension loads without

considering compression or bending. However, such three-dimensional tensile structures can be subjected to unplanned bending loads and bending stresses due to concentrated transversal force. These forces can be an accidental impact, concentrated external or support/reaction forces, which may cause significant damage or failure of the whole construction (Guo & Yang, 2013).

In modern engineering practice, some problems require a solution that considers the plastic properties of metal-like steel. Considering the development of plastic deformations (ultimate load method or limit state design) during calculations and designs allows for reducing metal consumption compared to the application of working stress methods. Heavily loaded structural elements, such as shells of building structures, rockets, chemical reactors, thin-walled pipes, and other structures, are designed using calculation methods that take such plastic deformations into account. Since, in these cases, the systems are elastoplastic, the calculations are carried out outside the elasticity of the material. Using this approach, local plastic deformations are allowed in the calculations, i.e., the construction material no longer follows Hooke's law in the process of loading. Calculations considering plastic deformations often allow access to additional reserves of structural strength in steel structures and increase available workloads (in the case of profile bending, up to 45%) or ultimate bending moment (for beams, up to 1.5 times), in comparison with the results achieved by traditional working stress methods (exploitation only in elastic conditions) (Rzhanicyn, 1954; Valiullin, 2012).

The application of steel with higher mechanical strength (including compressive, tensile, and bending strength) is very significant for thin-walled constructions. In many cases, the application of heat treatment helps to increase the yield and ultimate strength of structural steel.

Another effective solution to increase strength (particularly bending strength) is changing the dimensions of parts, modifying the shape, or the application of special strengthening elements (Jones, 1999). Techniques, such as different heat treatment or thermochemical treatment processes and the addition of strengthening elements, complex geometry profiles, and structural thickenings (Kurkin, 1991; Guo, 2013b), are mostly used to improve the mechanical properties of steel products and their surface. But the application of strengthening elements, complex geometry profiles, and structural thickenings increase the manufacturing costs and the weight of metal parts and require complex equipment and accurate designs. Heat treatment and thermomechanical treatment technologies are expensive, complicated, and long-running processes. This technology is not appropriate for large constructions and heavy sections from non-alloy and low-carbon steels containing less than 0.3% carbon, but thin plates and sheets from such steels can still be hardened and provide different combinations of strength and toughness after heat treatment. Therefore, in this case, modern

laser metalworking technologies can be a fairly effective alternative solution to local surface treatment and are also useful and easily applicable to increase the rigidity and other exploitation properties of shell structures made of non-alloy structural steels with a carbon concentration of up to 0.3% by using simple and inexpensive Nd:YAG lasers.

1.2. Overview of microstructural features of non-alloy steels

Non-alloy structural steels are widely used to manufacture parts and metal products for non-critical structures in engineering (for example, tubes, vessels, beams, shells, panels, folds, membrane structures, and other forms used in metalworking) and in other industries (Feschenko, 2016). The properties of non-alloy and high-quality low-carbon steel and its semi-finished steel products are highly dependent on chemical composition, heat treatment method, and delivery state (Vorobeva et al., 2013).

The main emerging structures responsible for the obtained properties of such structural steels during processing are both equilibrium phases, austenite and perlite, and non-equilibrium phases, martensite and residual austenite, sorbite, or troostite (i.e., quasi-eutectoid mixtures of ferrite and cementite, in which the carbon content is greater or less than 0.8%). The formation of a particular structure is dependent on the temperature of its formation, the composition of the alloy, the cooling medium, and other factors. The products of perlite transformation have a lamellar structure. Sorbite, troostite, and perlite differ mainly in the degree of dispersion of cementite inclusions and the hardness of the structure, which are summarized in Table 1.1 (Frolova, 2016). The degree of dispersion of the ferrite-cementite structure affects its mechanical properties: with its increase, hardness, strength limits, yield strength, and endurance increase. The plasticity characteristics turn out to be the largest in sorbite and the smallest in troostite.

The bainitic (intermediate) transformation of supercooled austenite occurs in the temperature range located below the pearlite but above the martensitic interval (Kozvonin, 2017; Kuklina, 2018). At an isothermal exposure temperature of more than 350 °C, upper bainite (~ HB 450) with a feathery structure resembling that of perlite is formed; at an isothermal exposure temperature of less than 350 °C, lower bainite (~HB 550) is formed, having a needle-like structure similar to that of martensite. However, obtaining such a structure is possible after very long isothermal treatment (many hours of exposure in the furnace) in a certain temperature range (~350 °C) (Davidova, 2006).

Table 1.1. Parameters of constituent microstructural phases in steels (Frolova, 2016; Chiudina et al., 2013)

Parameters	Perlite	Sorbite	Troostite	Bainite	Martensite
Sheet thickness L, μm	0.6–2.0	0.2–0.3	0.1–0.2	0.08–0.12	0.15–0.25
Hardness HB	HB 180–250	HB 250–300	HB 300–400	HB 450–550	HRC 40–65

At a very high cooling rate (i.e., above 1200 °C/sec), diffusion decomposition of austenite becomes impossible, and then austenite is supercooled and turns into martensite. In contrast to the pearlite transformation (eutectoid decomposition), the martensitic transformation is polymorphic (diffusionless or shear-type). The transformation of austenite into martensite does not go through to the end. Therefore, in quenched steel, along with martensite, there is always a certain amount of residual austenite. A significant interval between the temperature of the beginning and the end of the martensitic transformation leads to the presence in steels of several types of martensite (plate or lath), which are formed at different temperatures. Each type of martensite has different characteristics and properties (grain size, chemical composition, etc.). The formation of a particular type of martensite is favored by the temperature of its formation, which depends on the composition of the alloy, the cooling media, and other factors. The plate (or lenticular) martensite structure is formed at a temperature below 200 °C (Aleksandrov, 2015). It is typically only for high-carbon (i.e., more than 0.6% C) and alloy steels. The properties of such type of martensite, which is observed in the structure of the steel in the form of plates, determine the presence of the midrib of martensite plate. The fractions of plate martensite usually have a thickness of 5–30 nm. The hardness of this type of martensite is in the range of 60–75 HRC. Lath martensite is a characteristic microstructure of low- and medium-carbon steels (i.e., less than 0.5% C) (Gulyaev, 1986). The temperature range at which the formation of a martensitic structure occurs in such steels is above 300 °C. Martensite of this type has the form of laths oriented in one direction, the thickness of each is in the range of 0.2–2 μm (while their length is about five times greater than the width). Multiple laths with similar crystallographic orientation form a block, a structure that is visible even with light optical microscopy. Multiple blocks with the same habit plane form a packet. Interlayers of austenite can be found between adjacent laths. The thickness of such interlayers in different alloys can be in the range of 10 to 20 nm. This type of martensite is characterized by a lower hardness of 40–60 HRC but greater wear resistance, dynamic viscosity, and ductility compared to lamellar martensite (Natapov, 1980; Bogoduchov & Kozik, 2011). Based on the above-mentioned features of each microstructure, it can be

concluded that the most advantageous structure for thin-walled elements made of non-alloy steel with less than 0.3% carbon is lower bainite or sorbite.

1.3. Overview of the features of the processing of structural steels

Steel-making processes and heat treatment of various steel structures are well established. Various methods of heat treatment, thermo-chemical, thermo-mechanical, and mechanical processing can be used in the metallurgical and metalworking industry to improve the operational properties of semi-finished or finished metal products. Heat treatment is one of the most common for steel and iron. Depending on the cooling rate during treatment, austenite can be transformed into various structures: martensite, troostite, sorbite, perlite, sorbite, and troostite, which are presented in Table 1.2.

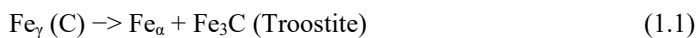
Table 1.2. Influence of cooling rate on austenite transformation and microstructure of steels (Frolova, 2016; Kozlovskij & Kolobov, 2017)

Structure	Perlite	Sorbite	Troostite	Bainite	Martensite
Temperature range of transformation during cooling	650–700 °C	600–650 °C	600–500 °C	250–500 °C	Below 250 °C
Degree of austenite supercooling	Cooling in the oven at a rate of several degrees per minute	Air cooling at a rate of several tens of degrees per minute	Cooling in oil at a rate of several tens of degrees per second	Isothermal exposure in the range of 500–250 °C	Cooling in water at a rate of Several Hundred degrees per second

The main types of heat treatment of steels include annealing, quenching, and tempering. Also, along with these types of heat treatment, normalizing is often used to reduce residual stresses in steel and create a more formable product with a uniform and fine-grained structure. Normalization is not defined as one of the main types of heat treatment. But normalization can be a kind of either annealing or quenching, depending on the steel grade and size of the workpiece.

The purpose of annealing is to obtain a steel microstructure close to equilibrium; then carbon steels are cooled at a rate of 0.05–0.1 °C/sec (Natapov, 1980; Bogoduchov & Kozik, 2011). After annealing of carbon pre-eutectoid steel,

a microstructure is obtained: ferrite and perlite. In pre-eutectoid steels, normalizing allows for obtaining a homogeneous fine-grained structure. Therefore, in low-carbon steels (i.e., up to 0.3% C), it is sometimes used instead of annealing. Normalizing is a more economical heat treatment than annealing since less time is spent on cooling the steel (Saber et al., 2020). The cooling rate, presented in Table 1.3, during normalizing, is usually in the range of 1–10 °C/sec (Maniruzzaman et al., 2013). The transformation of supercooled austenite occurs with the formation of pearlite-like structures by reactions Eq. 1.1–1.2, when steel is cooled from the austenitic state with speeds less than the critical, but higher than the speed that ensures the equilibrium transformation of austenite to perlite (Chiudina et al., 2013):



and



The above transformation takes place by diffusion. The dispersed structure of sorbite at carbon steel is often obtained after normalizing under conditions of cooling in an airstream at a cooling speed of 10°C/sec and higher. The structure of troostite is formed under conditions of even more intense cooling in oil at a rate of about 100–150 °C/c (Natapov, 1980; Bogoduchov & Kozik, 2011).

Bainite is usually not formed during continuous cooling of carbon steel, such an intermediate transformation with the formation of bainite is possible only with isothermal exposure in the temperature range of 500–250 °C, and this is, in principle, unrealizable during welding or laser processing (Chiudina et al., 2013). The minimum cooling rate at which all austenite is supercooled and transformed into martensite is called the critical quenching rate. Low-carbon steels with a carbon content of less than 0.3% have the highest critical quenching rate (above 1200 °C/sec) (Kucher, 1987). Therefore, such steels are practically not quenched by traditional heat treatment using a cooling media, so the required quenching speed of austenite transformation into martensite is not achievable. Carbon steels with a carbon content of more than 0.3% are usually tempered in water. Based on the above-presented information, the heat treatment for obtaining lower bainite is the most preferable and, at the same time, difficult way to improve the mechanical properties of steel products made of low-carbon steel (with a carbon content of less than 0.3%), since lower bainite has a higher hardness and strength compared to pearlite structures. Moreover, the lower bainite has sufficiently high plasticity and viscosity. The upper bainite is quite brittle, which is associated with the release of coarse carbides along the boundaries of ferritic grains. But the hardness and strength of steel consisting of the upper bainite microstructure do not increase at the same time.

Table 1.3. The typical cooling rate of steel in various cooling media (Frolova, 2016; Pertash, 1959)

Cooling media	Cooling rate, °C/sec	
	650–550	300–200
Water at a temperature of 18 °C	600	270
Water at a temperature of 25 °C	500	270
Water at a temperature of 50 °C	100	270
Water at a temperature of 75 °C	30	200
Soapy water at 18 °C	30	200
Emulsion oil in water	70	200
Water saturated with carbon dioxide	150	200
Distilled water	250	250
10% aqueous solution of caustic soda at 18 °C	1200	300
10% aqueous solution of table salt at 18 °C	1100	300
10% aqueous solution of sulfuric acid at 18 °C	750	200
10% aqueous soda solution	800	270
5% solution of potassium permanganate	450	100
Kerosene	160–180	40–60
Industrial oil	100–150	20–50
Transformer oil	120	25
Copper cooling plate	60	20
Iron cooling plate	30	15
Air	12	3
Compressed air	30	10

Other well-known methods of chemical-thermal surface treatment (cementation, nitro cementation, micro-alloying, and others) are also used to improve the performance of steel parts (Michael & Madhu, 2013).

The cementation process applies to steels with a carbon content of up to 0.2%. But this technology is possible mainly for parts with small dimensions and low-responsible components. In this case, austenite is converted into a ferrite–perlite mixture under the cemented layer during processing. The parts are heated using a furnace in the temperature range of 850–950 °C to carburize the outer surface layer. Technologically, the cementation of steels is carried out in various media (solid, liquid, or gas), which are commonly called carburetors. Cementation of parts is a rather long process. The rate of carbon diffusion is 0.1 mm per hour, and

the thickness of the hardened layer does not exceed 0.2–0.5 mm. Thus, the 0.5 mm required for long-term operation can be obtained in 5 hours (Allen, 2013).

Nitrocementation of steel is very similar to the previous process of saturation of the steel surface with carbon and nitrogen simultaneously at 700–950 °C in a gas media consisting of carbonizing gas and ammonia (Kalinin & Novikova, 1965). Most often, nitrocementation is carried out at 850–870 °C. The process of nitrocementation has become widespread in mechanical engineering for parts operated in conditions when a sufficient thickness of the hardened layer of the order will not exceed 0.5 mm (Mittemeijer, 2013).

Another well-known alternative to surface hardening technology is microalloying, i.e., the addition of a small amount of alloying elements into a metal or alloy, the total amount of which should not exceed 0.1% of the mass of the initial metal or alloy. The main microalloying elements are vanadium, titanium, boron, niobium, zirconium, many rare earth elements (cerium, yttrium, lanthanum, etc.) and their mixtures, aluminium, nitrogen, barium, calcium, and magnesium. The microalloying technique is similar to the alloying methods in metallurgy (Zimmerman, 2013).

The most used typical boration technologies give stable results but at the same time have low productivity and high costs. For example, it is necessary to wash and neutralize drains during electrolysis and liquid boration of parts. Boration using powder does not allow for fully mechanizing and automating the process and has a high cost of the saturating mixture. A common disadvantage of boration methods is the long duration of the procedure, which is at least several hours. The methods to accelerate boration using the electron beam, electric spark, micro-arc, induction heating, plasma spraying, excitation of a glow discharge during saturation from powders, the application of ultrasound, vibro- and fluidization of the saturating mixture under electrical action, chemical, and physical vapor deposition has been proposed. Still, despite the reduction in the duration of saturation, these methods have not become widespread due to the technical complexity of the procedure, lack of versatility, and energy intensity of the process. In some cases, multicomponent boration can be performed when, together with boron saturation, the surface of the part is additionally saturated with other elements, i.e., chromium, aluminium, silicon, etc. Such saturation is carried out to increase the corrosion resistance and wear resistance of the surface layer of the metal part. However, the results obtained by increasing the resistance are not so great that these microalloying processes are widespread. After microalloying, the thickness of the diffusion layer with the presence of alloying elements is, on average, from 20 to 40–50 µm, which can be sufficient mainly for parts operating under conditions of abrasive wear or in corrosive environments (Davidian, 2019).

In industrial practice, mechanical surface treatment is also used, which involves plastic deformation of thin surface layers (surface hardening). As a result,

the strength properties and electrical resistance increase, the rate of diffusion processes increases, plasticity decreases, and corrosion resistance of the treated layer decreases. Surface treatment by plastic deformation is effectively used in the finishing operations of the technological process of manufacturing machine parts. There are two types of such treatment: DSPD and SSPD. The surface is hardened by bombarding it with a stream of metal shot, balls, or a suspension containing abrasive particles; rolling with rollers, balls, or smoothing with a diamond tool; and chasing. Explosion energy can be used to harden the surface by the PPD method. In this case, the hardening of the surface occurs at a high rate using an explosive. The most common variant of DSPD carried out in dynamic mode is shot blasting of the surface. For these purposes, metal or corundum shot with particle sizes of the order of 0.5–2.0 mm is used. The optimal particle velocity at the moment of collision with the treated surface is 50–70 m/sec, and the angle of incidence of the fraction is 75–90°. The processing time usually does not exceed 2–3 minutes, and the thickness of the hardened layer does not exceed 0.2–0.4 mm. The density of lattice defects increases in the surface layer, and the shape and orientation of the grains may change. As a result, the microhardness of the near-surface layers can be increased up to 50%. The microhardness of steel 20 after such treatment, according to some data, can increase from 1600 MPa to 2400 MPa. The disadvantage of this method can be attributed to high capital investments in the construction of the chamber. This method is mainly used for large-sized and thick-walled structures and is not applicable to finished thin-walled products and parts whose wall thickness does not exceed 1.5–2 mm. In addition, all the steel qualities acquired during shot blasting are lost if the metal is heated above 450 °C. So, the metal parts, after shot blasting, cannot be subjected to heat treatment. Moreover, it must be considered that the surfaces subjected to blasting lose their corrosion resistance (Stepankova, 2009a).

Another well-known technique of local surface treatment is laser treatment. Laser treatment is one popular technique of surface modification, which is designed to change the microstructure of metals through controlled heating and cooling. Laser surface treatment technologies (laser hardening, nitriding, and carburization) allow the enhancement of various properties, such as the surface strength, hardness, roughness, coefficient of friction, chemical resistance, and corrosion resistance of the surface of various metals (Höche et al., 2015a).

The heating rate during laser treatment is above 1000 °C/sec. It should be noted that laser processing involves not only fast heating of the material but also sufficiently rapid cooling. During laser processing, cooling of the heated zone occurs due to intensive heat dissipation into the metal mass. Therefore, for more efficient cooling, the total volume of the part must be significantly larger than the volume of the laser-treated zone or must be artificially increased by applying a massive substrate with high thermal conductivity. The cooling rate at a heating

temperature below the melting point is usually $(5-10) \cdot 10^3$ °C/sec, and during crystallization from a liquid phase, $\sim 10^6$ °C/s because the volume of the welding bath during laser treatment is very small and the surrounding metal remains practically cold (Furlani et al., 2021; Ion, 2002; Höche et al., 2015).

The usual practice is the laser processing of part of a large construction surface, which is possible with laser technology. The laser-processing methods include techniques with remelting and without surface melting.

LTH is often used for the surface hardening of cast iron, medium-carbon steel, and tool steel. LTH is a method in which a high-power laser beam quickly irradiates the surface of the workpiece to rapidly increase the surface temperature to a temperature higher than the austenite transformation temperature but lower than the melting point (Babu, 2012). Melting is usually undesirable in LTH (Zang & Guan, 2014). The typical thickness of the hardened layer after LTH by CO₂ laser, without melting the surface, usually does not exceed 0.3 mm, applying a laser pulse of 0.15 mm (Nath & Sarkar, 2018). Then, a more concentrated laser beam or a powerful laser (1 kW) is applied; the depth of hardening can be increased up to 1.5 mm (Ion, 2002; Nath & Sarkar, 2018).

Most of the mixtures and composite material properties (including their structural strength) obtained by laser processing follow the additivity rule and are linearly dependent on the percentage quantity or volume of individual components of the mixture. Therefore, the approximate strength of dual-phase steels can be calculated according to the rules of mixtures (Penchal et al., 2017):

$$H_c = H_m F_m + H_r F_r \quad (1.3)$$

where H_c – hardness of composite phase; H_m – hardness of matrix phase; H_r – hardness of reinforcement phase; F_m , F_r – volume fraction of matrix and reinforcement phase, respectively.

According to this rule, the efficiency of such laser processing and the resultant strength of the laser-treated zone depends on the total area of the treated zone and the depth of hardening. This means that the effectiveness of LTH is limited by the small thickness of the hardened layer because a very large area of the surface must be treated without melting. The “wide-spot” method uses a laser with a large spot, which moves evenly along a treated area. The scanning method uses a small laser spot in combination with a laser scanning head, which allows fast laser spot displacements. However, the LTH of large surface areas, large or thick-walled components, and the entire surface of metal parts are still complicated. Thus, LTH is mostly used for other purposes, e.g., to improve the friction, wear, or corrosion resistance of work surfaces through hardening. LTH without metal melting is not effective for the creation of specially oriented

structural strengthening ribs, which strengthen metal constructions against outward deflection. However, according to some research data (Zhang et al., 2014; Panchenko, 2009; Kovanlenko et al., 1981), laser processing can be performed without melting the metal (when the temperature in the laser-heated zone is close to the melting temperature), as well as with melting (at higher temperatures), because the increase of hardness in the hardened zone and melted zones of carbon steel are similar. The difference comes from the presence of the melted zone and potential changes in the hypereutectoid steel microstructure, and the depth of the hardened zone. Laser treatment with melting allows the greatest depth of treatment.

Due to phase transformations and local changes in material structure at the area of the laser beam exposure, it is possible to create structural strengthening ribs with modified hardest microstructure. This can significantly affect the overall strength of the thin-walled metal parts. Existing equipment and laser processing techniques offer ample opportunities to control the laser beam, which allows for the treatment of local areas, formation of structural strengthening ribs in the desired areas, changing their orientation, depth, and other geometrical parameters of the treated layer (Rehman et al., 2021).

The typical industrial lasers are fiber, neodymium (yttrium aluminium garnet), and semiconductor (Fathi, 2021). Semiconductor (diode) lasers operate in continuous mode, while Nd:YAG lasers and fiber lasers can operate in either pulsed or continuous mode.

Continuous wave (CW) lasers are commonly used for laser cutting (Leone et al., 2021), welding, and cleaning thicker workpieces. Typically, such lasers are used for metal plates with a thickness of more than 2 mm. The mechanism of action of the laser is often remelting with deep penetration, with a large aspect ratio of more than 5:1, high processing speed, and small thermal deformation.

In continuous mode, the impact zone has the shape of a strip of a certain width, and in pulse mode, it has the shape of a circle. At the same time, it is possible to regulate the degree of overlap and multiple heating zones, as well as control the rate of metal cooling.

For the processing of metals of small thicknesses, softer modes are required, which are ensured when using pulsed laser processing. The processing process belongs to the heat conduction type; when the overall temperature rise of the workpiece is small, the thermal impact range and the workpiece deformation are small (Xinxin, 2020).

The main advantage of pulse generation is the ability to achieve maximum peak power. If solid-state lasers reach a generation power of 1–3 kW in continuous mode, then the average power of a pulsed laser reaches 10 kW when operating in the free-running mode and with a pulse duration of $10^{-3} - 10^{-4}$ sec.

When operating in a pulsed mode, the most significant disadvantage of a solid-state laser is the low efficiency (up to 2%) compared to continuous-wave lasers (up to 10%). However, the cost of laser diodes for CW lasers is significantly higher. In addition, the processing speed in the pulsed mode is also several times lower than when using a continuous laser (up to 100 m/h). However, the pulsed nature of the processing ensures the minimum depth of metal heating processing and the absence of overheating.

There are industrial pulsed lasers with various pulse durations, which are divided into millisecond, micro-second, nanosecond, picosecond, and femto-second lasers (Chichkov, 1996).

When assessing the efficiency of using short laser radiation pulses, it should be considered that the depth of the heated layer mainly depends on the pulse duration and the thermal diffusivity of the material. The shorter the pulse duration, the smaller the thickness of the layer of laser exposure. Therefore, for thin steel parts or processed layers ($\sim 0.1\text{--}0.3$ mm), millisecond pulsed lasers with a pulse duration of the order of 5–10 ms are most suitable, and pulsed laser processing with a penetration depth of more than 1 mm is complicated (Liu et al., 2022).

1.4. Conclusions of the First Chapter and formulation of tasks of the dissertation

1. The modern laser technologies, compared to other not-always-rational, ineffective, or hardly applicable metalworking methods (design solutions, thermal, thermo-chemical, or mechanical processing), can be very useful to increase the rigidity and other operational properties of shell structures made of structural non-alloy steels with a carbon content of up to 0.3%.
2. Laser processing technologies provide local heating, high-temperature gradients, and achievable cooling speed ($10^4\text{--}10^6$ °C/sec) due to high thermal conductivity. Therefore, by laser processing achieving microstructural changes leading to improved mechanical properties of non-alloy structural steels with less than 0.3% carbon is also possible. However, the application of laser transformation hardening without melting for strengthening non-alloy structural steels with less than 0.3% carbon is limited by the low thickness of the hardened layer since a very large surface area must be treated. Whereas laser processing with melting gives the largest thickness of the treated layer, and it is preferable for local processing by laser for strengthening thin-walled steel products.

Based on the literature survey, the following issues are raised for this study:

1. Calculate and select the optimal parameters for laser processing of thin-walled non-alloy steel products, and perform local laser processing of objects using the selected laser processing parameters.
2. Determine the microstructure of the surfaces of laser-processed samples to study the most important mechanical properties of products processed in different ways in tension and bending loads.
3. Simulate the behavior of laser-processed products under tension and bending load, and evaluate the influence of laser processing parameters and processing texture on the final mechanical properties of processed products.
4. Compare the results of experimental tests and simulations and evaluate the accuracy of the model used in strength calculations.

Analysis methodology and materials for laser treatment

Analytical and experimental research methodologies have been selected and developed to elucidate the effect of technological parameters of applied laser processing processes on the surface microstructure and the mechanical performance of thin-walled non-alloy steel products with up to 0.3% carbon concentration. The results of this chapter are published in the author's publications (Kapustynskyi et al., 2019; Kapustynskyi & Višniakov, 2020; Kapustynskyi et al., 2020).

2.1. Object of the study

Samples of household non-alloy structural and low-carbon steels 1.1151 (EN 10083-2:2006) and 1.0402 (EN 10250-2:2022), which are widely used in the manufacture of various thin-walled metal products (such as sheets, edges, tubes) as well as more complex forms (e.g., tanks, membranes, profiles) were used in this research. Tables 2.1–2.4 summarize the main information about the studied steels. 1.1151 (EN 10083-2:2006) steel is a simple structural carbon steel used in the production of low-load machine parts and structures with good weldability, not requiring high strength properties in a heat-treated state.

1.0402 (EN 10250-2:2022) is a carbon (non-alloy) steel formulated for

primary forming into wrought products. The cited properties are appropriate for the normalized condition. It has a moderately low tensile strength among wrought carbon or non-alloy steels.

Table 2.1. Chemical composition of steels

Steel	Chemical Elements, wt%	C	Si	Mn	P	S	Cr + Mo + Ni
1.1151	Typical composition of steel according EN 10083-2:2006	0.17–0.24	Max 0.4	0.4–0.7	Max 0.03	Max 0.035	Max 0.63
	Sample	0.17	0.13	0.44	0.02	0.02	0.12
1.0402	Typical composition of steel according EN 10250-2022	0.17–0.24	Max 0.4	0.4–0.7	Max 0.045	Max 0.045	Max 0.63
	Sample	0.18	0.18	0.45	0.02	0.02	0.15

Table 2.2. Mechanical properties of steel 1.1151 according to standard EN 10083-2:2006

Heat Treatment	Yield Strength, MPa	Ultimate Tensile Strength, MPa	Elongation, %	Hardness, HB
	Min	Min	Min	Max
Hot rolled 850–1100 °C		490	7	207
Annealing or tempering 550–660 °C	230	390	21	163
Normalizing 880–940 °C	240	430	24	101–143
Quenching 860–900 °C	340	590	18	370
Quenching 860–940 °C + tempering 550–660 °C	340	500–650	20	143–179

The mechanical properties and microstructure of the considered structural steels vary depending on the heat treatment method and the delivery condition. A thin sheet sample of 2 mm thickness was subjected to laser processing. All the used samples were taken from one large sheet. The cutting orientation and preparation of the surface samples were identical. All the samples were heat-treated by tempering for stress relief. Both sides of the sheet were mechanically processed to ensure uniform absorption of laser radiation on the steel surface. The abrasive blasting using a PowerPlus tool and quartz sand SAKRET with grain size 0.1–0.5 mm was applied for the mechanical preparation of surfaces. The surface

roughness, Ra, after blasting was not more than 5 μm . Then, this metal sheet was subjected to local laser processing with varying parameters. The pulsed laser beam (impulse time 1–5 μs) heats the surface of the thin sheet to temperatures inducing the phase transformation in steel or melting. The resulting temperature gradients cause subsequent rapid cooling of the surface at a speed of 10^3 – 10^4 $^\circ\text{C}/\text{sec}$ due to heat dissipation to the surrounding metal. This promotes the formation of hardened zones, which microstructure can be determined using the CCT diagrams.

Table 2.3. Mechanical properties of steel 1.0402 according to standard EN 10250-2:2022 and EN 10297-1

Heat Treatment	Yield Strength, MPa	Ultimate Tensile Strength, MPa	Elongation, %	Hardness, HB
	Min	Min	Min	Max
Cold rolled	450	570	5	207
Annealing 650–700 $^\circ\text{C}$ or tempering 550–660 $^\circ\text{C}$		390	21	163
Normalizing 880–920 $^\circ\text{C}$	175	350	25–28	101–143
Quenching 860–900 $^\circ\text{C}$	340	500	19	332
Quenching 860–920 $^\circ\text{C}$ + tempering 550–660 $^\circ\text{C}$	240	480	20	143–179

Table 2.4. Mechanical properties of steel samples

Steel	Elastic Modulus E , GPa	Yield Strength $R_{0.2}$, MPa	Tensile Strength R_m , MPa	Relative Extension A , %	Hardness, HV
1.1151	210	275	450	32	135
1.0402	200	256	410	30	125

The laser-treated zone of the steel sheet is usually characterized by a large structural heterogeneity and varying depth of penetration. The achieved depth of penetration, final microstructure, mechanical strength, and hardness of steel sheet after laser processing depends on the mesh and texture of the treated layer, multiple passes overlapping character and parameters of the laser processing, as well as on the chemical composition and initial microstructure of the material. Usually, the laser-treated zone of hypoeutectoid steel sheets consists of a near-surface region with a more uniform microstructure and underlying layers with a non-uniform microstructure (Butalov, 1962). The main parameters that influence the formation and characteristics of these zones are the laser power, laser focus

position relative to the target surface, spot size, and travelling speed of the laser beam.

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 of phases such as martensite, troostite, which then becomes troostite-ferrite, and then ferritic microstructure (at the interface with the original steel microstructure). The zone of homogeneous martensite is absent at higher laser speeds, and the troostite-ferrite structure around individual martensite segments can be formed at the surface, causing a decrease in hardness.

The martensite is prevalent, and the local microhardness can reach 4300–5000 MPa at a little lower treatment speeds with continuous laser (Uglova, 1985). Therefore, it is more desirable to treat hypoeutectoid steels at lower laser speeds, typically less than 8.0 mm/s. (Kalugin & Bakulin, 2014).

2.2. Research methodology

Samples of thin-sheet non-alloy steels containing less than 0.3% carbon were laser treated. The microstructure was analyzed using SEM, EDS, color microscopy, XRD and Mössbauer spectroscopy. The research methodology is presented below: 1) methodology of laser processing and calculation of laser parameters – in the chapter 2.2.1; 2) methodology of investigation of structure and composition – in the chapter 2.2.2; 3) methodology of experimental research – in the chapter 2.2.3; 4) methodology of modeling -in the chapter 2.2.4.

2.2.1. Methodology of laser processing and calculation of laser parameters

High-power solid-state Nd:YAG lasers are among the most widely used types of lasers for industrial material processing and different applications. They typically emit light with a wavelength of 1064 nm, which makes them ideally suited for most steels and non-ferrous metals due to good absorption. Nd:YAG lasers can be operated in both pulsed and continuous-wave (CW) modes. Nd:YAG laser systems have excellent pulse control and offer high peak power, which enables the melting and heating of metals with large optical spot sizes. Calculation and optimization of the required parameters of laser processing were performed considering the characteristics of the used laser equipment and properties of the steel. Laser processing of the surface was carried out on the Nd:YAG 4-axis laser-welding machine BMM400 (China), of which the technical characteristics are presented in Table 2.5. 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 a pulse regime, and then this laser can produce a peak power that is greater than its average power (Zhou, 2008).

Table 2.5. Technical specification of laser machine (Višniakov et al., 2019)

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

It is possible to calculate the main parameter of laser treatment (the required critical power) based on the relationship between melt depth and pulse duration in Eq. 2.1. During technological tests, other laser parameters (travelling speed, spot size, and pulse frequency) were varied (within a range of the technical characteristics of the available equipment) 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. The appropriate processing mode was calculated considering the physical properties of the metal, which are summarized in Table 2.6, and the technical limitations of the available laser equipment laser-welding machine BMM400, using the methodology presented in reference literature (Višniakov et al., 2019). Parameters for laser processing in a pulse mode are mainly selected based on the critical energy density necessary for melting a given material. Fig. 2.1 shows the melting or LTH of most metals occurs at low energy density in the range of 10^3 – 10^5 W/cm².

Table 2.6. Physical properties of carbon steel (George, 2006)

Melting Temperature T_m , K	Initial (Room) Temperature T_0 , K	Absorptivity, A	Reflection Coefficient, R	Density ρ , kg/m ³	Specific Heat c , J/kg·K	Melting Temperature T_m , K
1733	295	0.09	0.91	7800	462	1733

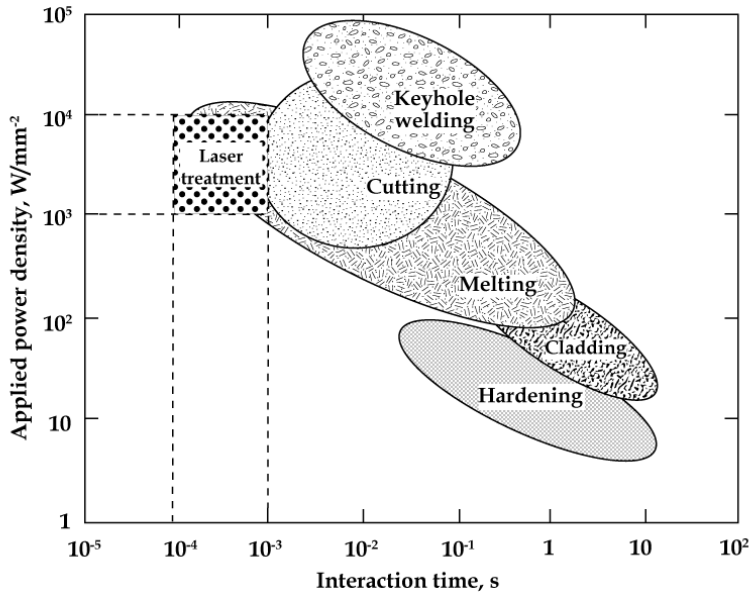


Fig. 2.1. Influence of the power density and laser interaction time on the treated surface (Ion, 2005)

According to the data of published studies, the parameters of laser processing of steel with a carbon equivalent C_{eq} of about 0.22% make it possible to perform welding or surface treatment and at the same time achieve steel hardness up to 250 HV, as shown in Fig. 2.2 (Ion, 2004; Kovacs, 2018).

The critical power density for local laser treatment in pulse mode can be calculated according to the following equation (Višniakov et al., 2019; Zhou, 2008; Angelov, 2015; Veiko & Shahno, 2014; Parfenov, 2011; Steen & Mazumder):

$$P_d = \frac{\rho(T_e - T_0)ch}{At_p} \quad (2.1)$$

where P_d – critical power density (W/m^2); A – absorptivity $A = (1 - R)$; R – reflection coefficient; c – specific heat ($\text{J}/(\text{kg} \cdot \text{K})$); T_0 – initial (room) temperature (K); T_e – heating temperature, material melting or evaporation temperature (K); ρ – density (kg/m^3); t_p – duration of the laser pulse (sec); h – thickness of the material or melted layer (m).

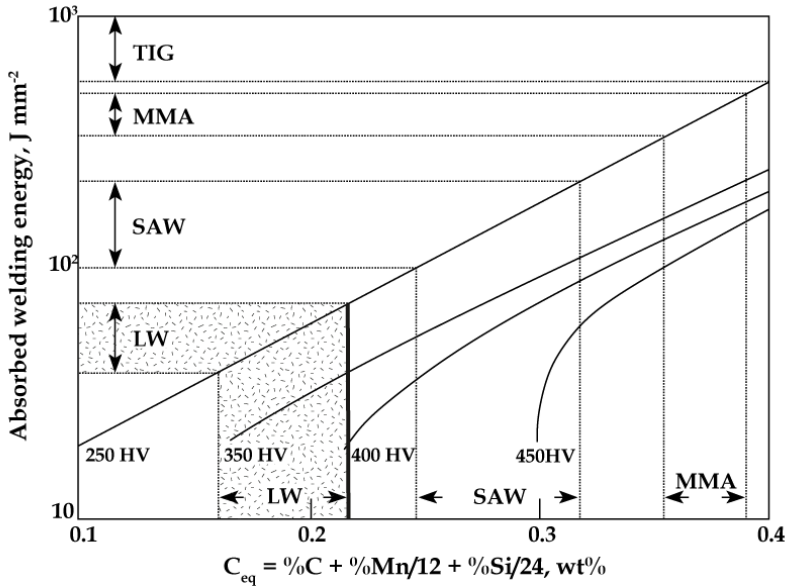


Fig. 2.2. Influence of absorbed welding energy and steel carbon equivalent on the hardness of the treated surface (Ion, 2005)

The penetration depth should be minimal to avoid excessive embrittlement, cracking, and deformation of the treated material (Montealegre et al., 2010, Abboud et al., 2017). Mathematical calculations demonstrate that there are multiple options for local laser processing, depending on the required laser penetration depth, possible pulse duration, and diameter of the laser spot, as well as critical and peak power. The most appropriate laser processing parameters for the available equipment were selected according to the mathematical calculations. The selected parameters (laser spot diameter, laser speed, pulse duration, pulse frequency, energy per pulse) remained constant throughout all experiments. The alterable parameters are the number of laser tracks and the distance between them.

To determine the optimal position of the application of reinforcing ribs, experiments with metal sheets were carried out on samples of the same batch and size and with the same processing areas in each series of experiments. Differences in the laser processing area were caused only by differences in the sizes of samples required for various types of mechanical tests (i.e., extension and bending under different conditions). At the same time, the step between the reinforcing strips in all technological experiments remained the same (with an overlap of 0.35 mm. and 0.7 mm between the strips), and the direction, the number of laser-treated runs, as well as the treated surfaces (single or double-sided treatment) changed, as shown in Fig. 2.3.

During laser processing, not only optimal energy parameters were observed, but also other important technical conditions were considered. The metal sheets were tightly fixed to a 3-coordinate metal table base to avoid distortion of the samples. The Nd:YAG laser radiation is readily absorbed by the workpiece during the laser processing of mild or non-alloy steel. Carbon dioxide, as a shielding gas for laser welding, provides nearly the same penetration (about 70%) as helium. The major drawback to its use as a shielding gas for mild or non-alloy steel is that it can cause porosity and other weld discontinuities. But the results of several investigations indicate that carbon dioxide can be used as a cost-effective shielding gas for melting and welding non-alloy and low-carbon steels. The porosity-free welds and melted pools were formed during laser processing of semi-killed steel (with 0.22% Si) (Kuo, 2007).

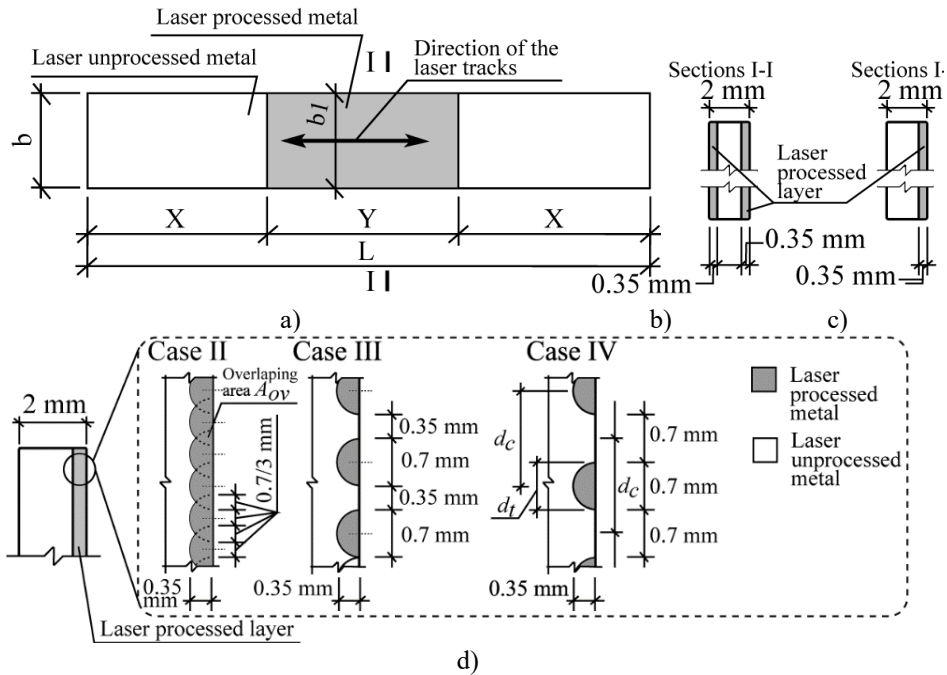


Fig. 2.3. General view of the laser-treated specimen cases: (a) sketches of their cross-sections: (b) of the one-side laser-treated sheet, (c) and the two-side laser-treated sheet; (d) and cases of the laser tracks (Kapustynskiy et al., 2020)

Therefore, there is no need to use expensive inert shielding gas (pure Argon or gases mixtures with a helium content). A shielding gas mixture of Ar-CO₂ (20% CO₂) was used for the Nd:YAG laser processing of steel samples (Motlagh et al., 2013). The typical shielding gas flow rate of 20 l/min was used for the prevention of metal oxidation.

2.2.2. Methodology of investigation of structure and composition

The microstructure chemical composition and mechanical properties of the steel and laser-treated surface layer were determined to establish the correct input data for the finite element analysis (FEA) simulation and the analysis of laser processing influence on the surface layer. The methodology of investigation of structure and composition using optical and scanning electron microscopy, X-Ray diffraction analysis and energy dispersive spectroscopy, optical emission and Mössbauer spectroscopy is presented below in the following sub-chapter.

2.2.2.1. Microscopic and macroscopic investigation

Macroscopic and microscopic examination of laser-treated samples was done according to ISO 17639:2003. The metallographic examination of the steel and the laser-treated layer and analysis of the geometry and dimensions of the laser-treated layer was carried out using Eclipse MA200 optical microscope (Nikon, Japan) with a Lumenera Infinity 2-2 video camera and a JEOL JSM-7600 (Japan) scanning microscope with an energy dispersive spectrometer (EDS) INCA Energy X-Max20 (Oxford Instruments, UK) at different magnifications (up to $\times 1500$).

Etchants for macroscopic and microscopic examination were selected according to ISO/TR 16060:2003. A Nital solution (3 wt % concentrated nitric acid in ethyl alcohol) was used for etching the steel samples.

In addition, an additional tool for studying the phase composition was the technique of microscopic analysis using reagents for color etching. In this case, several of the most popular complexes of metallography etchants were used to determine various possible structural components in steels:

A) “base” reagent – 4% picric acid solution in ethyl alcohol

B) “typical” acid etchings based on a combination of picric acid and Nital etchant: 1st reagent – 4% picric acid solution in ethyl alcohol, 2nd reagent – 1.4% nitric acid solution in ethyl alcohol. Sequential etching of the sample was carried out first for 2 seconds in one solution and then up to 10 seconds in two solutions. Picric acid has long been known to be the best acid etcher for detecting the structure of ferrite, perlite, or dispersed varieties of perlite and bainite in low-carbon steels. The etching of steels by this method colors the structure of sorbite and trostite in brown or dark brown, quenching structures such as martensite in blue and austenite in weak orange.

C) “tint” based on sodium metabisulfite: 1st reagent – 4% solution of picric acid in ethyl alcohol (4 g of dry picric acid / 100 ml of ethanol), 2nd reagent sorbite and trostite aqueous solution of hyposulfite (1 g $\text{Na}_2\text{S}_2\text{O}_5$ / 100 ml distilled H_2O). The sample surface was treated with one mixture (4% picric acid) for 15 seconds.

After preliminary etching, the sample was etched with a mixture of two for 15 seconds. The sample fluctuated during the entire time of the pre-etching and etching stages. Always after the pre-etching or etching stage, the sample surface was washed with water and ethanol and dried in warm air. Aqueous sodium metabisulfite is a very good color etcher for mixed microstructures, which reveals the grain boundaries of ferrite, perlite, or dispersed varieties of perlite, bainite, and martensite. The etching steels by this method colors the structure of sorbite and troostite in brown or dark brown, the structure of bainite in blue, martensite in light brown, ferrite white, and austenite in tin-white.

D) “enhanced tint” etchant based on sodium thiosulfate: 1st reagent is a 4% solution of picric acid in ethyl alcohol (4 g of dry picric acid/100 ml of ethanol); 2nd reagent is 10 g of $\text{Na}_2\text{S}_2\text{O}_3$ and 3 g of $\text{K}_2\text{S}_2\text{O}_5$ /100 ml of distilled water. The sample surface was treated with one mixture for 15 seconds. After preliminary etching, the sample was etched with a mixture of 2 for 30 seconds with constant oscillation. The etching of steel by this method color the structure of the lower bainite blue and grey, martensite light brown, and cementite white.

2.2.2.2. Scanning electron microscopy / Energy dispersive spectroscopy

Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM-EDS) non-destructive analytical technique was used to identify the phase structure of base metal and laser-treated sample surfaces. The scanning microscope JEOL JSM-7600 (Japan) with an energy dispersive spectrometer (EDS) Oxford INCA Energy X-Max20 (UK) at different magnifications (up to $\times 1500$) was used for SEM-EDS element mapping, line scan, and point analysis of the distribution and concentration of chemical elements.

2.2.2.3. Optical emission spectrometry

The chemical composition of the steel samples was determined using the PMI Master PRO (Oxford Instruments, UK) optical emission (OES) spectrometer, equipped with CCD detectors and optic, which cover the whole spectral range between 170 and 420 nm (determining C, P, S, B, Sn at ppm level in steels).

2.2.2.4. Qualitative X-Ray diffraction analysis

The qualitative X-ray diffraction (XRD) analysis of the phase composition of materials was performed. Two models of diffractometers of different precision and with different detection limits were applied:

1. Diffractometer DRON-7 (Russia). Graphite-monochromated Cu $K\alpha$ radiation ($\lambda = 0.154178$ nm) was used. The parameters of the tests were as follows: voltage – 30 kV; current – 12 mA; the range of the diffraction angle – from 4° to 120° , with detector movement steps of 0.04° ; the duration of the intensity measured in each step – 2.0 s.

2. Diffractometer SmartLab (Japan) with 9 kW rotating anode X-ray source, Johansson $K\alpha_1$ optics, CALSA ultra-high-resolution spiral analyzer, and database PDF4.

2.2.2.5. Mössbauer spectroscopy

Mössbauer spectroscopy was carried out for investigation of physical properties and characterization of phase composition of treated by laser layer. Mössbauer spectrometer (Wissenschaftliche elektronik GMBH, Germany) was used. Measurements were performed in both transmission geometry and conversion electron geometry (CEMS). Magnetic splitting of the pure iron spectrum was used for speed calibration. The speed scale was calibrated when measuring the standard ultra-pure iron foil (thickness of 25 μm). The sample size was up to 10×10 mm². The software package WinNormos was used for the mathematical description of the spectra. The concentration of the identified substance in the test samples was evaluated by comparing the spectral areas of the sample with the spectral area of the standard (α -Fe foil).

2.2.2.6. Investigation of steel cooling diagrams

It is necessary to consider the phase and structural transformations occurring at different heating and cooling rates before laser processing steels. When steel is cooled, the kinetics and mechanism of austenite transformation can be analyzed using isothermal diagrams. Diagrams of the isothermal decomposition of austenite can only approximate the transformations occurring during the continuous cooling of steel since these diagrams are based on studies at constant temperatures. These Continuous Cooling Transformation (CCT) phase diagrams are typically used in the development of heat treatment regimes (Smallman & Nagan, 2014). In practice, the isothermicity of the transformation is not always

achieved, especially in welding or laser processing conditions at a continuously changing temperature. In the process of welding or laser processing, transformations occur during the continuous cooling of the metal (Jegorove et al., 2014; Gould et al., 2006). Therefore, in addition to the diagrams of the isothermal decomposition of austenite (necessary for various isothermal processing methods), thermokinetic (anisothermal) diagrams of austenite transformation are used for characterizing the decomposition of austenite at different cooling rates. Using these Time-Temperature Transformations (TTT) diagrams, it is possible to obtain more accurate data on the temperature intervals of the phase transformations during continuous cooling and about the structural components formed in this case (Piekarska et al., 2017, p. 8; Miettinen & Louhenkilpi, 1994).

In complex systems, such computational methods as CALPHAD (Computer Coupling of Phase Diagrams and Thermochemistry) are employed to simulate multicomponent phase behavior. CALPHAD aims to promote computational thermodynamics through the development of models to represent thermodynamic properties for various phases, which permit the prediction of properties of multicomponent complex systems and alloys. There are several commercial products on the market (FactSage, MTDATA, PANDAT, MatCalc, JMatPro, Thermo-Calc) as well as open-sources codes (OpenCalphad, PyCalphad, and ESPEI) (Kattner, 2016; Perrut, 2015). JMatPro is simulation software that calculates a wide range of material properties for alloys and is particularly aimed at multicomponent alloys used in industrial practice. JMatPro (version 7.0, Surrey Technology Centre, UK) (*JMatPro user's guide*, 2005, p. 89) was applied in this research using the data from Table 2.1. The calculations of phase transformations were carried out applying modules: 1) TTT/CCT diagrams, 2) Phase and properties during solidification of general steels.

This software also allows for simulating approximate stress-strain curves of a particular material at room temperature. The capabilities of the JMatPro software make it possible to predict other physical properties of the alloys over a wide temperature range by considering the exact chemical composition of the metal, as shown in Figs. 2.4–2.9. However, in this case, the experimentally obtained values were used for greater accuracy. A comparative analysis of the results showed that the real mechanical properties of the steel and the treated layer and their calculated values are very close.

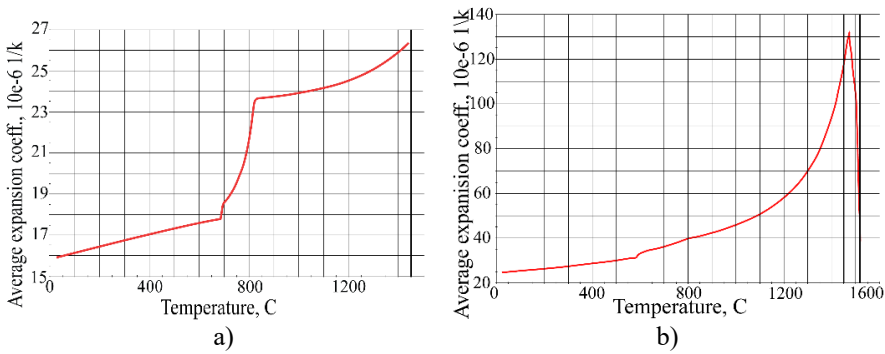


Fig. 2.4. Thermal expansion of materials: (a) base steel; (b) laser track

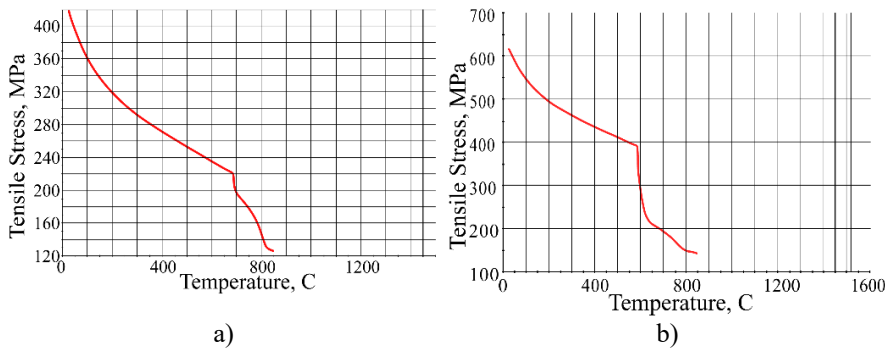


Fig. 2.5. Yield strength of materials: (a) base steel; (b) laser track

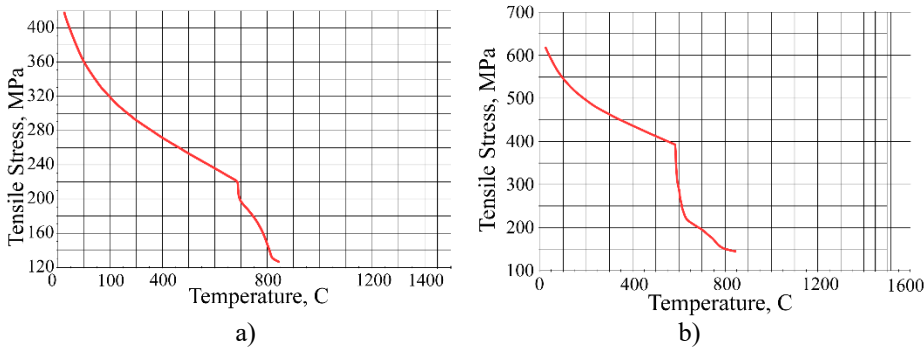


Fig. 2.6. Tensile strength of materials: (a) base steel; (b) laser track

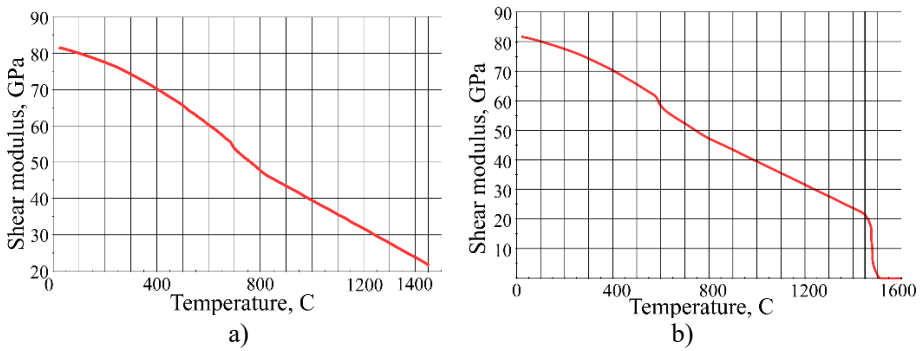


Fig. 2.7. Shear modulus of materials: (a) base steel; (b) laser track

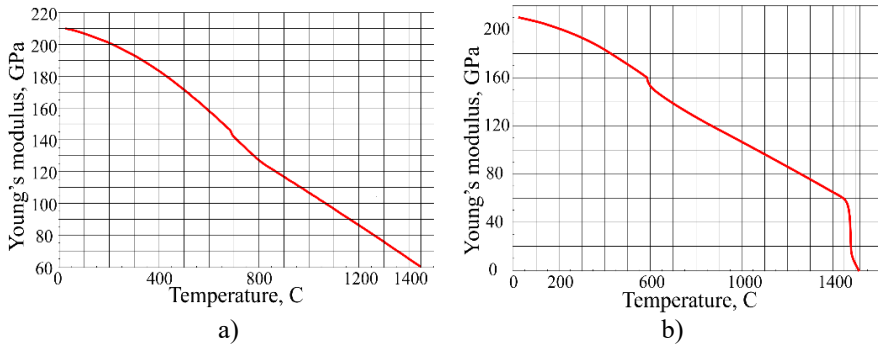


Fig. 2.8. Young modulus of materials: (a) base steel; (b) laser track

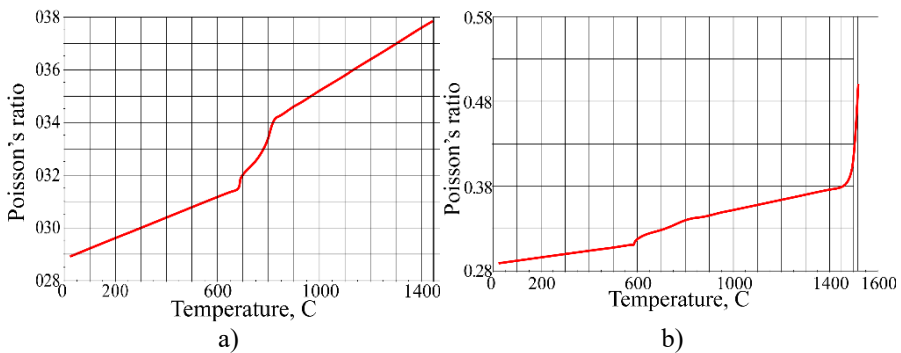


Fig. 2.9. Poisson coefficient of materials: (a) base steel; (b) laser track

2.2.3. Methodology of experimental research

The properties of the laser-treated steel thin sheets were evaluated by different types of mechanical testing (i.e., bending, tensile, and microhardness). The methodology of experimental research using hardness and microhardness, bending and tensile tests is presented below in the following sub-chapter.

2.2.3.1. Hardness and microhardness testing

Hardness was determined using the ZwickRoell ZHμ hardness tester (Swiss):

- The steel hardness was determined using the Vickers method with a square-based tetrahedral pyramid, with a load of 9.807 N according to EN ISO 6507-1 (“Metallic materials – Vickers hardness test – Part 1: Test method” 2018).
- The hardness of the laser-treated surfaces was determined using a diamond square-based tetrahedral pyramid tip with a load of 2.942 N. The hardness was measured on the surface of the treated layers and its cross-section according to EN ISO 4516 (“Metallic and other inorganic coatings – Vickers and Knoop microhardness tests” 2002).

The corresponding mechanical properties of the laser-treated metal, i.e., $\sigma_{0.2,l}$ and $\sigma_{0.2,B}$ were determined indirectly by using the empirical relationships between the corresponding mechanical properties and determined hardness. Expressions relating to the hardness, tensile strength, and yield strength of steels and laser-treated layers useful for the approximation of mechanical strength are the following (Cahoon et al., 1971; Cahoon, 1972; Pavlina & Van, 2008):

$$\sigma_B = \frac{HV}{2.9} \left(\frac{n}{0.217} \right)^n, \quad (2.2)$$

$$\sigma_{0.2} = \frac{HV}{3} 0.1^n, \quad (2.3)$$

where σ_B and $\sigma_{0.2}$ – tensile strength and yield strength, respectively, n – strain-hardening exponent (for carbon steel, n is in the range from 0.15–0.26).

2.2.3.2. Bending tests

Bending tests were carried out under various conditions. They were performed following the ISO 7438:2016 requirements or using non-standard loading conditions that are closer and simulate the conditions for bending shell structures from random loads. The elastoplastic bending of the thin sheet was conducted by

using a three-point bending device. The scheme of the bending test is shown in Fig 2.10.

A universal tensile testing machine 2055 P-5 (Tochpribor, Russia) with a bending test tool, Labview version 2020 (National Instruments, USA) software, and PXI system hardware (chassis NI PXIe-1073 and controller NITB-4330) was used for the tensile and bend tests. A tension dynamometer up to 5 kN was used for the bending test.

The precision of testing equipment, load, and deformation measurement sensors was $\pm 0.03\%$. The rounding radius and the mandrel width were “D” mm (Fig 2.10a). The tests were conducted using the strain control mode with a velocity of displacement of from 1 to 1.5 mm/s. The load F_{exp} was imposed in the middle of the span at point B. The load F_{exp} ranged from 0 N up to the maximum load $F_{exp} < 2000$ N, corresponding to the greatest deflections of the experiment equal to 2 mm. The deflections were measured at the middle of the sheet span, i.e., at point B. The principal view and the calculation scheme of the bending test device are summarized in Fig 2.10.

In the first series of experiments, Ex1, the distance between supports was 40 mm, the mandrel width was 10 mm, and the maximum load used was 128012,5N. The distance between supports was set larger than that required in ISO 7438:2016 (“Metallic materials – Bend test” 2016) for the bend test, and it was equal to the length of the laser processing area.

In the second series of experiments, Ex2, the distance between supports was 70 mm. The mandrel width was chosen as 10 mm, which is larger than that required according to LST EN ISO 7438 (“Metallic materials – Bend test” 2016) to decrease the influence of shear strains on the deflections.

In the third series of experiments, Ex3, the elastoplastic bending of the thin sheet was conducted according to LST EN ISO 7438. The radius of the mandrel was specified for normal-strength steels according to the dependence $D/2 = 2a$. The distance between supports was specified using the standard equation $l = D + 3a$. The distance between supports was 14 mm, and the diameter and width of the mandrel were both 8 mm. Bending testing parameters and samples’ geometry are summarized in Table 2.7.

In the case of bending a one-side laser-treated sheet, the laser-treated layer can be under tension or under compression. Three different loading variants were considered to evaluate the influence of the stress–strain state of the laser-treated layer on the deflections or the bending stiffness of the sheet.

For example, in Variant A Ex2, the bending load F_{exp} was imposed on the laser-treated side of the one-side laser-treated sheet so that the laser-treated layer was under compression. In Variant B Ex2, F_{exp} was imposed on the laser-untreated side of the one-side laser-treated sheet, so that the laser-treated layer was under tension. In Variant C Ex2, F_{exp} was imposed on the two-side laser-

treated sheet. In this case, the top laser-treated layer was under compression, while the bottom laser-treated layer was under tension. All bending cases are summarized in Table 2.8.

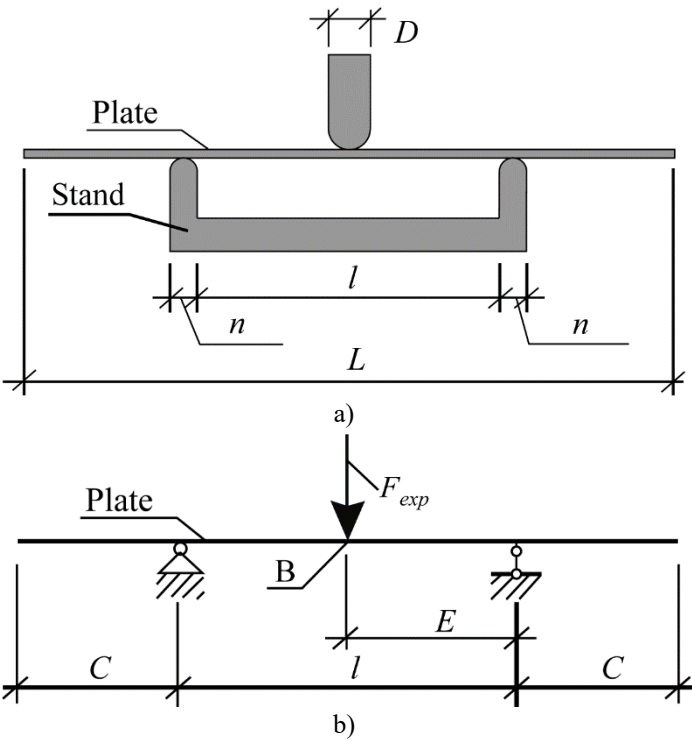


Fig. 2.10. Bending test device: (a) the principal view; (b) calculation scheme

Table 2.7. Bending testing parameters and samples geometry

Set of bending samples	Thickness of the test piece a , mm	Width of the test piece b , mm	Length of the test piece L , mm	Size of the treated area $Y \times b$, mm	Distance between supports l , mm	Diameter of mandrel D , mm	Radius of supports n , mm	Rate of displacement v , mm/s
Ex1	2	30	150	40x30	40	10	3	1.0–1.2
Ex2		20	150	40x20	70			
Ex3			100	20x20	14	8		

Table 2.8. Samples' geometry and positioning of laser ribs

Experiment name	Number of ribs (total)	Overlay coefficient of laser-processing on the sheet	Position and stress-strain state of the laser-treated layer	Position of the ribs	Material
Ex1 Case I	0				1.1151
Ex1 Case II A	56	Overlap	Top under compression	Horizontal	
Ex1 Case II B	27	0.35			
Ex1 Case II C	21	0.7			
Ex2 Case I	0				1.1151/ 1.0402
Ex2 Case II A	38	Overlap	Top under compression	Horizontal	
Ex2 Case II B	38		Bottom under tension		
Ex2 Case II C	76		Double side		
Ex2 Case III A	17	0.35	Top under compression		
Ex2 Case III B	17		Bottom under tension		
Ex2 Case III C	34		Double side		
Ex2 Case IV A	14	0.7	Top under compression		
Ex2 Case IV B	14		Bottom under tension		
Ex2 Case IV C	28		Double side		
Ex3 Case I	0				1.0402
Ex3 Case II A	76	Overlap	Double side	Horizontal	
Ex3 Case II B	76			Vertical	
Ex3 Case II C	108			45 degrees	
Ex3 Case III A	34	0.35		Horizontal	
Ex3 Case III B	34			Vertical	
Ex3 Case III C	52			45 degrees	
Ex3 Case IV A	28	0.7		Horizontal	
Ex3 Case IV B	28			Vertical	
Ex3 Case IV C	40			45 degrees	

2.2.3.3. Tensile tests

A universal tensile-testing machine TIRAtest 2300 (TIRA, Schalkau, Germany), with a bending test tool and Catman-Express software (version 5.1, HBM, Germany), was used for the tensile and bend tests. A tension dynamometer of up to 50 kN was used for the tensile test. The precision of testing equipment, load, and deformation measurement sensors was $\pm 0.03\%$.

The machined test pieces' geometries for tensile testing conform to specifications given in Annex B of LST ISO 6892-1 (initial gauge length $L_0 = 50$ mm, length $L_c = 60$ mm, and initial cross-section $S_0 = 10$ mm²). The size of the affected area was 60x5 mm, and the testing rate was based on the strain rate control (method A).

The mechanical properties of the base, i.e., laser-untreated metal, stress–strain diagram, modulus of elasticity E_b , offset yield stress (proof stress) $\sigma_{0.2,B}$, ultimate and fracture stress, and fracture strains $\epsilon_{ul,b}$ were determined by the static tensile test.

The three samples were used for mechanical tests and estimating the means $m_x = \sum_{i=1}^N x_i$ in each case of Ex4. Samples in each series of Ex4 have different processing directions and orientations (along, across, and at an angle of 45 degrees relative to the direction of the tensile load) with bilateral symmetrical processing for mechanical tensile tests. Tensile testing parameters and samples' geometry are summarized in Tables 2.9–2.10.

Table 2.9. Tensile testing parameters and samples' geometry

Experiment name	Number of ribs (total)	Overlay coefficient of laser-processing on the sheet	Position and stress–strain state of the laser-treated layer	Position of the ribs
Ex4 Case I	0	–	–	–
Ex4 Case II A	16	Overlap	Double side	Horizontal
Ex4 Case II B	236	Overlap	Double side	Vertical
Ex4 Case II C	178	Overlap	Double side	45 degrees
Ex4 Case III A	8	0.35	Double side	Horizontal
Ex4 Case III B	114	0.35	Double side	Vertical
Ex4 Case III C	86	0.35	Double side	45 degrees
Ex4 Case IV A	6	0.7	Double side	Horizontal
Ex4 Case IV B	84	0.7	Double side	Vertical
Ex4 Case IV C	64	0.7	Double side	45 degrees

Table 2.10. Tensile testing parameters and samples' geometry

Original width of parallel part b_0 , [mm]	Original thickness a_0 , [mm]	Original gauge length L_0 , [mm]	Parallel length L_c , [mm]	Free length between grips L_f , [mm]	Total length of test piece L_t , [mm]	Length of gripped size C , [mm]	Transition radius r , [mm]	Width of gripped ends B , [mm]	Strain rate $\dot{\epsilon}_{L_0}$, S^{-1}	Original width of parallel part b_0 , [mm]
5	2	50	60	74	100	13	25	20	0.002	5

2.2.4. Methodology of modeling

Experimental results were compared with thin-walled object deformation modeling results simulated using the finite element method. The methodology of modeling of thermal cycles, stress and strain FEA analysis is presented below in the following sub-chapters.

2.2.4.1. Simulation of thermal cycles during laser processing

In this study, thin steel sheets were the object of processing rather than complex metal structures. Therefore, simple methods can be used for calculations and analysis of temperature fields during the laser processing of steel. Modeling of the shape and depth of the volume of the melted metal in the process of laser processing of steel sheets was performed using the Smartweld version 3 software package. This software provides interactive displays of fusion zone, heat treated zones dimensions, and temperature contours versus laser parameter levels by computing solutions of models of conduction heat transfer. The programming module ISO-3D GAUSS for determining the temperature dissipation to a weld was used. Module ISO-3D GAUSS is valuable for simulating defocused laser beams and other distributed heat sources and allows for specifying a spot diameter of up to 5 mm wide. The model is based on the Eagar and Tsai integral solution to the conduction heat flow equation for a moving Gaussian distributed source. Thermal properties were used in the calculations, typical for plain carbon steels: thermal conductivity 51 W/mK and specific heat capacity 462 J/kg·K. The welding parameters were used exactly those that were selected by calculation and then used further for the laser processing of samples. Laser welding parameters: spot diameter of 3 mm, welding speed of 240 mm/min, the base-ambient temperature of 20 °C, and average laser power of 150 W.

2.2.4.2. Methodology of finite element analysis simulation of deformations of a thin metal sheet

The tensile and bending of the laser-treated thin-metal samples were simulated by FEA. The Ansys workbench software package (version 16.0) was used for mechanical stress-strain simulation and analysis. A numerical model of the bending and the tensile test was created identical to the experimental test devices for each series of experiments. The general views of the numerical models are shown in Fig. 2.11. The geometry and dimensions of the FEA models of the samples were identical to the samples used in the experimental investigation. The shape and depth of the laser-treated metal (0.35 mm) were identical for all FEA models of the samples.

Table 2.11 presents two different mechanical properties of the base metal and laser-treated layer used for the FEA simulation of elastoplastic deformation during the tensile and bending process of samples.

Table 2.11. Parameters of base metal and laser-treated layer used to simulate elastoplastic deformation of samples (Zhukov et al., 1967; Dvokin, 2017; Tsiklis, 1965)

Type of steel	Material	Modulus of elasticity, E , GPa	Shear modulus G , GPa	Yield strength $\sigma_{0.2}$, MPa	Ultimate strength σ_B , MPa	Poisson' s ratio ν	Strength coefficient E_1 , GPa	Yield stress strains ϵ_1 (10^{-3})	Ultimate strains ϵ_{ul} (10^{-3})
1.1151	Base metal	200	78.1	275	450	0.28	0.45	1.37	302.0
	Laser-treated layer	212	84	420	670	0.30	0.72	1.98	302.0
1.0402	Base metal	200	78.1	256	410	0.28	0.51	1.28	302.0
	Laser-treated layer	210	82	412	665	0.28	0.84	1.96	302.0

Base-steel properties are applied in modeling for the area outside the melted pool area, which has the form of semicircles. A depth of penetration of about 0.35 mm was used in all models. The width of the track of the laser-treated metal was approximately 0.7 mm. The number of treated sides, the number of laser tracks, the orientation of tracks, and the distance between them were varied. Examples of a cross-section of laser-treated areas and the geometry of the laser-treated areas are shown in Fig. 2.12.

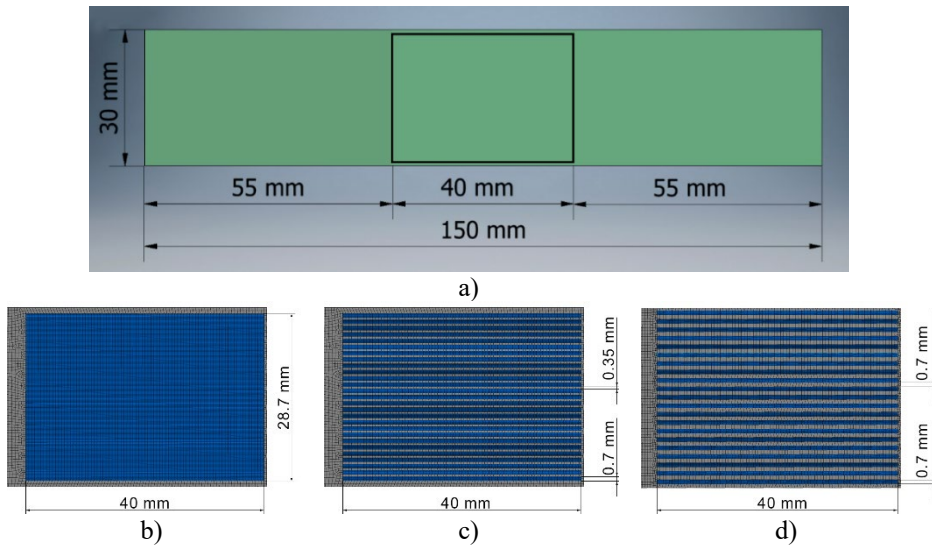


Fig. 2.11. Views of the surface of samples in Ansys software: (a) general view of the metal sheet with dimensions of the treated area; (b) Ex1 Case II A; (c) Ex1 Case II B; (d) Ex1 Case II C

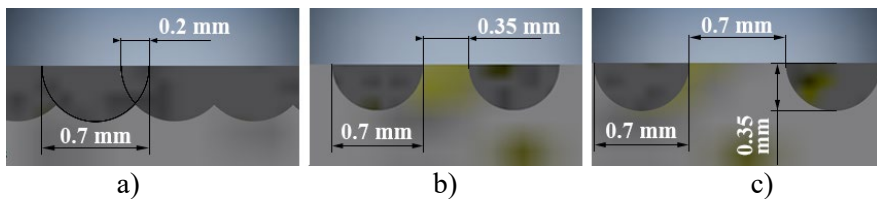


Fig. 2.12. Cross-sectional view of the laser-treated zones in FEA software: (a) Ex1 Case II A; (b) Ex1 Case II B; (c) Ex1 Case II C

The mechanical properties of the steel used in the simulation were established by mechanical testing (i.e., tensile and bending) of specimens, applying approximations, and using published data (Zhukov et al., 1967; Dvokin, 2017; Tsiklis, 1965). The approximate yield strength and ultimate strength of the laser-

treated layers were obtained by applying the relations between hardness and strength (Cahoon et al., 1971; Cahoon, 1972; Pavlina & Van). The modulus of elasticity, Poisson's ratio, and other required properties of laser-treated layers are taken from elsewhere (Zhukov et al., 1967).

The 3D Solid brick and tetrahedral elements were used for the discretization of the complex geometry of the modeled samples with laser-treated areas (Steppankova, 2009b). Large-scale finite elements with a maximum size of 0.7 mm were used to mesh the laser-untreated parts of the sample, while a finer mesh with finite element sizes up to 0.12 mm was adopted for the discretization of the laser-treated area.

A relatively simple plasticity model, i.e., the multilinear isotropic hardening model, was used for FEA (Jones, 2009). The stress–strain curves of the basic metal and the treated layer are provided from the experimental data. However, the dependences of the nonlinear part of the curves are simplified to linear as it is traditionally used for the Bilinear isotropic hardening model. Consequently, only the yield strength and the tangent modulus of the material are used as input parameters, as shown in Fig. 2.13 (Jones, 2009b).

The total deformation in the model is represented as the sum of the elastic and plastic deformation components (Höche et al., 2015b; Višniakov, 2003):

$$\varepsilon = \varepsilon^e + \varepsilon^p \quad (2.4)$$

where ε^e – elastic deformation, ε^p – plastic deformation.

Bilinear constitutive laws of the laser-untreated and laser-treated parts of the sheets were adopted for mechanical analysis of the sheets by the finite element method, see $\hat{\sigma}_b$ and $\hat{\sigma}_l$ stress–strain curves of materials depicted in Fig. 2.13. These constitutive laws are approximations of the real physical stress–strain ($\sigma - \epsilon$) curves of the laser-treated and untreated metals. The direct investigation of the $\sigma - \epsilon$ curve of the laser-treated layer of metal is very complicated. Therefore, the simplified bilinear $\sigma - \epsilon$ diagrams already mentioned were adopted for the FEA.

Below, explanations are given of the obtained and adopted mechanical parameters of the laser-untreated and treated metals of the sheets. The $\sigma - \epsilon$ curve of the basic, i.e., laser-untreated, metal (1.1151 (EN 10083-2:2006) and 1.0402 (EN 10250-2:2022)) was obtained experimentally.

The methodology of experimental data adaptation is explained by using the strain–stress curve of 1.0402 (EN 10250-2:2022) steel sample.

From the $\sigma - \epsilon$ curve, the yield strength $\sigma_{0.2,b} = 256$ MPa, the ultimate strength $\sigma_{B,b} = 410$ MPa and the ultimate strains $\epsilon_{ul,b} = 0.302$ of the base metal were obtained directly. The $\sigma - \epsilon$ curve is denoted as σ_b , is depicted as a smooth curve in Fig. 2.13.

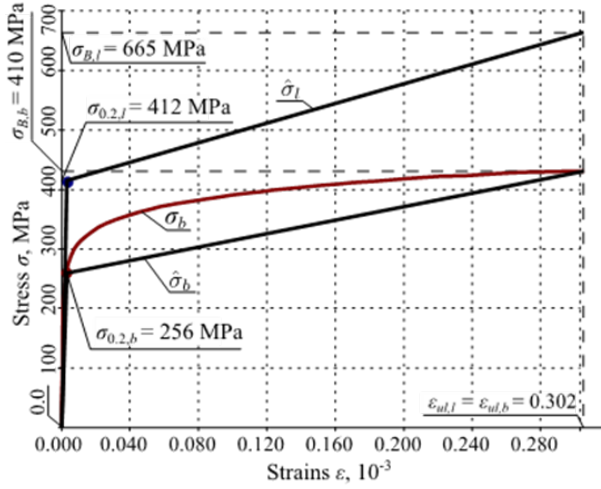


Fig. 2.13. Stress–strain curves: σ_b denotes the (steel 1.0402) base metal $\sigma - \epsilon$ curve; $\hat{\sigma}_b$ denotes the bilinear approximations of σ_b ; $\hat{\sigma}_l$ denotes the bilinear approximation of the $\sigma - \epsilon$ curve of unknown laser-treated metal; yield strengths, ultimate strength, and fracture strains of the base metal and the laser-treated metal are denoted by $\sigma_{0.2,b}$, $\sigma_{0.2,l}$, $\sigma_{B,b}$, $\sigma_{B,l}$, $\epsilon_{ul,b}$ and $\epsilon_{ul,l}$, respectively

As Fig. 2.13 shows, the $\sigma - \epsilon$ curve does not exhibit a clear yield plateau. After reaching the yield strength, the so-called work hardening is specific to the base metal. Due to the difficulty of experimental investigation of the mechanical properties of the laser-treated metal, the real $\sigma - \epsilon$ curve of this metal is unknown. Only indirect estimations of the yield strength, $\sigma_{0.2,l} = 412$ MPa, and the ultimate strength, $\sigma_{B,l} = 665$ MPa, were obtained using the Cahoon equations (Cahoon et al., 1971; Cahoon, 1972a; Cahoon, 1972b), which establish the relations between the metal hardness and strength. However, the ultimate strains, $\epsilon_{ul,l}$ of the laser-treated metal are still unknown. Therefore, it is assumed that the ultimate strains of the laser-treated metal are the same as for the laser-untreated metal, i.e., it is assumed that $\epsilon_{ul,l} = \epsilon_{ul,b} = 0.302$.

The moduli of elasticity, $E_b = 200$ GPa and $E_l = 210$ GPa, Poisson's ratios $\nu_b = \nu_l = 0.28$, and the shear moduli, $G_b = 78.1$ GPa and $G_l = 82$ GPa of the base metal and the laser-treated metal, respectively, were taken from the reference literature (Pavlina & Van, 2008). Having the yield strength, $\sigma_{0.2,i}$, and the moduli of elasticity, E_i , $i \in \{b, l\}$, the strains $\epsilon_{1,b} = 1.28 \cdot 10^{-3}$ and $\epsilon_{1,l} = 1.962 \cdot 10^{-3}$ that correspond to the yield strength $\sigma_{0.2,i}$ were calculated by the formula $\epsilon_{1,i} = \sigma_{0.2,i}/E_i$.

The strength coefficients of the laser-treated and untreated metals, $E_{1,b} = 512$ MPa and $E_{1,l} = 843$ MPa, respectively, were calculated by the formula $E_{1,i} = (\sigma_{B,i} - \sigma_{0.2,i})/(\epsilon_{ul,i} - \epsilon_{1,i})$, $i \in \{b, l\}$, where $\sigma_{0.2,b} = 256$ MPa and $\sigma_{0.2,l} = 412$ MPa are the yield strengths of the base metal and the laser-treated metal, respectively, while $\sigma_{B,b} = 410$ MPa and $\sigma_{B,l} = 665$ MPa are the ultimate strengths of the same metals.

Based on the obtained values of the mechanical properties of the materials, the bilinear approximations of $\sigma - \epsilon$ curves of the laser-untreated and treated metals $\hat{\sigma}_b$ and $\hat{\sigma}_l$, respectively, are depicted in Fig. 2.13. All the values of the mechanical properties discussed above of the two metals are summarized in Table 2.11.

2.2.4.3. Methodology of finite element analysis simulation of a thin metal sheet bending

Thin-walled metal parts are manufactured from non-alloy steel. They are most often stressed by bending load and modeled using FEA. The simulation of the elastoplastic deformation of the sheets under bending load was done using a 3D device model. The general view of the numerical models is shown in Figs. 2.14a and 2.15. The size of the 3D models and the shape and depth (0.35 mm) of the treated layer were identical to those that were used during the experimental bend tests. The different mechanical properties of the base metal and laser-treated layer were used in the FEA models from Table 2.11.

The treated layers were oriented in different directions by analogy with the strengthening of composite materials with continuous fiber strengthening elements. Several variants of metal sheet processing with different degrees of overlapping (the distance between the layers) treated by the laser beam were simulated to assess the influence of the geometry of the melted layer on the required bending load and stiffness of the sheet sample. The localization of treated layers and the depth of penetration (0.35 mm) remained unchanged in the set of experiments, summarized in Table 2.12.

The distance between supports varied from 14 to 70 mm based on the data presented in Table 2.7 for imitation of different sheet product bending conditions and corresponding to the requirements of the different standards. The structural supports were modeled as roller movable supports. The mandrel rounding radius, the width, and the distance between the supports were the same as in the real bending tests.

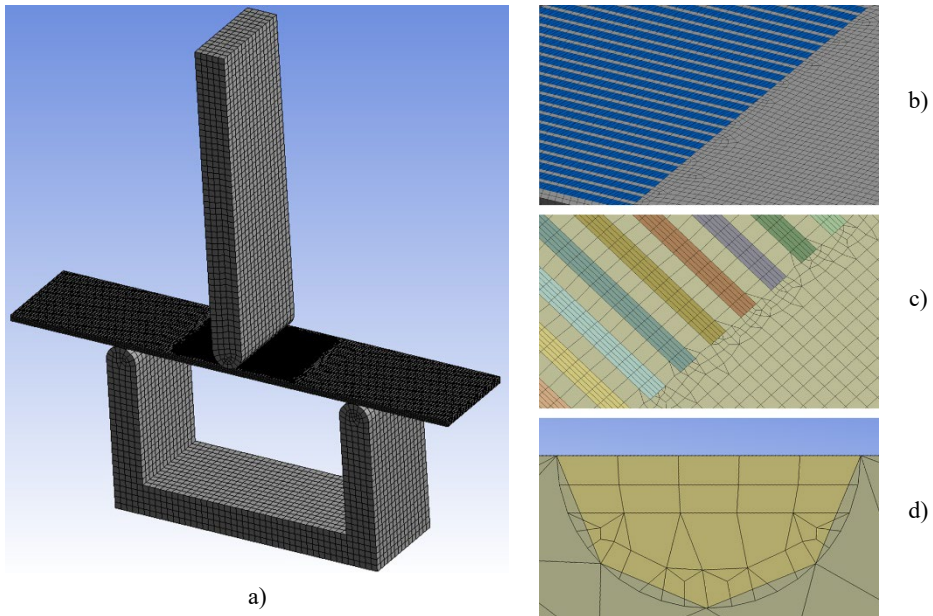


Fig. 2.14. Finite element mesh of a model Ex1 in Ansys Workbench: (a) general view; (b) enlarged view of the mesh of laser tracks; (c) enlarged view of the surface mesh of the laser-treated area; (d) cross-sectional view of the mesh of an individual laser track

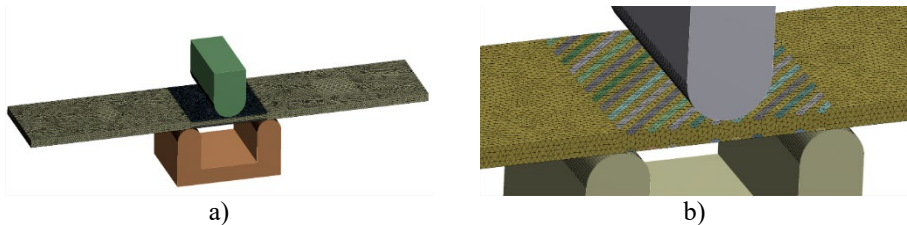


Fig. 2.15. Finite element model Ex3 for a bending simulation: (a) general view; (b) enlarged view of the mesh of laser tracks

For all bending variants presented in Fig. 2.10 and Figs. 2.16–2.18, the load was imposed in the middle of the span of the stand. The maximum deflection (2 mm) in the bending simulations was identical to those used during the experimental bend tests.

All laser processing cases and loading variants used in the FEA are summarized in Table 2.8. The texture and cross-view of the laser-treated area of samples Ex3 are presented in Table 2.13.

Table 2.12. The geometry of the treated area

Laser processing case	Laser-treated surface, length x width, mm x mm	Number of the laser processing tracks, pc	Volume of the laser-treated metal, mm ³	Ratios of volumes of the laser-treated metal to the total bent volume, %
Ex1 Case I	Without laser processing area	0		
Ex1 Case II A	40x30	56	430.9	17.9
Ex1 Case II B		27	207.8	8.7
Ex1 Case II C		21	161.6	6.7
Ex2 Case I	Without laser processing area	0		
Ex2 Case II A	40x20	38	292.4	18.3
Ex2 Case II B		38	292.4	18.3
Ex2 Case II C		76	584.8	36.5
Ex2 Case III A		17	130.8	8.2
Ex2 Case III B		17	130.8	8.2
Ex2 Case III C		34	261.6	16.3
Ex2 Case IV A		14	107.7	6.7
Ex2 Case IV B		14	107.7	6.7
Ex2 Case IV C		28	215.5	13.5
Ex3 Case I	Without laser processing area	0		
Ex3 Case II A	20x20	76	291.8	36.5
Ex3 Case II B		76	291.8	36.5
Ex3 Case II C		108	311.3	38.9
Ex3 Case III A		34	130.6	16.3
Ex3 Case III B		34	130.6	16.3
Ex3 Case III C		52	146.4	18.3
Ex3 Case IV A		28	107.5	13.4
Ex3 Case IV B		28	107.5	13.4
Ex3 Case IV C		40	111	13.9

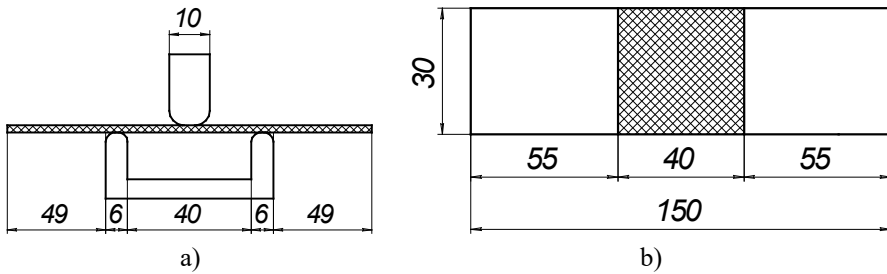


Fig. 2.16. Schematic of the bending test Ex1: (a) general view and sizes of 3-point fixtures; (b) the geometry of samples

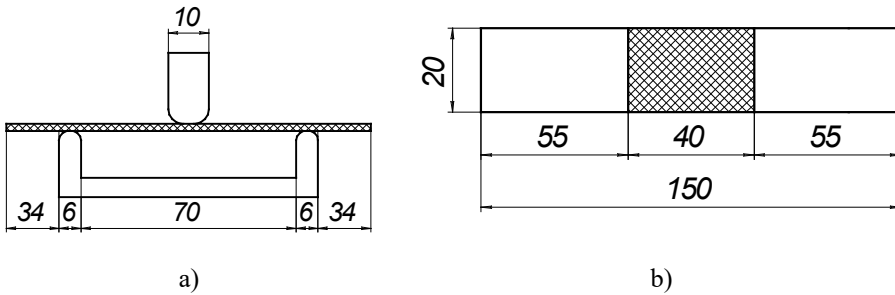


Fig. 2.17. Schematic of bending test Ex2: (a) general view and sizes of 3-point fixtures; (b) the geometry of samples

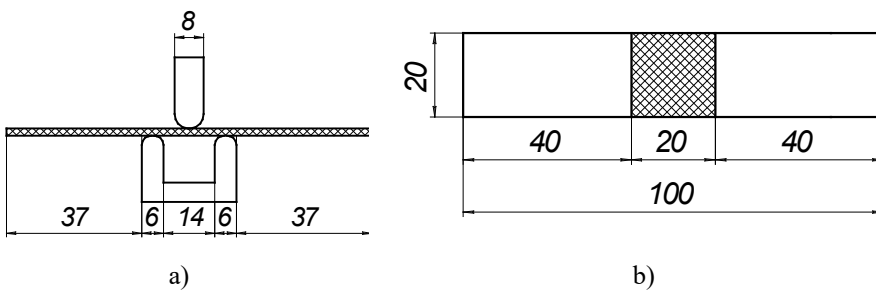
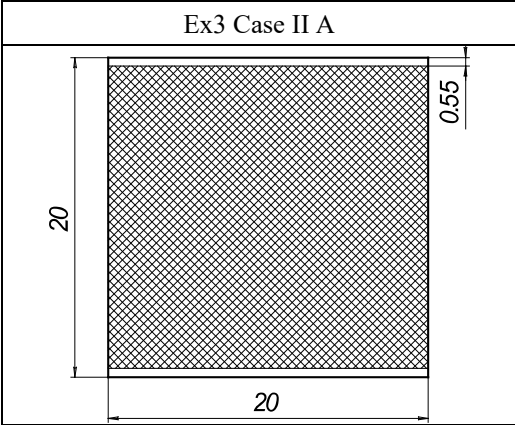
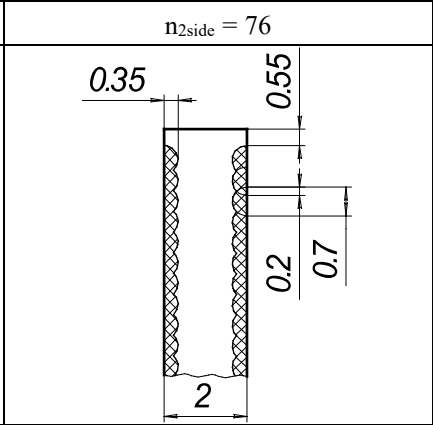
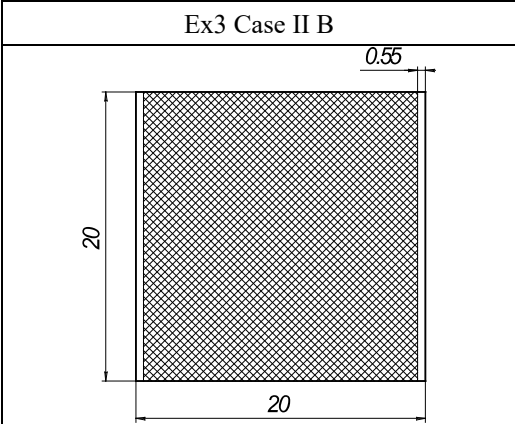
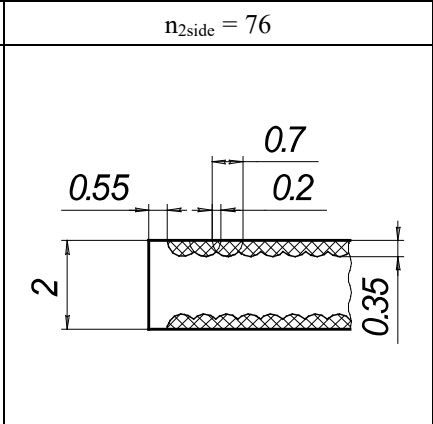
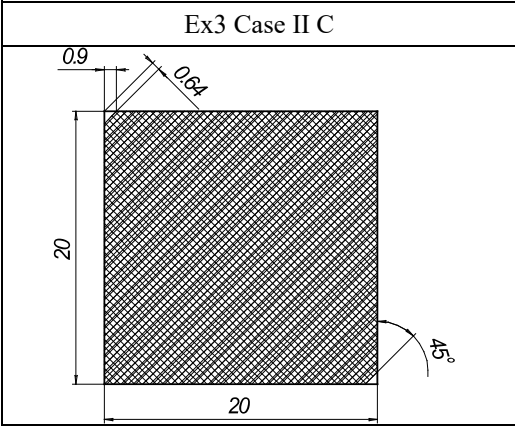
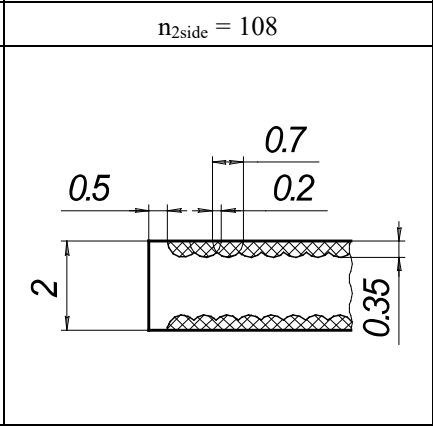
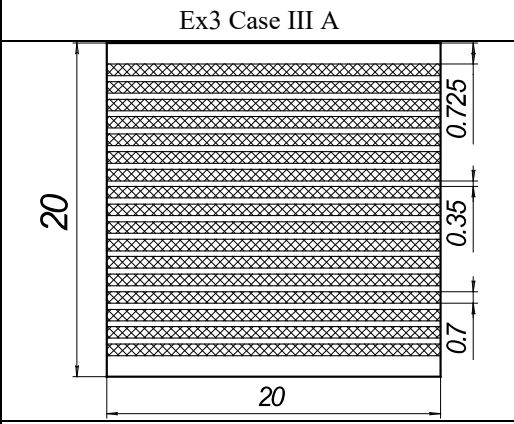
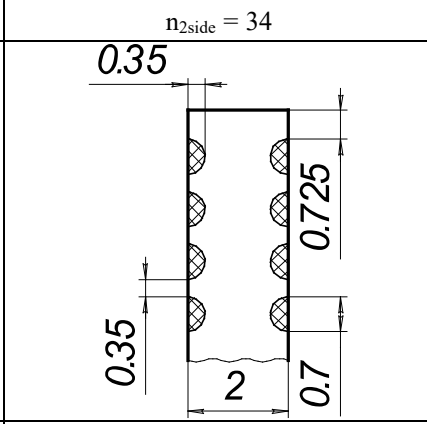
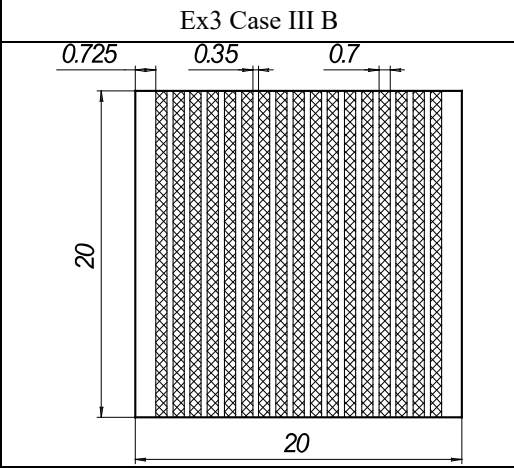
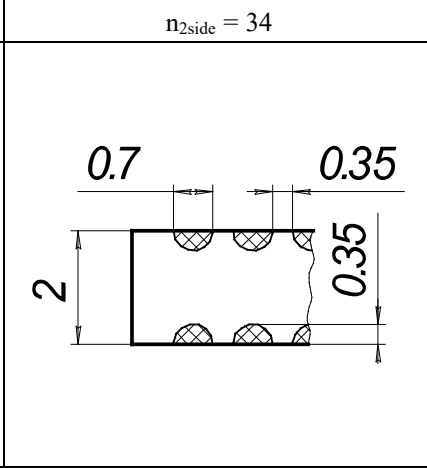
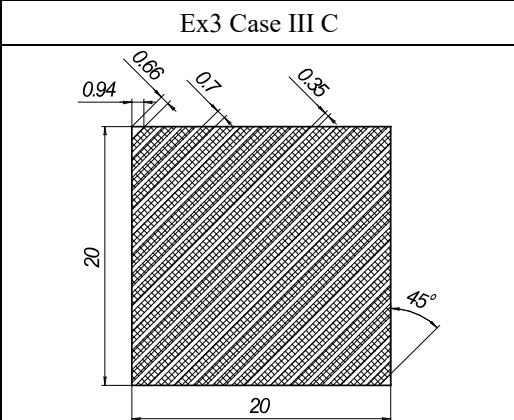
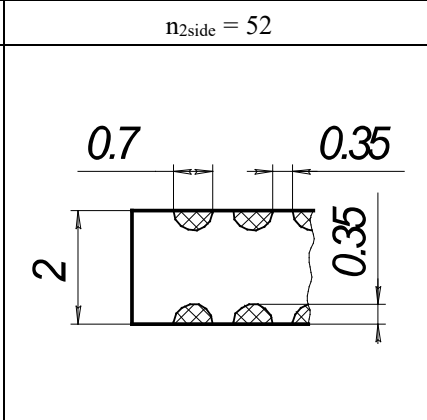


Fig. 2.18. Schematic of bending test Ex3: (a) general view and sizes of 3-point fixtures; (b) the geometry of samples

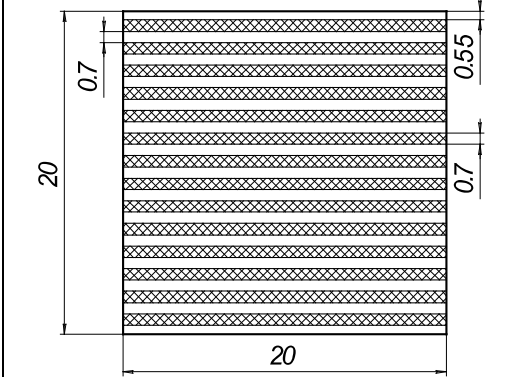
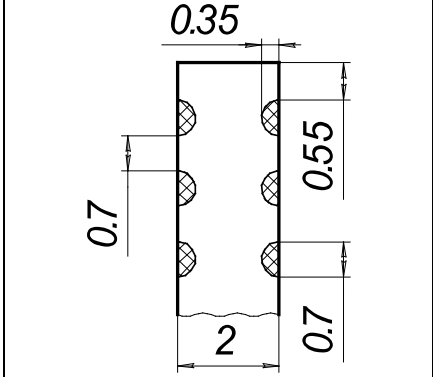
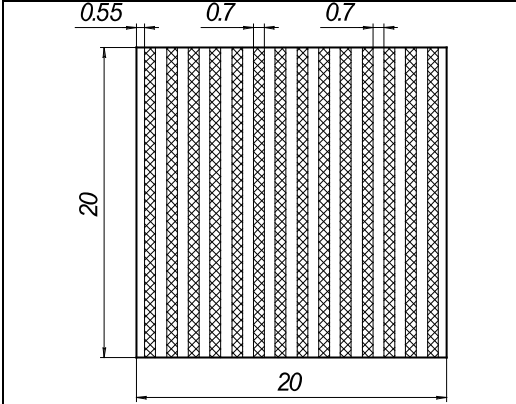
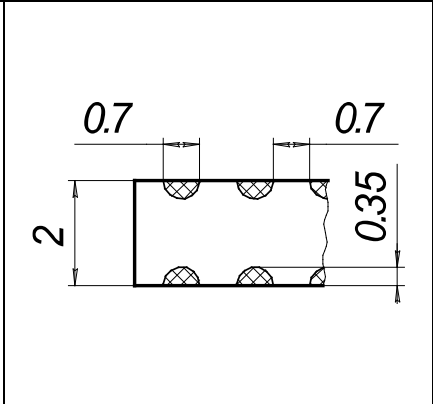
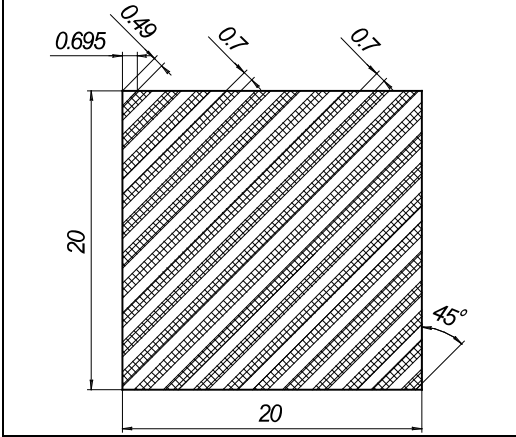
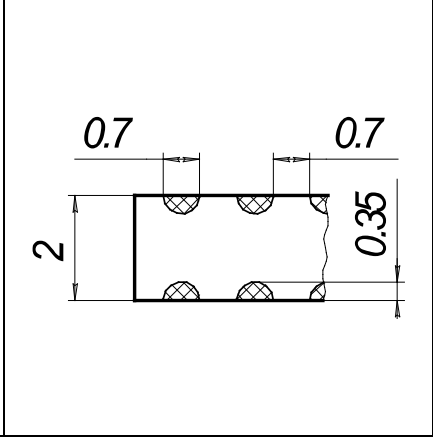
Table 2.13. Texture and cross view of the laser-treated area of samples Ex3 for the three-point bending test

Ex3 Case II A 	$n_{2\text{side}} = 76$ 
Ex3 Case II B 	$n_{2\text{side}} = 76$ 
Ex3 Case II C 	$n_{2\text{side}} = 108$ 

Continued Table 2.13

Ex3 Case III A 	$n_{2\text{side}} = 34$ 
Ex3 Case III B 	$n_{2\text{side}} = 34$ 
Ex3 Case III C 	$n_{2\text{side}} = 52$ 

End of Table 2.13

Ex3 Case IV A 	$n_{2side} = 28$ 
Ex3 Case IV B 	$n_{2side} = 28$ 
Ex3 Case IV C 	$n_{2side} = 40$ 

2.2.4.4. Tensile of thin metal sheet

Additional simulations of the tensile tests were carried out after modeling the bending tests and identifying the most successful processing options with similarly treated samples. The geometry and dimensions of all models corresponded to the real samples with different processing directions and orientations (i.e., along, across, and at an angle of 45° relative to the direction of the tensile load), which underwent mechanical tensile tests.

The same original gauge length (60 mm) and free length between grips (74 mm) were used. The tensile samples in FEA modeling are shown in Figs. 2.19–2.20. All laser processing cases used in the FEA are summarized in Table 2.9. The numerical model, geometry, texture, and cross view of the laser-treated area of samples Ex4 are also summarized in Tables 2.14 and 2.15.

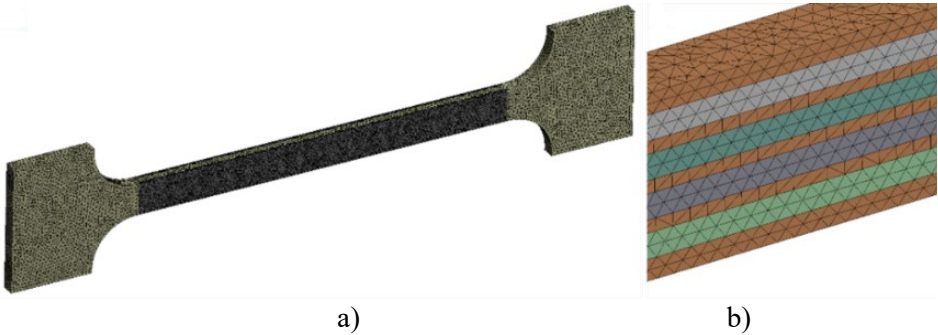


Fig. 2.19. Finite element mesh of a model for tensile testing simulation: (a) general view; (b) enlarged view of the mesh of laser tracks

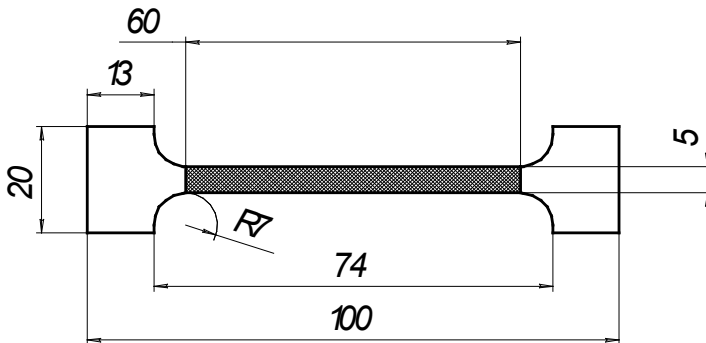
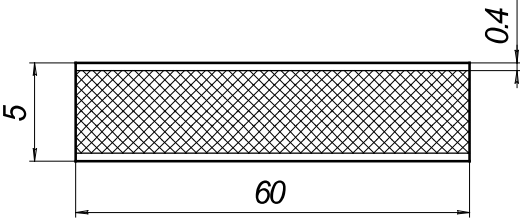
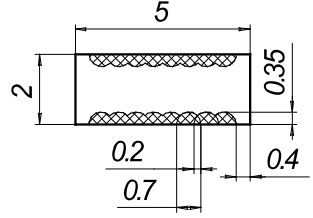
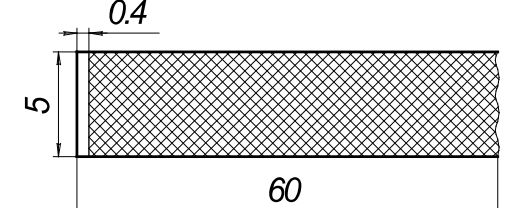
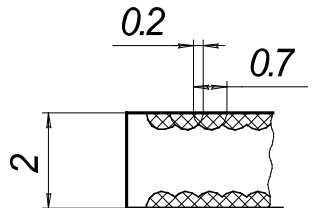


Fig. 2.20. Geometry of samples for tensile testing

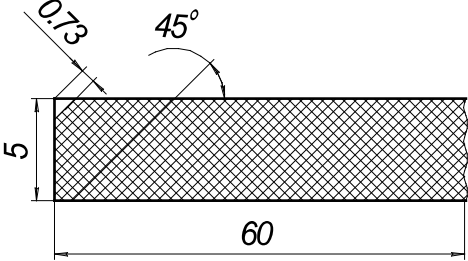
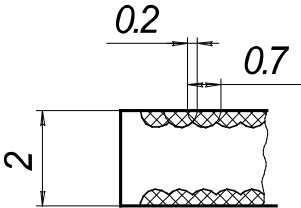
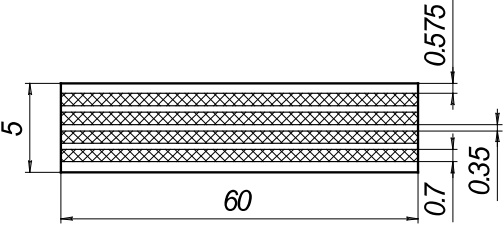
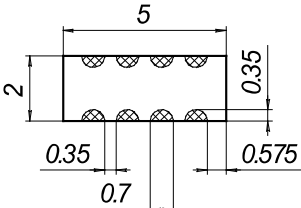
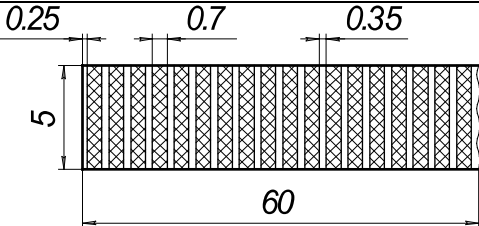
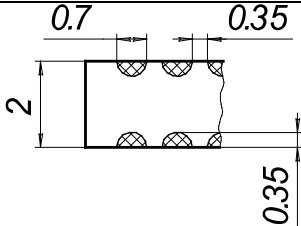
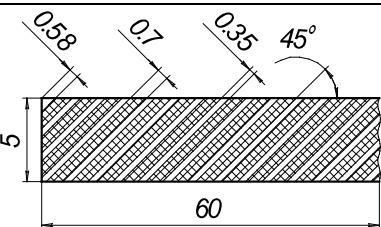
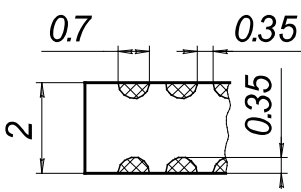
Table 2.14. The geometry of the treated area

Laser processing case	Laser-treated surface, length x width, mm x mm	Number of laser processing tracks, pc	Volume of the laser-treated metal, mm ³	Ratios of volumes of the laser-treated metal to the total bent volume, %
Ex4 Case I	Without laser processing area	0		
Ex4 Case II A	60x5	16	184	30.7
Ex4 Case II B		236	227	37.8
Ex4 Case II C		178	227.7	37.9
Ex4 Case III A		8	92.4	15.4
Ex4 Case III B		114	109.7	18.3
Ex4 Case III C		86	111.4	18.6
Ex4 Case IV A		6	69.3	11.5
Ex4 Case IV B		84	80.8	13.5
Ex4 Case IV C		64	82.3	13.7

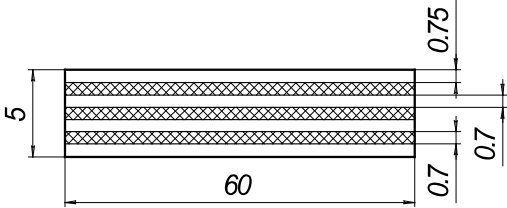
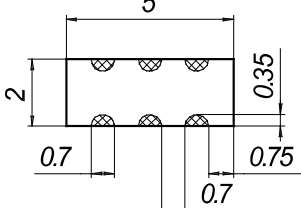
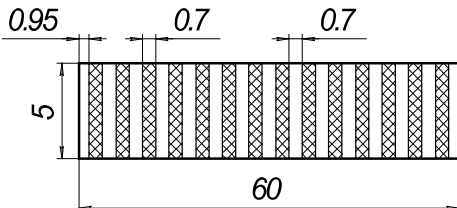
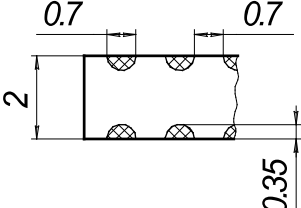
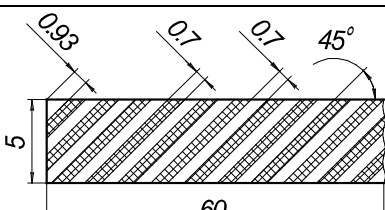
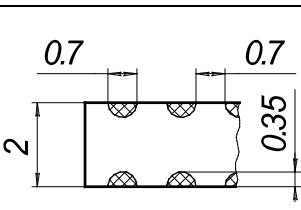
Table 2.15. The texture of laser-treated area of samples for tensile test. Ex4, steel 1.0402, sheet dimension (WxLxT) 20x100x2 mm.

Ex4 Case II A	$n_{2\text{side}} = 16$
	
Ex4 Case II B	$n_{2\text{side}} = 236$
	

Continued Table 2.15

Ex4 Case II C	$n_{2\text{side}} = 178$
	
Ex4 Case III A	$n_{2\text{side}} = 8$
	
Ex4 Case III B	$n_{2\text{side}} = 114$
	
Ex4 Case III C	$n_{2\text{side}} = 86$
	

End of Table 2.15

Ex4 Case IV A	$n_{2side} = 6$
	
Ex4 Case IV B	$n_{2side} = 84$
	
Ex4 Case IV C	$n_{2side} = 64$
	

2.2.4.5. Methodology for analyzing the stiffness of the laser-untreated and treated steel sheets

The geometry and dimensions of the modeled sheet are given in Fig. 2.3. The material properties are also given in Table 2.11. The main assumptions are as follows:

- (1) the laser-treated metal has a perfect bond with the base metal. This means no slip occurs between the laser-treated layer and the layer of the base metal,
- (2) the hypotheses of the plane sections are valid,
- (3) the influence of the Poisson’s ratio is ignored,
- (4) only the normal stresses σ acting along the laser tracks (Fig. 2.3a) are considered, and
- (5) the stress–strain curve for the laser-treated layer and the base metal is bilinear (Fig. 2.13).

Under the accepted assumptions, the total axial force acting on the cross-section of the sheet, $N(\epsilon) = N_b(\epsilon) + N_l(\epsilon)$; where $N_b(\epsilon) = A_b \hat{\sigma}_b(\epsilon)$ and $N_l(\epsilon) = A_l \hat{\sigma}_l(\epsilon)$ are the axial forces acting in the base metal and laser-treated metal of the sheet, respectively. A_b and A_l are the cross-sectional areas of the base metal and the laser-treated metal, respectively, and $\hat{\sigma}_l$ are the stress functions of the base and the laser-treated metals, respectively, depending on the strains, ϵ .

When the bilinear stress-strain diagrams are applied (Fig. 2.13), then $\hat{\sigma}_b$ and $\hat{\sigma}_l$ can be expressed as follows:

$$\hat{\sigma}_i(\epsilon) = \begin{cases} E_i \epsilon, & \text{as } \epsilon \leq \epsilon_{1,i}, \\ E_i \epsilon_{1,i} + E_{1,i}(\epsilon - \epsilon_{1,i}), & \text{as } \epsilon_{1,i} < \epsilon \leq \epsilon_{ul,i}, \quad i \in \{b, l\}, \\ 0, & \text{as } \epsilon > \epsilon_{ul,i}. \end{cases} \quad (2.5)$$

Here, E_b , $E_{1,b}$, E_l , $E_{1,l}$, $\epsilon_{ul,b}$ and $\epsilon_{ul,l}$ are the moduli of elasticity, the stiffness moduli and the ultimate strains of the base and the laser-treated metals, respectively, based on the data presented in Table 2.11 and Fig. 2.13.

Since $\epsilon_{1,b} \leq \epsilon_{1,l}$ and $\epsilon_{ul,b} \leq \epsilon_{ul,l}$, then, by putting functions $\hat{\sigma}_b$ and $\hat{\sigma}_l$ (Eq. 2.5) in $N(\epsilon) = \sum_{i \in \{b, l\}} A_i \hat{\sigma}_i(\epsilon)$, an explicit function is obtained for the axial force, N :

$$N(\epsilon) = \begin{cases} \epsilon \sum_{i \in \{l, b\}} A_i E_i, & \text{as } \epsilon \leq \epsilon_{1,b}, \\ A_b (E_b \epsilon_{1,b} + E_{1,b}(\epsilon - \epsilon_{1,b})) + A_l E_l \epsilon, & \text{as } \epsilon_{1,b} < \epsilon \leq \epsilon_{1,l}, \\ \sum_{i \in \{l, b\}} A_i (E_i \epsilon_{1,i} + E_{1,i}(\epsilon - \epsilon_{1,i})), & \text{as } \epsilon_{1,l} < \epsilon \leq \epsilon_{ul,b}, \\ A_l (E_l \epsilon_{1,l} + E_{1,l}(\epsilon - \epsilon_{1,l})), & \text{as } \epsilon_{ul,b} < \epsilon \leq \epsilon_{ul,l}, \\ 0, & \text{as } \epsilon > \epsilon_{ul,l}. \end{cases} \quad (2.6)$$

2.2.4.6. Methodology for evaluating the cross-sectional area of a laser-treated metal track

The geometry of the laser-treated layer is complex rather than a simple rectangular form (Fig. 2.3). Therefore, it is worth discussing the evaluation of the cross-section area of the laser-treated metal, A_l . As Figs. 2.3 and 2.14d show, the cross-sections of the laser-treated layer and a single laser-treated track are not rectangular. If the laser tracks do not overlap, i.e., $d_c \geq d_t$, where d_t is the laser-treated track width and d_c is the distance between the tracks of the laser-treated metal, and the number of laser tracks, n_{tr} , is known, then the cross-section of the laser-treated metal can be calculated easily.

$$A_l = n_s n_{tr} A_{tr,1}, \text{ if } d_c - d_t \geq 0, \text{ and } n_{tr} \text{ is known,} \quad (2.7)$$

where $A_{tr,1} = \pi d_t^2/8$ is the cross-sectional area of one laser-treated track, assumed to be a semicircle, $n_s \in \{1,2\}$ is the number of laser-treated sides of the sheet. It should be noted that, in Eq. 2.7 and hereafter in the article, the number of laser tracks, n_{tr} , cannot be an integer, i.e., in general, $n_{tr} \in \mathbb{R}$.

However, if n_{tr} is not known or the laser-treated tracks overlap, i.e., $d_c < d_t$, then the exact evaluation of A_l can be complicated. Some suggestions are made below on the following assumptions: the cross-section of a laser track is a semicircle whose area $A_{tr,1} = \pi d_t^2/8$, where d_t is the width of the laser track (Fig. 2.3d). The width of the tracks, d_t , is constant for all laser tracks and the entire length of all laser tracks. The distances between the centers of the laser tracks, d_c (Fig. 2.3d), is also constant for all pairs of the vicinal laser tracks.

The calculation of A_l depends on the distances between the tracks, d_c . If the difference $d_c - d_t > 0$ then the laser tracks do not overlap each other, and, in general, the exact evaluation of A_l is impossible without knowledge of the exact position of the laser tracks. However, the lower and upper bounds $A_{l,inf}$ and $A_{l,sup}$ can be suggested to estimate A_l , $A_{l,inf} \leq A_l \leq A_{l,sup}$:

$$A_{l,inf} = n_s A_{tr,1} \text{floor}(b_l/d_c), \text{ if } d_c - d_t > 0, \quad (2.8)$$

$$A_{l,sup} = n_s A_{tr,1} \text{ceil}(b_l/d_c), \text{ if } d_c - d_t > 0. \quad (2.9)$$

Where $\text{floor}(x) = \max\{y \in \mathbb{Z}, y \leq x\}$ and $\text{ceil}(x) = \min\{y \in \mathbb{Z}, y \geq x\}$ are ceiling and floor functions; $\mathbb{Z}$ is the set of the integer numbers; b_l is the width of the laser-treated area. When b_l/d_c increases, then the relative differences in the estimations $(A_{l,sup} - A_{l,inf})/A_{l,sup}$ and $(A_{l,inf} - A_{l,sup})/A_{l,sup}$ decreases.

For the present Ex2 case, where $d_t = 0.7$ mm, and $d_c \in \{1.05, 1.4\}$ mm (Fig. 2.3d), Eqs. 2.8 and 2.9 give: $A_{l,inf} = 14A_{tr,1}$ and $A_{l,sup} = 15A_{tr,1}$ when $d_c = 1.4$ mm, and $A_{l,inf} = 19A_{tr,1}$ and $A_{l,sup} = 20A_{tr,1}$ when $d_c = 1.05$ mm.

If n_{tr} is unknown, then it can be estimated as follows:

$$\hat{n}_{tr} = b_l/d_c, \quad (2.10)$$

Eq. 2.10 can be used to evaluate the distance between the laser-treated tracks $d_c = b_l/\hat{n}_{tr}$.

When $d_c - d_t = 0$ and n_{tr} is known, then A_l can be calculated by Eq. 2.7. Otherwise, when the number of laser-treated tracks, n_{tr} is not known, then A_l can

be calculated by assuming that there are no laser-untreated bands between the laser-treated tracks by the following formulae:

$$A_l = n_s A_{tr,1} b_l / d_c, \text{ if } d_c - d_t = 0, \quad (2.11)$$

when $d_c - d_t < 0$, then the laser tracks overlap each other and we should consider the overlapped areas of the tracks (Fig. 2.3d), Case II. Therefore, Eqs. 2.7, 2.8, 2.9 and 2.11 are not valid. Based on the above assumptions, the following bounds infimum $A_{l,inf}$ and supremum $A_{l,sup}$, $A_{l,inf} \leq A_l \leq A_{l,sup}$, of the cross-section area A_l of the laser-treated metal are derived when n_{tr} is not known:

$$A_{l,inf} = n_s \hat{n}_{tr} (A_{tr,1} - A_{ov}), \text{ if } d_c - d_t < 0, \quad (2.12)$$

$$A_{l,sup} = \min\{n_s (\hat{n}_{tr} A_{tr,1} - (\hat{n}_{tr} - 1) A_{ov}), b_l / 2 d_t\}, \text{ if } d_c - d_t < 0, \quad (2.13)$$

where $\hat{n}_{tr}$ is an estimation of the number of laser-treated tracks:

$$\hat{n}_{tr} = \text{floor}\left(\frac{b_l}{d_c}\right) - 1 + \left(1 + \text{frac}\left(\frac{b_l}{d_c}\right)\right) \frac{d_c}{d_t}, \quad (2.14)$$

where $\text{frac}(x) = x - \text{floor}(x)$ is the fractional part of a number x . When the number of the tracks n_{tr} is known:

$$A_l = n_s (n_{tr} A_{tr,1} - (n_{tr} - 1) A_{ov}), \text{ if } d_c - d_t < 0 \text{ and } n_{tr} \text{ is known}, \quad (2.15)$$

In Eq. 2.12, 2.13 and 2.15, A_{ov} is the overlapping area of two adjacent laser tracks (Fig. 2.3d, Case II). Under the accepted assumptions, A_{ov} can be calculated as the area of the circle segment $A_{ov} = d_t^2 (\alpha - \sin(\alpha)) / 8$, where $\alpha = 2 \tan^{-1} \left(\sqrt{d_t^2 - d_c^2} / d_c \right)$ is the sector angle, $\tan^{-1}$ is the inverse tangent function. It should be noted that $A_{l,inf} \leq A_{l,sup} \leq A_{l,upp} = 1/2 b_l d_t$, where $A_{l,upp}$ is the upper bound of the cross-section of the laser-treated layer.

2.3. Conclusions of the Second Chapter

1. A methodology was developed for local laser surface processing of thin-walled non-alloy steel products with up to 0.3% carbon concentration. This method ensures the protection of the laser-treated surface area from the surrounding environment by applying laser power density from 10^3 W/cm^2 – 10^6 W/cm^2 to 10^5 W/cm^2 and using the 1064 nm wavelength radiation.
2. A modeling methodology was developed for bending and drawing properties of laser-treated thin-walled products made of non-alloy steels with a carbon

concentration of up to 0.3%, considering the properties of the laser-treated layer and the configuration and texture of the laser processing area.

3. A methodology was prepared for determining the microstructure and mechanical properties of the laser-treated surface of thin-walled products made of non-alloy steels with a carbon concentration of up to 0.3% following EN and ISO standards.

Results of microstructure analysis, testing of mechanical properties, process simulation and discussion

This chapter presents and analyzes the study results of microstructure, mechanical properties and process modeling of non-alloy steel laser-treated surfaces by various methods. The chapter's results were published in the author's publications (Kapustynskyi et al., 2019; Kapustynskyi & Višniakov, 2020; Kapustynskyi et al., 2020).

3.1. Determining laser processing modes and parameters

One of the center criteria for the selection of appropriate processing modes was the required depth of laser penetration. The calculation of approximate laser processing parameters is executed according to the methodology presented in Chapter 2.2.1. The calculated values of the laser's critical power are presented in Fig. 3.1 as a function of the pulse length and the depth of the laser penetration into the material.

Macroscopy examination results of the samples treated locally by laser showed the following correlation between laser processing parameters and experimental depth and width of laser penetration, summarized in Table 3.1. Some of the low laser speed modes lead to 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's rigidity. Some examples of the laser-treated zones are presented in Fig. 3.2. Based on these results, it is possible to conclude that the optimal critical power of the laser beam of 3 mm in diameter for the generation of inner reinforcing ribs ranges between $2.5 \cdot 10^5$ and $4.5 \cdot 10^5$ W/cm², while the travelling speed of the beam is to be set between 20 and 50 mm/min. The 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 the increased speed of movement (more than 50 mm/min) decreases the penetration depth by half.

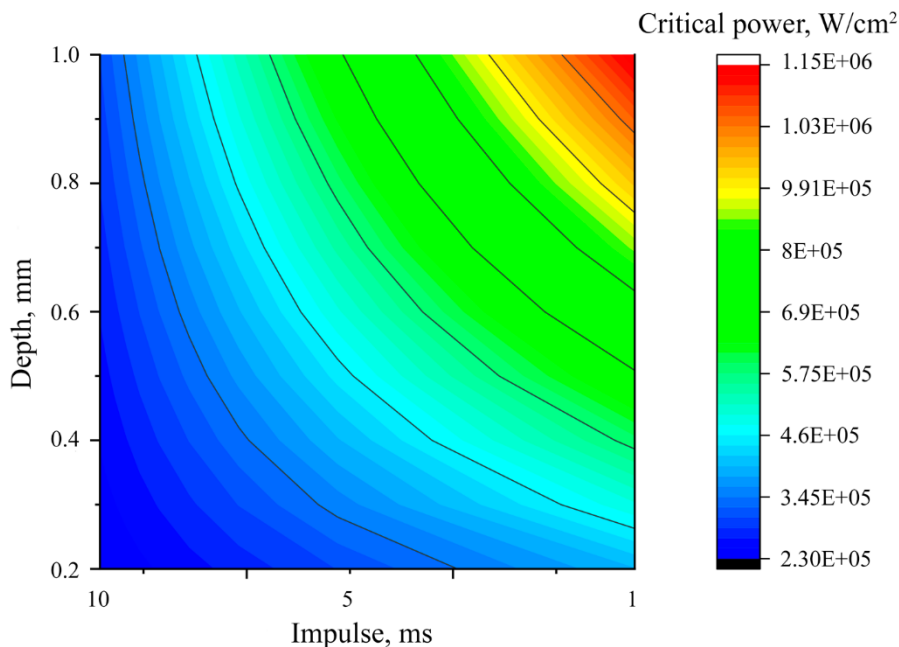


Fig. 3.1. Calculation of the laser critical power

The preferred mode from the variety of applied laser processing parameters is given in Table 3.2. An appropriate depth of laser penetration, in this case, is about 0.35 mm (~20% of the total thickness of the metal sheet). The critical power of $3.98 \cdot 10^5$ W/cm² and other selected laser parameters based on Table 3.2 ensure that the depth of the metal melting zone will reach the required value.

Table 3.1. Correlation between the laser parameters and the geometry of the melted zone

Depth, mm	Cutting	Speed, v, mm/min	f, Hz	Single pulse energy, J	Spot size,	Peak power, k W	Overlap coefficient, P_{er}	Calculated critical power, P_{dl} , W/cm ²	Real critical power, P_{d2} , W/cm ²
0.718	Present	120	20	11.8	2	2.3 6	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	2.3 6	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		$1.11 \cdot 10^5$

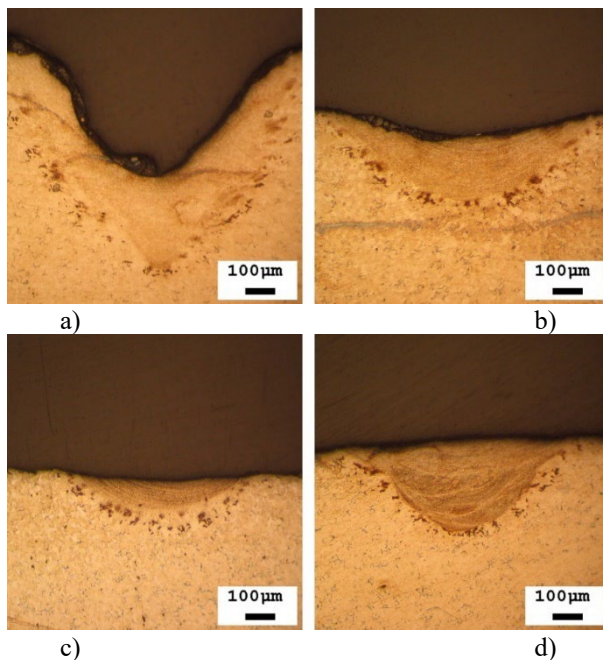


Fig. 3.2. View of laser-treated zones; (a) critical power $8.27 \cdot 10^5 \text{ W/cm}^2$; (b) critical power $3.9 \cdot 10^5 \text{ W/cm}^2$; (c) critical power $1.11 \cdot 10^5 \text{ W/cm}^2$; (d) critical power $3.59 \cdot 10^5 \text{ W/cm}^2$

Table 3.2. Parameters of Nd:YAG laser processing

Depth, h , mm	Speed, v , mm/min	Frequency, f , Hz	Pulse duration, t_p , ms	Single pulse energy, E_p , J	Spot size, d , mm	Peak power, P_p , kW	Overlap coefficient, P_{cr} , %	Critical power, P_{dl} , W/cm^2	Real critical power, P_{d2} , W/cm^2
0.346	240	10	5	14.4	3	2.8	97-98.6	$4.11 \cdot 10^5$	$3.98 \cdot 10^5$

3.2. Results of microstructure analysis and chemical composition

Samples contained less than 0.3% carbon. The microstructure of the samples of laser-treated thin-sheet non-alloy steel was analyzed using SEM, EDS, color

microscopy, XRD, and Mössbauer spectroscopy. The results of microstructure analysis and chemical composition are presented below.

3.2.1. Microscopic examination

The metallographic analysis of cross-sections indicated that the expected thickness (depth) of the laser-treated layer (i.e., 0.35 mm) could be achieved by using the calculated parameters of the laser beam in real processing. Fig. 3.3 provides a comparison of FEA and a real laser-treated specimen's cross-section. The surface of the laser-treated area was free of superficial defects and other indications of improper laser processing, as shown in Figs. 3.4 and 3.5. The shape of the laser track is almost hemispherical, as shown in Fig. 3.6. FEA simulations used the same layer shape, as shown in Fig. 2.3, 2.12, 2.14, and 3.3.

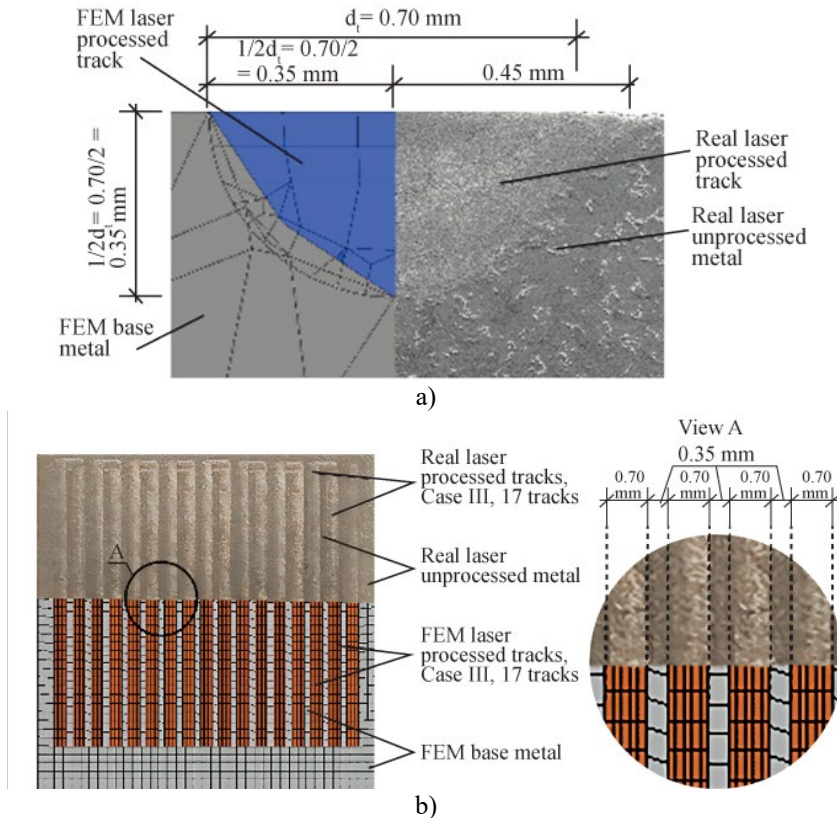


Fig. 3.3. Cross-sections of (a) the laser-treated area of a FEA and a physical specimen; (b) the general view of the laser-treated tracks of Ex2 Case III of the experimental specimen and the FEA model

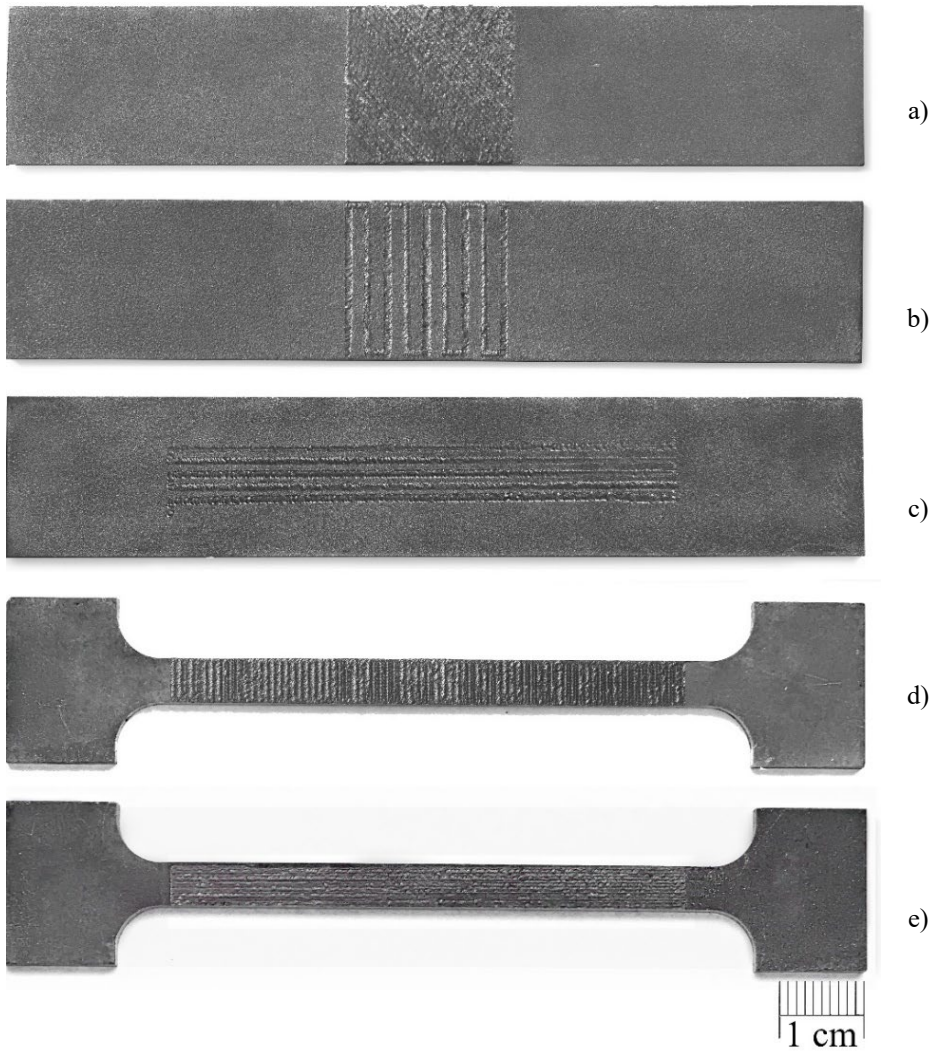


Fig. 3.4. General view of laser-treated samples: (a) Ex3 Case II C; (b) Ex3 Case IV B; (c) Ex4 Case III A before cutting; (d) Ex4 Case II B; (e) Ex4 Case IV C after cutting

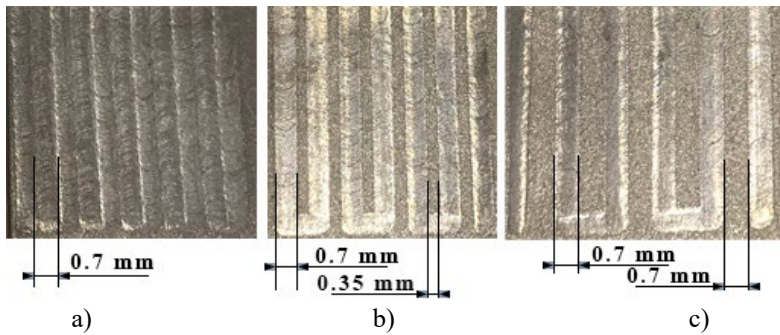


Fig. 3.5. General view of laser-treated area: (a) Ex1 Case II A, (b) Ex1 Case II B, (c) Ex1 Case II C

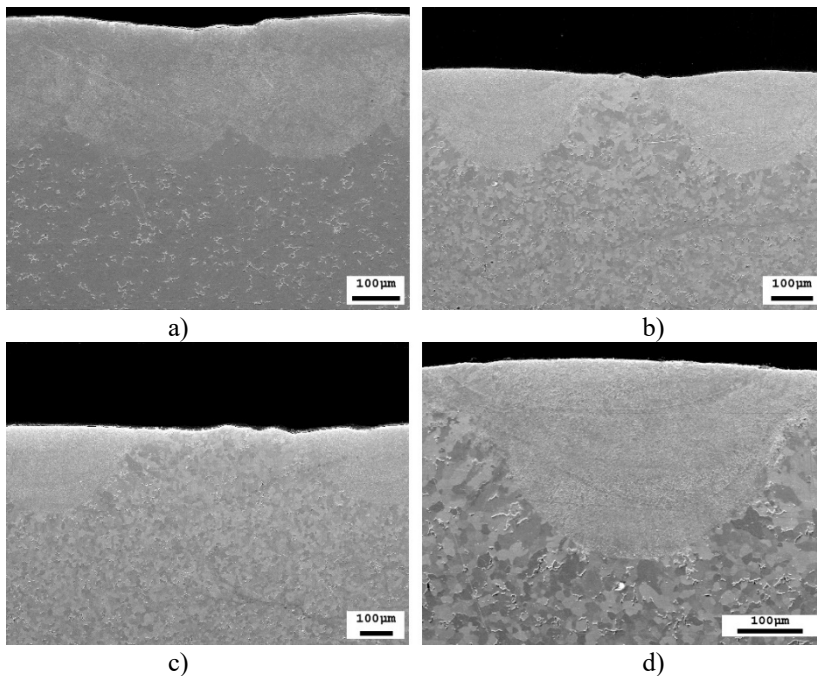


Fig. 3.6. Cross-section view of laser-treated area: (a) Ex1 Case II A; (b) Ex1 Case II B; (c) Ex1 Case II C; (d) shape of a separate laser track

Furthermore, an additional tool to study the phase composition was a microscopic analysis technique using reagents for color etching. Each method confirmed the presence of a sorbite structure (brown or dark brown color) and the absence of a harder bainite structure (blue or grey color) in the laser-treated area. The results of color microstructure treatment are summarized in Fig. 3.7.

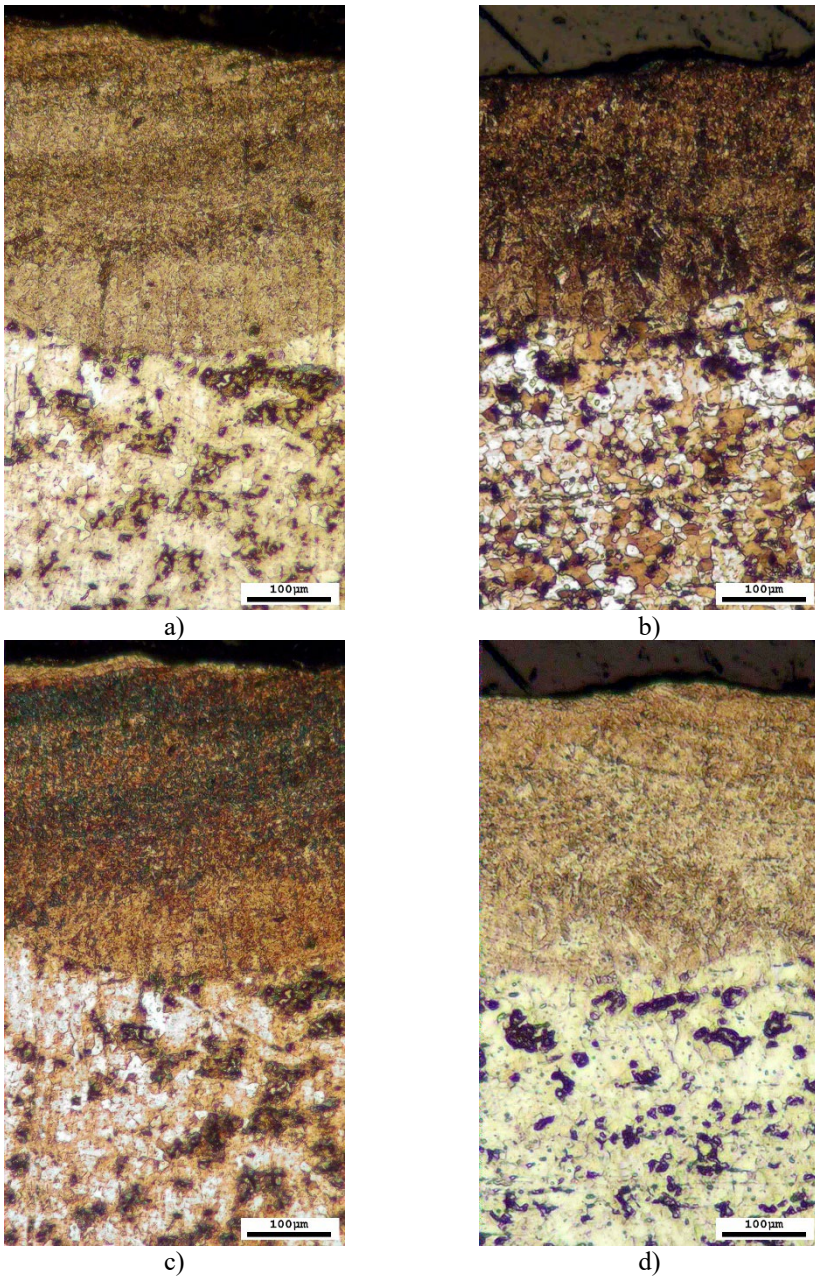


Fig. 3.7. Microstructure after color treatment. (a) A solution; (b) B solution; (c) C solution; (d) D solution

3.2.2. Scanning electron microscopy analysis

The scanning electron microscopy (SEM) analysis of metallographic cross-sections shows that local laser processing of sheet steels 1.1151 (EN 10083-2:2006) and 1.0402 (EN 10250-2:2022) causes local changes in their microstructure.

The structure of the steel crystal lattice in the heated and remelted zones is modified, turning from ferrite-pearlite structure (characteristic of steels 1.1151 (EN 10083-2:2006) and 1.0402 (EN 10250-2:2022) after tempering or normalizing) into a sorbite structure, i.e., ferrite-cementite mixture, which has more fine texture than pearlite, as shown in Fig. 3.8. Grain size in the treated zone decreased from G8 (average grain diameter about 20 μm) to G11 (average grain diameter about 7 μm).

The SEM analysis of laser-treated steel samples of 1.1151 (EN 10083-2:2006) and 1.0402 (EN 10250-2:2022) shows that the measured distance between the lamellae in the obtained dispersed sorbite structure is less than 0.3 micrometers. This distance is typical for sorbite because pearlite has a distance between lamella of about 0.6–0.7 μm , troostite about 0.1 μm , martensite and bainite about 0.2 μm , and the thickness of retained austenite lamellae is 0.05–0.2 μm (Gulyaev, 1986, p. 544; Vorobeva et al., 2013).

In general, sorbite is formed during the accelerated cooling of decomposing austenite in the temperature range of 600–700 $^{\circ}\text{C}$ or during the tempering of martensite.

The sorbite structure of the laser-treated layer was formed due to the applied high overlap coefficient of laser spots, with inevitable additional heating and partial remelting of the crystallized pool during the next laser pulse. This effect allows the cooling rate of the melted pool to be reduced and prevents the formation of more brittle quenched structures in the laser-treated layer.

The sorbite structure has many advantages in this case since it has a finer texture and higher dispersity and stiffness than pearlite. This increases the strength and wear resistance of the laser-treated metal parts without loss in plasticity, which is typical for hard and brittle quenching (martensite or bainite) microstructure (Aronovich & Lahtin, 1952).

No hard and brittle quenching structures or other undesirable inclusions and internal defects were formed in the laser-treated (remelted) layer or along the edge of melted zones, as shown in Figs. 3.9 and 3.10.

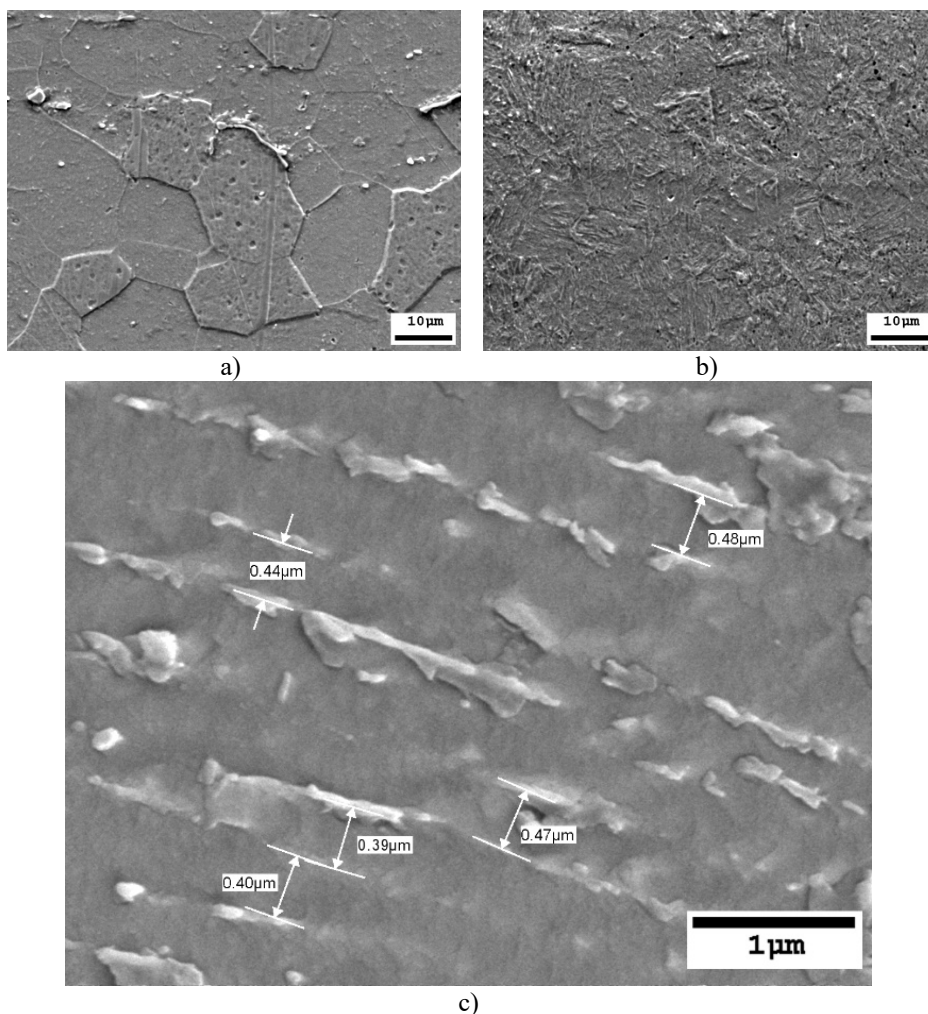


Fig. 3.8. Microstructure of steel: (a) laser-untreated area of steel with ferrite-pearlite structure (65% ferrite and 35% pearlite according to GOST 8233-56 ("Microstructure standards" 1956), grain size G8 according to ISO 643:2012 ("Steel – Micrographic determination of the apparent grain size" 2012), magnification $\times 1500$); (b) laser-treated layer (dispersed sorbite structure, grain size G11 according to ISO 643:2012 ("Steel – Micrographic determination of the apparent grain size" 2012), magnification $\times 1500$); (c) laser-treated layer (dispersed sorbite structure, according to GOST 8233-56 ("Microstructure standards" 1956), magnification $\times 20000$)

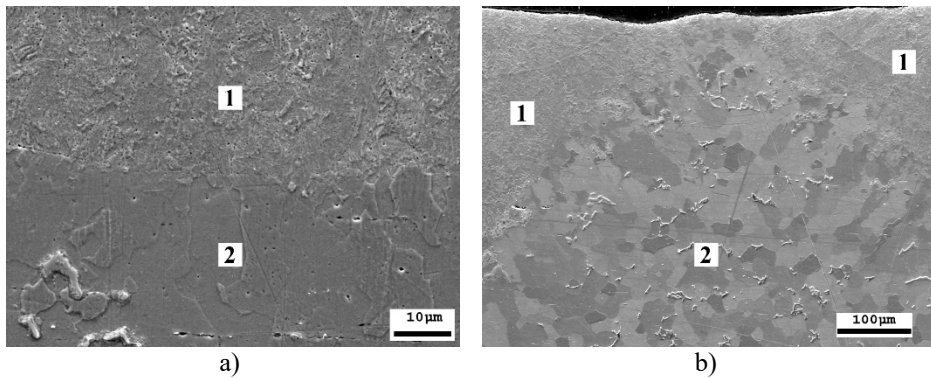


Fig. 3.9. Microstructure of the transition zone: (a) magnification $\times 1000$; (b) magnification $\times 250$; (1) surface layer after laser processing, (2) laser-untreated zone

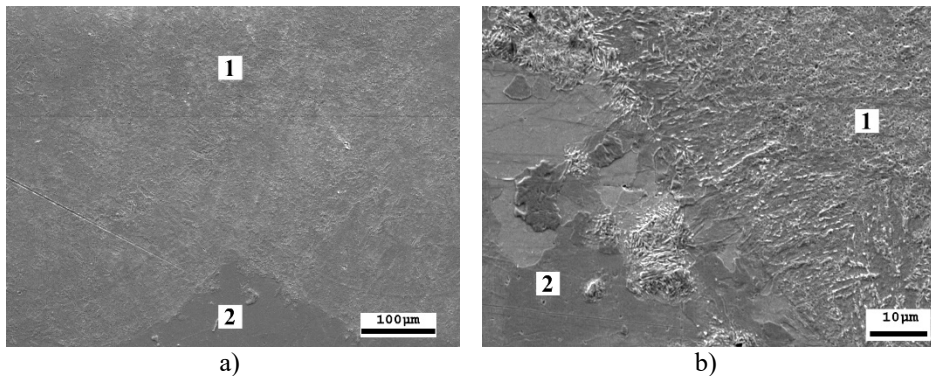


Fig. 3.10. Microstructure in the zone of overlapping individual tracks: (a) magnification $\times 250$; (b) magnification $\times 1000$; (1) surface layer after laser processing, (2) laser-untreated zone

Results of chemical element distribution in the treated (remelted) layers showed no significant chemical heterogeneity in this area. SEM-EDS element mapping, line scan, and point analysis of the distribution and concentration of chemical elements showed that the distributions of C, Mn, and Si are fairly uniform across the sample. This uniform distribution of the chemical elements and the homogeneous structure of the remelted layer can positively influence the mechanical properties of the laser-treated layers and the entire sheet. The results of SEM-EDS analysis are summarized in Figs. 3.11 and 3.12, and Table 3.3.

Table 3.3. Chemical compositions (by energy-dispersive X-ray spectroscopy analysis) of regions 1 and 2, Figs. 3.11 and 3.12)

Material	Region	Chemical Elements, wt%				
		C	Fe	Si	Mn	Other
1.1151	Laser-treated layer	3.52	95.20	0.33	0.39	0.56
	Base metal	2.31	96.50	0.33	0.40	0.46
1.0402	Laser-treated layer	1.49	97.28	0.20	0.42	0.61
	Base metal	1.13	97.67	0.21	0.43	0.56

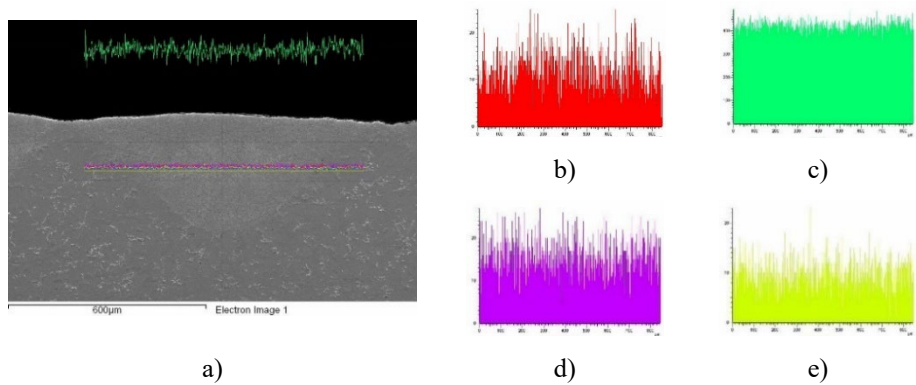


Fig. 3.11. Line scan element analysis along the surface of laser-treated layer: (a) place of line scan in cross-section of layer; (b) C distribution; (c) Fe distribution; (d) Si distribution; (e) Mn distribution

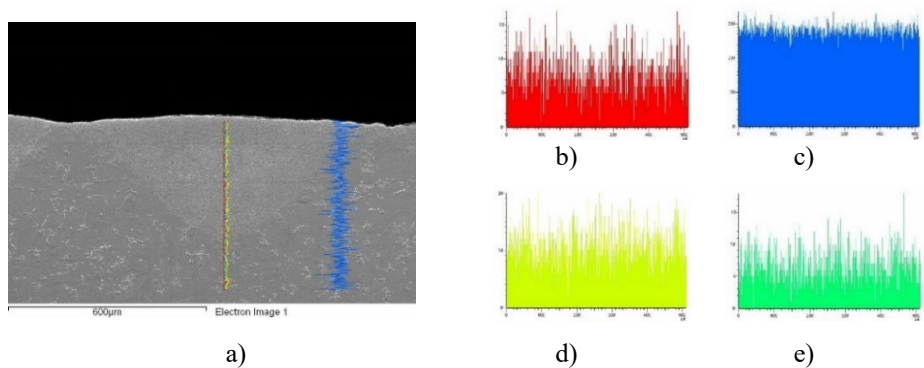


Fig. 3.12. Line scan element analysis normal to the laser-treated surface: (a) place of line scan in cross-section of layer; (b) C distribution; (c) Fe distribution; (d) Si distribution; (e) Mn distribution

3.2.3. X-ray diffraction analysis

According to the X-ray Diffraction (XRD) data analysis which is presented in Table 3.3, the X-ray diffraction pattern of the laser-treated layer is typical for the ferrite microstructure family (including sorbite and troostite) with BCC crystal structure.

The only diffraction peaks are those related to α -Fe that dominate in the XRD patterns of basic metal and the laser-treated area. Low-intensity diffraction peaks were assigned to SiC refractories and iron oxides (FeO , Fe_3O_4). These component traces remained on the analyzed surface after the surface polishing procedure.

The Fe_3C peak and other carbide peaks were not observed. Typically, the carbon content in steel is low or peak sensitivity is below the limit of sensitivity detection. Therefore, XRD analysis confirms only that there is no unstable retained austenite in the laser-treated area because the austenite has the FCC crystal structure and other XRD diffraction peaks. In low-carbon steel, high-retained austenite contents are usually found together with the martensite or bainite phase in the quenched steel after cooling (Figs. 3.13 and 3.14).

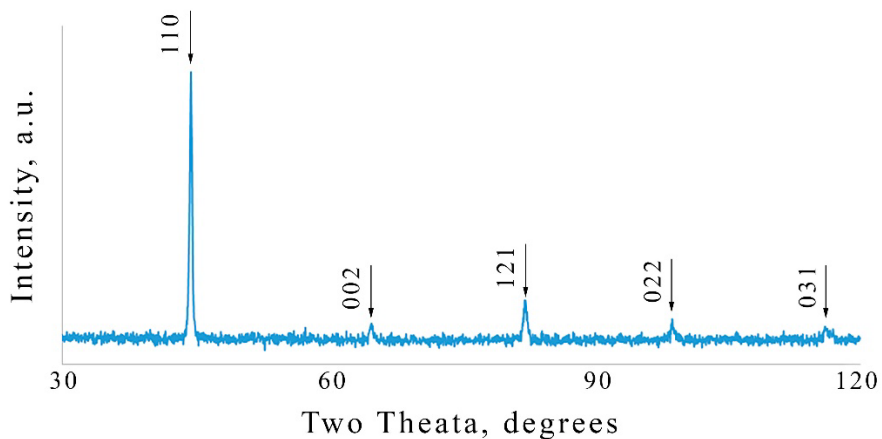


Fig. 3.13. XRD pattern of the laser-treated layer of steel 1.0402

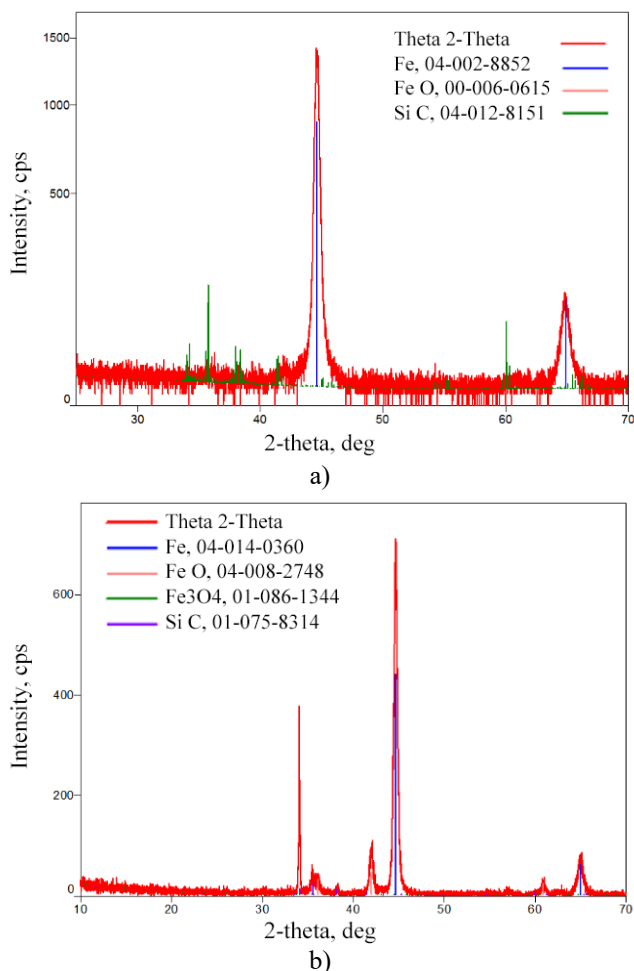


Fig. 3.14. XRD pattern of the laser-treated layer steel 1.1151: (a) surface of the basic metal; (b) area of the laser-treated layer

3.2.4. Mossbauer spectroscopy

Results of Mössbauer spectroscopy applied to the samples of laser-treated surfaces study showed Fe as the main phase. A comparison with the standard spectrum (isotropic iron ⁵⁷Fe) is also shown in Fig. 3.15. The concentration of other phases (carbides) in the laser-treated sample is under the measurement error (2%). Therefore, Mössbauer spectroscopy confirms only that there is no unstable retained austenite or martensite, or bainite phase in the laser-treated area.

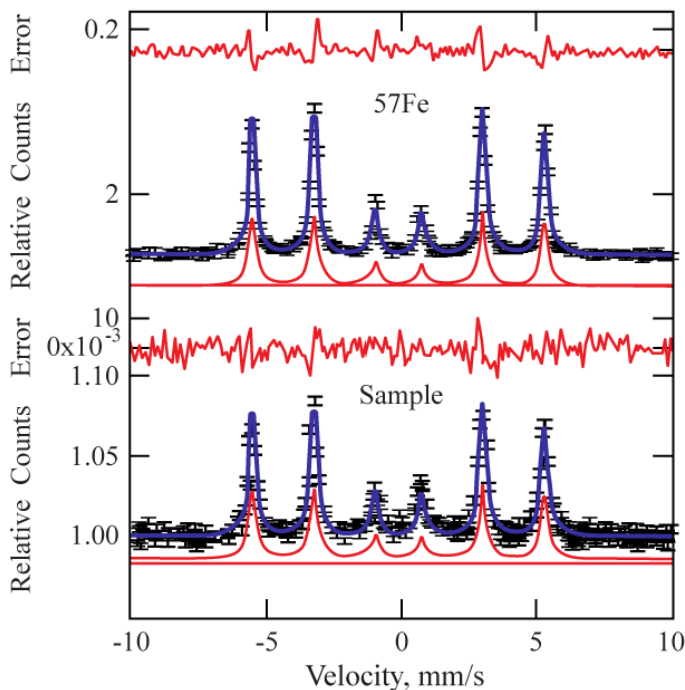


Fig. 3.15. The Mossbauer pattern of the laser-treated layer of steel 1.1151

3.2.5. Analysis of the temperature-time and continuous cooling transformation diagrams

The TTT and CCT diagrams, which are presented in Figs. 3.16 and 3.17 show that at low cooling rates (below $10\text{ }^{\circ}\text{C/s}$), only diffusion decomposition of austenite occurs in such steel samples with the formation of a ferrite-cementite structure of varying degrees of dispersion (perlite, sorbite, troostite). An increase in the cooling rate suppresses the pearlite transformation, and in this case, austenite undergoes decomposition with the formation of bainite (above $10\text{ }^{\circ}\text{C/s}$). This is an area of intermediate transformation since this transformation does not go through to the end, and therefore, after cooling, other phases will be present along with bainite (including residual austenite). According to the analysis results of the obtained diagrams, the most preferred method of laser-treated surface cooling can be in the air or using a jet of compressed air (or protective gas) since these cooling media provide the cooling rate necessary for the formation of a sorbite structure (about $10\text{ }^{\circ}\text{C/s}$).

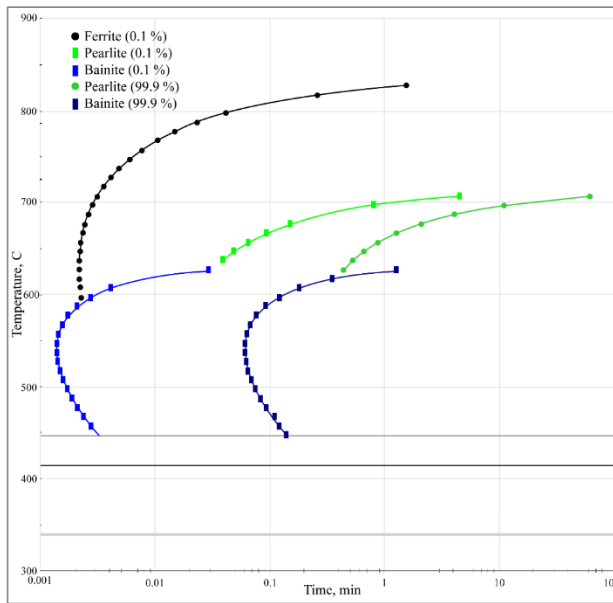


Fig. 3.16. TTT diagram of steel (1.0402 and 1.1151)

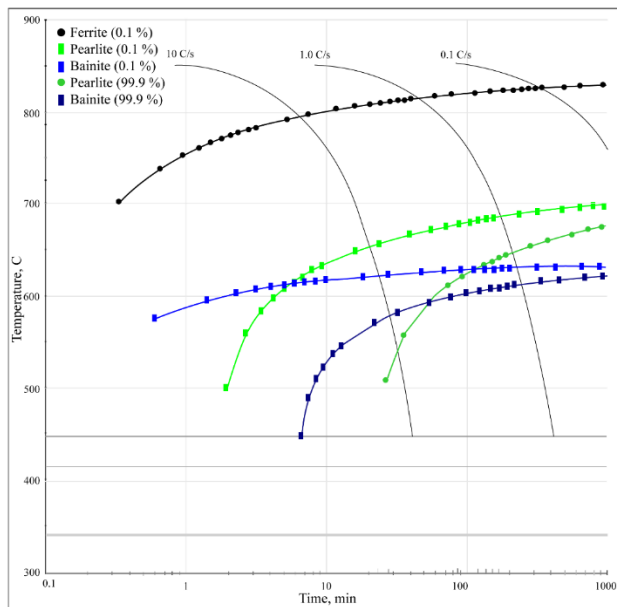


Fig. 3.17. CCT diagram of steel (1.0402 and 1.1151)

3.3. Mechanical properties testing

The mechanical properties testing of the laser-treated steel thin sheets determine the range of usefulness that can be expected from the material. Mechanical properties testing provides information on strength, ductility impact resistance, hardness, and fracture toughness. The mechanical bending tests in different conditions (applying different distances between supports) are performed using a three-point bending device. Additional tensile tests were carried out. The results of mechanical testing are presented below.

3.3.1. Hardness testing

The presence of the sorbite and the absence of hard and brittle quenching structures were also confirmed by measurements of microhardness on metallographic sections, as shown in Figs. 3.18 and 3.19. The measured hardness of the laser-treated layers corresponds to the typical hardness of sorbite, which must be in the range of 200–300 HV (Jianjun et al., 2019).

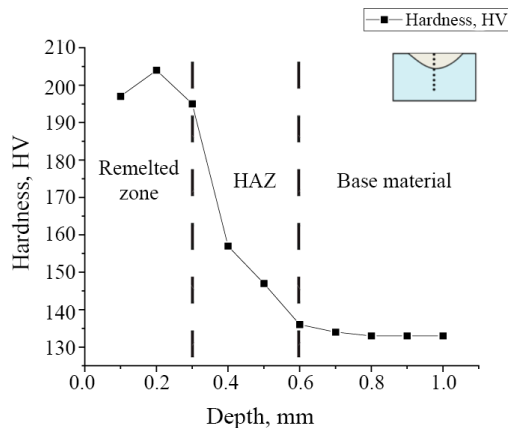


Fig. 3.18. Microhardness distribution in the laser-treated layer

The Vickers microhardness measurements show the hardness of the affected layer increases as follows:

- 1) up to 50% (up to 205 HV) compared to the laser-untreated zone, where hardness did not exceed 135 HV for steel 1.1151 (EN 10083-2:2006), as shown in Fig. 3.18.
- 2) up to 34% (up to 200 HV) compared to the laser-untreated zone, where hardness did not exceed 149 HV for steel 1.0402 (EN 10250-2:2022), as shown in Fig. 3.19.

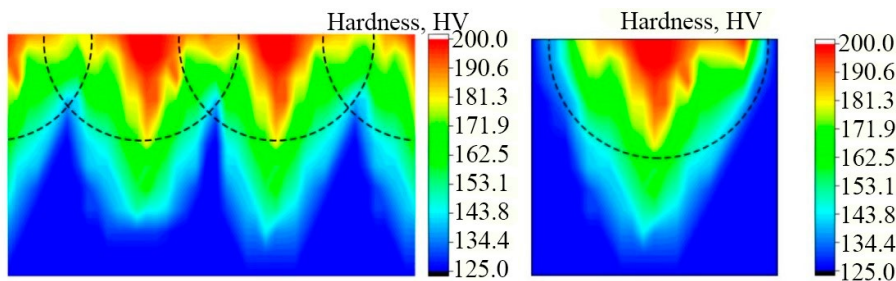


Fig. 3.19. Hardness distribution of the sample (cross-section of sample Ex1 Case IIA)

The hardness in the overlapping area of the tracks is very similar to the hardness in the middle of the laser-treated area, which was in the range of 195–205 HV. According to the hardness measurement results, there are no hard and brittle bainite and martensite microstructures in laser-treated areas, or their proportion is very low because such quenching microstructures have the highest hardness: bainite of about 400 HV and martensite of above 450 HV (Smallman & Ngan, 2014; Bkadeshia & Honeycombe, 2017). Consequently, to achieve the hardness of about 200 HV, it is necessary to have at least 25% of bainite or martensite structure in the present low-carbon steel after rapid cooling of the microstructure of the melted area. Otherwise, the microstructure of this steel sample should be strengthened by refining the grain size and creating a finely dispersed perlite (sorbite, troostite) structure.

3.3.2. Bending tests

The mechanical bending tests in different conditions (applying different distances between supports) showed that local laser processing increases the load required to reach the same level of deflection of laser-treated samples compared to untreated ones. Results of mechanical bend tests of steel samples are summarized in Figs. 3.20–3.22, and Table 3.4.

The experimental data confirmed that the strengthening and total resistance of the samples to bending are influenced by the position of the laser-treated area, the distance between laser tracks, the volume of the hardened phase, and its ratio to the volume of laser-untreated material in the area of maximum stress from the applied load.

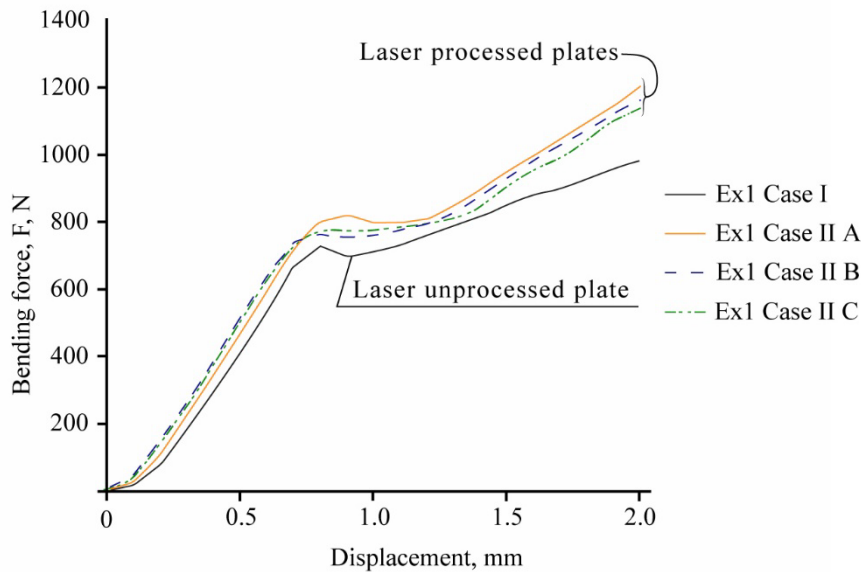


Fig. 3.20. Results of the bending test of one-side laser-treated 1.1151 steel sheet when the distance between supports is 40 mm for Ex1

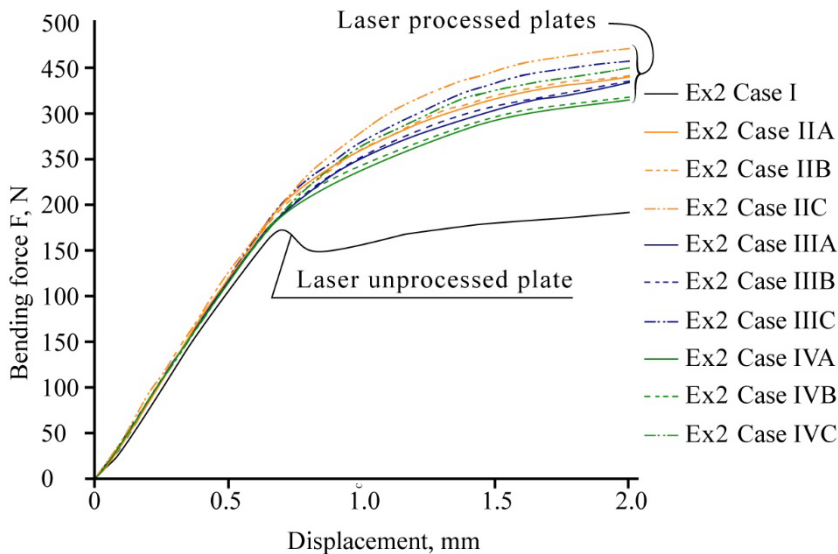


Fig. 3.21. Results of the bending test of 1.0402 steel sheet laser-treated on one side and both sides when the distance between supports is 70 mm for Ex2

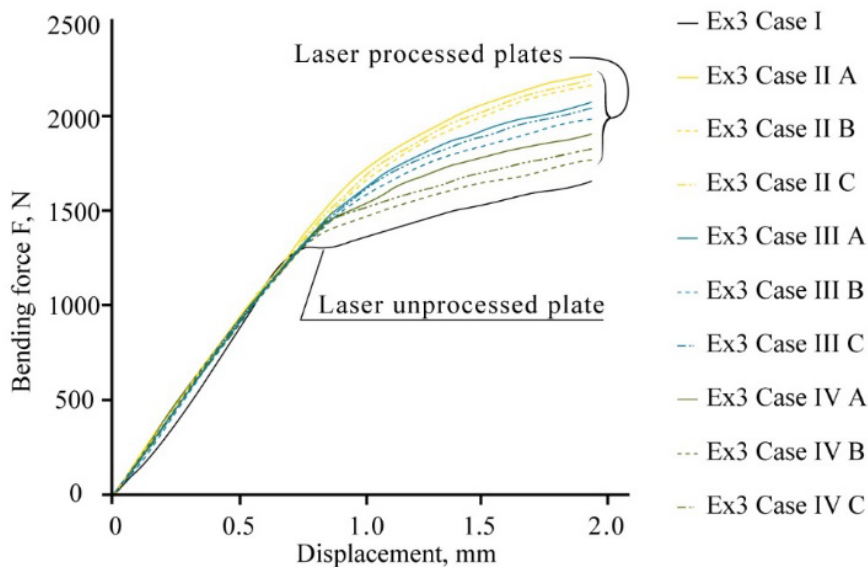


Fig. 3.22. Results of the bending test of 1.0402 steel sheet laser-treated on one side and both sides when the distance between supports 14 mm for Ex3

Table 3.4. Results of mechanical bend tests of steel samples

Experiment name	Maximum applied load at the deflection of 2 mm, N	Experiment name	Maximum applied load at the deflection of 2 mm, N
Ex1 Case I	986	Ex2 Case IV B	423
Ex1 Case II A	1206	Ex2 Case IV C	455
Ex1 Case II B	1167	Ex3 Case I	1690
Ex1 Case II C	1142	Ex3 Case II A	2263
Ex2 Case I	296	Ex3 Case II B	2209
Ex2 Case II A	445	Ex3 Case II C	2237
Ex2 Case II B	447	Ex3 Case III A	2113
Ex2 Case II C	475	Ex3 Case III B	2024
Ex2 Case III A	439	Ex3 Case III C	2083
Ex2 Case III B	440	Ex3 Case IV A	1943
Ex2 Case III C	463	Ex3 Case IV B	1804
Ex2 Case IV A	421	Ex3 Case IV C	1864

The maximum bending load to reach the limit of deflection in the elastic stage varies based on the applied variant of laser processing. For example, in the case

of one-side laser processing of 1.1151 (EN 10083-2:2006) steel sheet and bending testing with a distance of 40 mm between supports, the experimental bending load, F_{exp} , increases depending on the laser-treated case. For 0.5 mm deflection, the F_{exp} increases from 3% up to 27%, for 1.0 mm deflection, F_{exp} increases from 29% up to 48%, for 1.5 mm deflection, F_{exp} increases from 32% up to 55%, and for 2.0 mm deflection, F_{exp} increases from 30% up to 52%. Therefore, this data confirmed the possibility of increasing the bending load by using the laser-treated processing technology proposed in this dissertation.

3.3.3. Tensile test

The mechanical tensile tests showed that local laser processing increases the load required for sample destruction of laser-treated samples compared to untreated ones. Results of mechanical tensile tests of steel samples are summarized in Fig. 3.23 and Table 3.5.

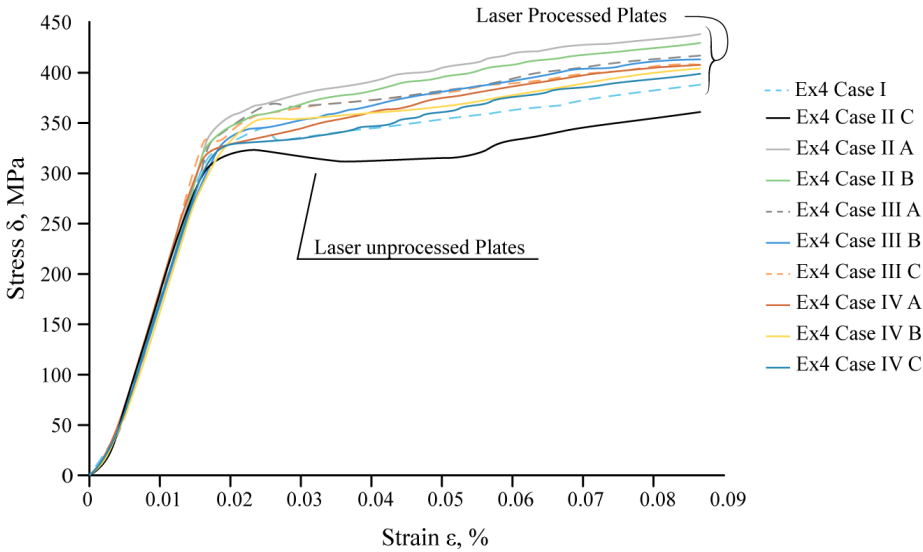


Fig. 3.23. Results of the tensile tests

Table 3.5. Results of the tensile tests of steel samples

Name of the specimen	Max. Deformation of all samples, mm	Maximum applied load for destruction, N	Deformation in the area L_0 , mm	Relative elongation δ , %
Ex4 Case I	18	4008	18	18
Ex4 Case II A	15	4145	15	15
Ex4 Case II B	9	4223	9	9
Ex4 Case II C	4	4385	4	4
Ex4 Case III A	10	4263	10	10
Ex4 Case III B	6	4260	6	6
Ex4 Case III C	5	4335	5	5
Ex4 Case IV A	10	4265	10	10
Ex4 Case IV B	8	4280	8	8
Ex4 Case IV C	7	4305	7	7

The experimental data confirmed that the total resistance of the samples to destruction is influenced by the position of the laser-treated area, the distance between laser tracks, the volume of the hardened phase, and its ratio to the volume of laser-untreated material.

The maximum tensile load to reach the destruction of the sample varies based on the applied variant of laser processing. In the case of 45° reinforcing ribs with an overlap (Ex4 Case II C), an additional 9% load should be applied compared to the overlapping vertical ribs (Ex4 Case II B) and an additional 5% load compared to the untreated sheet (Ex4 Case I).

3.4. Laser processing and sample deformation simulation

The FEA software is used to reduce the number of physical prototypes and experiments and optimize the methodology of local surface treatment of thin-walled metal products made of household non-alloy structural steel with a carbon concentration of up to 0.3%. The results of laser processing and sample deformation simulation are presented below.

3.4.1. Heat transfer during the laser processing

As a result of modeling heat distribution during laser processing, it was found that the shape of the molten core and the achieved penetration depth is very close to those obtained during the experiments. By using the laser processing parameters,

the penetration depth is about 0.35 mm and the width is 0.7 mm. The width of the zone of thermal influence (in the area of blueness, where the temperature is above 320 °C) under such laser processing modes can be in the range of up to 3.4 mm. Modeling results have been confirmed on real equipment using an infrared thermal camera Optris PI450i, as shown in Fig. 3.24.

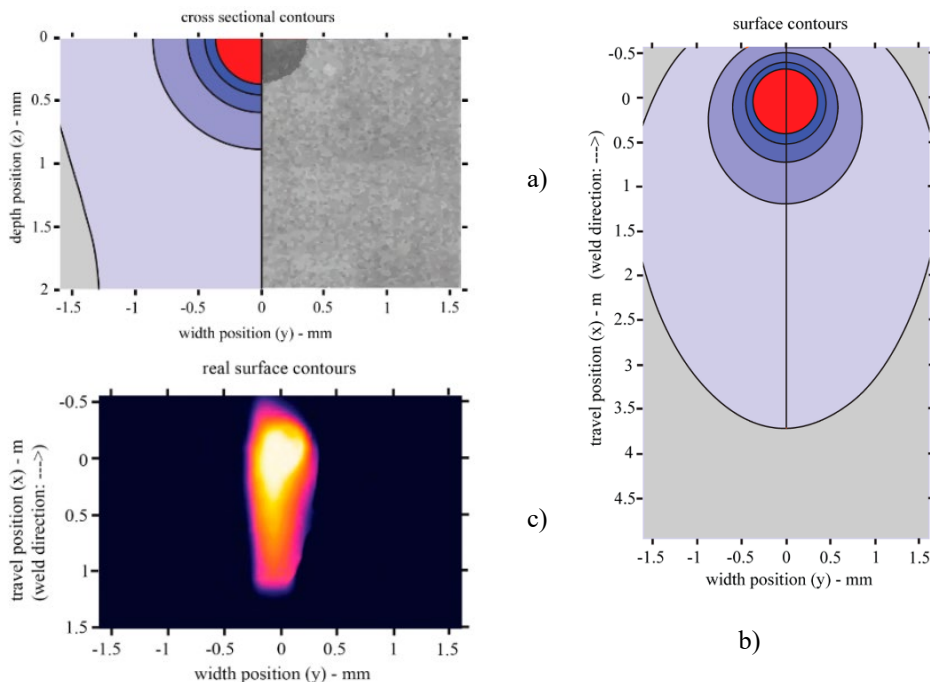


Fig. 3.24. Heat transfer during laser welding: (a) a cross-section view of the model and a comparison of the model and the real melted pool; (b) a top view of the model; (c) a top view from the Optris Infrared Camera PI450i

3.4.2. Finite element analysis simulation of tensile and bending of thin metal sheets

By simulating the processes of bending differently treated samples by the finite element method, the necessary data were obtained for comparative analysis and elucidation of the effectiveness of laser processing. Not only the processes of tensile and bending of differently treated samples by the finite element method were modeled, but also various loading conditions by changing the distance between the supports (from 14 to 70 mm). The distance between supports of 14 mm corresponded to bending conditions according to LST EN ISO 7438, while larger spacings were used to simulate shell structure deflection conditions from

random concentrated transverse loads. As a result, the necessary data were obtained for comparative analysis and elucidation of the effectiveness of local laser processing.

3.4.2.1. Modeling of bending test

The simulation results of the developed models mentioned in Figs. 2.14, 2.16–2.18 were subjected to a comparative analysis of stresses and strains under different loads and deflections. In cases where large non-standard distances between supports are used, the required bending loads for samples deflection of up to 0.5, 1, 1.5, and 2 mm were determined by FEA.

Bending experiment results and calculation for Ex1 according to the rules of mixtures (Eq. 1.2) showed that the average yield strength and ultimate strength of laser-treated metal sheets increase depending on the number of laser tracks and the volume of the treated area in comparison to laser-untreated samples.

It is established that metal sheets with a 30% overlay of laser tracks have the highest mechanical strength compared to other laser processing modes. However, simulations suggest that, in practice, it is also possible to use non-continuous processing (with a certain distance between tracks) because the difference in the efficiency of such processes is negligible.

Results of bending experiments and calculation for Ex1 are summarized in Tables 3.6–3.8 and Fig. 3.25.

Table 3.6. Mechanical properties of the bent sheet form 1.1151 steel of Ex1

Characteristics	Ex1 Case I	Ex1 Case II A	Ex1 Case II B	Ex1 Case II C
Yield strength $\sigma_{0.2}$, MPa	275	298.18	290.45	284.22
Ultimate strength σ_B , MPa	450	486.38	474.25	464.47

Table 3.7. Results of computer simulation of the elastoplastic deformation in the sheets Ex1 (with 2 mm deflection)

Objects	Ex1 Case I	Ex1 Case II A	Ex1 Case II B	Ex1 Case II C
Bending strain, w, mm	2	1.98	1.99	2
Maximum von Mises equivalent stress, MPa	416	462	444	436
Bending force, F_{calc} , N	1033	1280	1217	1167

Table 3.8. Results of computer simulation of the elastic deformation in the sheets Ex1 (with a load of 700 N)

Objects	Ex1 Case I	Ex1 Case II A	Ex1 Case II B	Ex1 Case II C
Bending strain, w, mm	0.92	0.75	0.80	0.85
Maximum von Mises equivalent stress, MPa	309	323	306	299
Bending force, F_{calc} , N	700	700	700	700

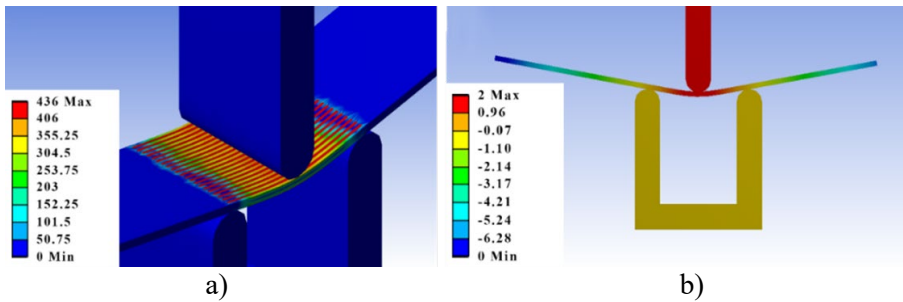


Fig. 3.25. FEA results of the bending Ex1 (when the distance between supports is 40 mm) modeling of the laser-treated 1.1151 steel sheets when the imposed vertical displacement of the sheet's middle point equals 2 mm: (a) stress distribution in a bent element; (b) strains degree of the bent element under load

As for the second series of experiments (Ex2), it was found that the maximum equivalent stress at the bent sheets depends on the volume and orientation of the laser-treated layer. The greatest increase in the required bending load and available stresses, according to the modeling results, was in the double-sided laser-treated samples, while the volume of processing was maximal (from 15.4% to 19.8% of the volume of the bent sheet part). The increased bending load required for similar deflection also depends on the orientation of the laser-treated layers. Better results were obtained in the bent samples where the zone of the laser-treated layer was subjected to tension rather than compression.

The increase in the bending force varied, depending on the sheet processing case, and deflection levels were found. For the 0.5 mm deflection, the force was larger by about 11–27%, and for the 1.0 mm deflection, it was larger by about 43–49%. This value was larger by about 32–55% for the 1.5 mm deflection and 30–52% for the 2.0 mm deflection. The increase in the maximum equivalent stresses varied according to the sheet processing case and deflection level. The maximum equivalent stresses are largest by about 13–30% for the 0.5 mm deflection, 13–

32% for the 1.0 mm deflection, 8–26% for the 1.5 mm deflection, and 8–25% for the 2.0 mm deflection.

Based results in Table 3.4, double-side laser-treated metal sheets with a 30% overlay of laser tracks had the highest resistance to bending compared to other processing modes. In this case, the orientation of the processing (rollers) is no longer of great importance. However, modeling results which are summarized in Table 3.9 and Fig. 3.26 show that it is possible to use a non-continuous laser with either one-side or double-side processing with a certain distance between tracks because the difference in the efficiency of such surface processing is small. The difference of the required bending loads for one deflection level of the sheet, applied to different positions of the laser-treated layer (cases A, B, C), was less than 20%.

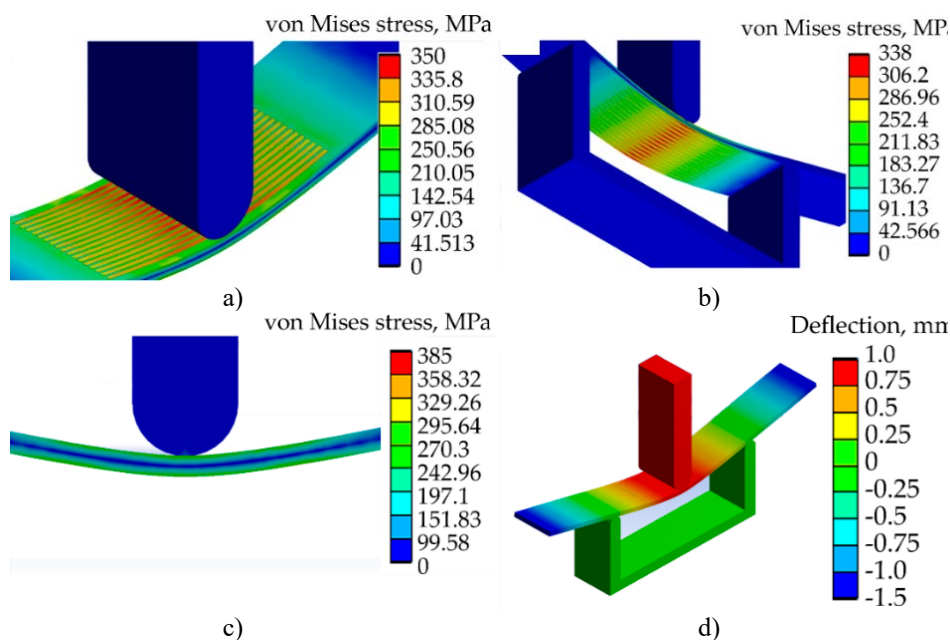


Fig. 3.26. FEA results of the bending (when the distance between supports is 70 mm) modeling of the laser-treated 1.0402 steel sheets when the imposed vertical displacement of the sheet's middle point equals 1 mm; von Mises stresses are shown in (a), (b) and (c): (a) for Ex2 Case III A; (b) for Ex2 Case IV B; (c) for Ex2 Case II C; (d) shows the deflections or vertical displacements of the sheet of Ex2 Case III A

Table 3.9. Maximum von Mises equivalent stresses [MPa] and corresponding forces F_{calc} [N] of the FEA simulation of the bending of the differently laser-treated sheets at different imposed vertical displacements $w \in \{0.5, 1.0, 1.5, 2.0\}$ mm of the middle point for Ex2

Imposed vertical displacement of the point, mm	0.5	1.0	1.5	2.0
Laser-untreated sheet Ex2 Case I				
Maximum von Mises stress, MPa	176	293	395	409
Bending force, F_{calc} , N	179	231	269	290
Laser-treated sheet Ex2 Case II A				
Maximum von Mises stress, MPa	217	369	460	468
Bending force, F_{calc} , N	215	318	390	409
Laser-treated sheet Ex2 Case II B				
Maximum von Mises stress, MPa	219	372	463	470
Bending force, F_{calc} , N	217	320	392	410
Laser-treated sheet Ex2 Case II C				
Maximum von Mises stress, MPa	228	385	497	510
Bending force, F_{calc} , N	228	345	417	442
Laser-treated sheet Ex2 Case III A				
Maximum von Mises stress, MPa	209	350	431	460
Bending force, F_{calc} , N	205	311	375	394
Laser-treated sheet Ex2 Case III B				
Maximum von Mises stress, MPa	210	352	432	462
Bending force, F_{calc} , N	206	312	378	398
Laser-treated sheet Ex2 Case III C				
Maximum von Mises stress, MPa	223	382	485	505
Bending force, F_{calc} , N	222	334	411	428
Laser-treated sheet Ex2 Case IV A				
Maximum von Mises stress, MPa	199	332	425	448
Bending force, F_{calc} , N	184	298	354	378
Laser-treated sheet Ex2 Case IV B				
Maximum von Mises stress, MPa	200	338	426	452
Bending force, F_{calc} , N	187	300	356	381
Laser-treated sheet Ex2 Case IV C				
Maximum von Mises stress, MPa	220	380	480	502
Bending force, F_{calc} , N	219	328	403	419

As for the third series of experiments (Ex3), it was found that the maximum equivalent stress at the bent sheets slightly depends on the direction of the laser-

treated layer (the maximum difference is only 11% compared to the other processing modes). The most significant increase in the required bending load and available stresses, according to the modeling results, was in the double-sided vertical laser-treated samples (by 31% compared to the laser-untreated sheet). Results of bending experiments and calculation for Ex3 are summarized in Table 3.10 and Fig. 3.27. The greatest increase in the required bending load and available stresses, according to the obtained results, was in the double-sided laser-processed samples with an overlap.

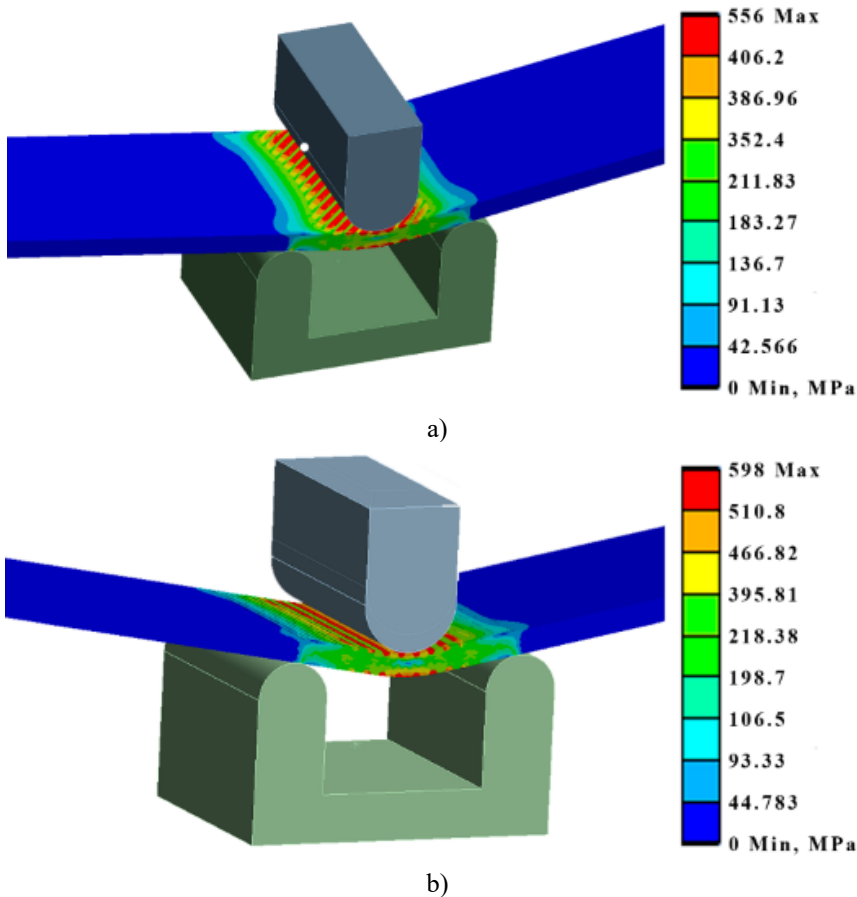


Fig. 3.27. Maximum deformations and equivalent von Mises stress in the samples: (a) equivalent stresses in the Ex3 Case III C; (b) deformations in the Ex3 Case IV B

Table 3.10. Bending modeling results. Maximum equivalent stresses and deformations of samples Ex3

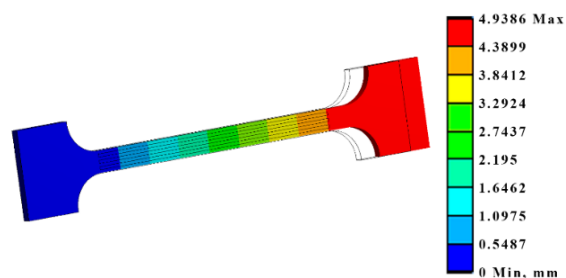
Imposed vertical displacement of the point, mm	0.5	1.0	1.5	2.0
Laser-untreated sheet Ex3 Case I				
Maximum von Mises stress, MPa	299	345	383	412
Bending force, F_{calc} , N	1446	1576	1701	1898
Laser-treated sheet Ex3 Case II A				
Maximum von Mises stress, MPa	448	493	524	559
Bending force, F_{calc} , N	1840	2005	2099	2238
Laser-treated sheet Ex3 Case II B				
Maximum von Mises stress, MPa	519	518	555	587
Bending force, F_{calc} , N	1845	2033	2171.9	2295
Laser-treated sheet Ex3 Case II C				
Maximum von Mises stress, MPa	448	502	539	569
Bending force, F_{calc} , N	1853	2036	2159	2282
Laser-treated sheet Ex3 Case III A				
Maximum von Mises stress, MPa	441	484	512	541
Bending force, F_{calc} , N	1591	1742	1852	1954
Laser-treated sheet Ex3 Case III B				
Maximum von Mises stress, MPa	455	491	521	550
Bending force, F_{calc} , N	1623	1776	1909	2030
Laser-treated sheet Ex3 Case III C				
Maximum von Mises stress, MPa	443	493	522	556
Bending force, F_{calc} , N	1584	1771	1875	1998
Laser-treated sheet Ex3 Case IV A				
Maximum von Mises stress, MPa	446	481	506	537
Bending force, F_{calc} , N	1584	1724	1820	1947
Laser-treated sheet Ex3 Case IV B				
Maximum von Mises stress, MPa	445	473	582	598
Bending force, F_{calc} , N	1524	1684	1802	1895
Laser-treated sheet Ex3 Case IV C				
Maximum von Mises stress, MPa	444	484	507	535
Bending force, F_{calc} , N	1566	1714	1814	1939

3.4.2.2. Modeling of samples' tensile test

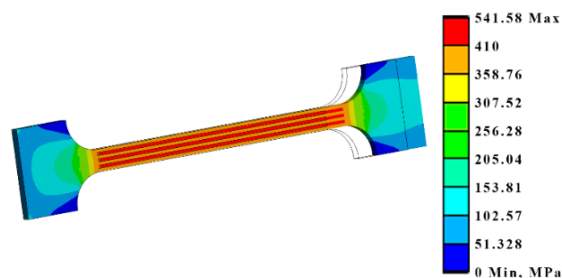
The analysis of FEA tensile testing results shows that the maximum equivalent stress and relative elongation at the tensile sheets depend on the volume and orientation of the laser-treated layer, under applying a maximal tensile force of 3750 N. The most exceptional increase in the required tensile load and available stresses, according to the modeling results, was in the double-sided laser-treated samples with the positioning of ribs at 45 degrees and an overlap, Ex4 Case II C (max deformation of the sample is only 3.33 mm, which is 1.6 times less than 5.77 mm at the base of a laser-untreated sheet), and the equivalent stress was 26% greater in Ex4 Case III C (558.24 MPa compared to the laser-untreated sheet 410.57 MPa). Tensile modeling results are summarized in Table 3.11 and Fig. 3.28.

Table 3.11. Tensile modeling results. Maximum equivalent stresses and deformations of samples Ex4

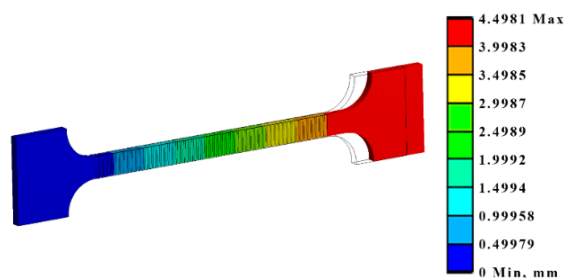
Name of the specimen	Max. deformation of all samples, mm	Max. equivalent stress, MPa	Deformation in the area L_0 , mm	Relative elongation δ , %
Ex4 Case I	5.77	410.57	5.56	9.3
Ex4 Case II A	3.91	525.26	3.72	6.2
Ex4 Case II B	3.54	523.05	3.35	5.6
Ex4 Case II C	3.52	532.83	3.33	5.6
Ex4 Case III A	4.66	540.12	4.46	7.4
Ex4 Case III B	4.49	545.4	4.30	7.2
Ex4 Case III C	5.28	558.04	5.07	8.4
Ex4 Case IV A	4.93	541.58	4.74	7.9
Ex4 Case IV B	4.83	539.14	4.63	7.7
Ex4 Case IV C	5.76	411.5	5.56	9.3



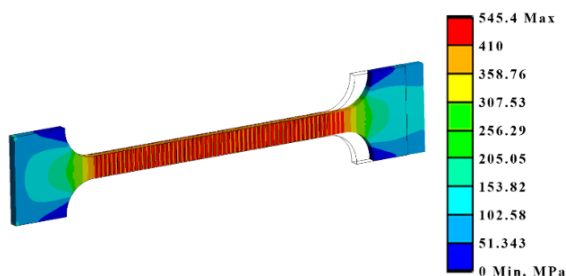
a)



b)



c)



d)

Fig. 3.28. Maximum deformations and equivalent von Mises stresses in the samples:
 (a) deformations in the Ex4 Case IV A; (b) equivalent von Mises stress in the Ex4 Case IV A; (c) deformations in the Ex4 Case III B; (d) equivalent von Mises stress in the Ex4 Case III B

3.4.3. Comparison of the experimental and modeling results

In this study, comparisons between the experimental and modeling results of the samples of thin-sheet non-alloy steels are made, which were untreated or laser-treated (by using different parameters described in previous chapters). A comparison of the experimental and modeling results are presented below.

3.4.3.1. Comparison of the experimental and modeling results of bending of samples

The FEA model was validated by comparing bending test results with the results of the real samples. Experimental results and deflection simulation results of laser-untreated samples were compared with the results of samples treated, applying different distances between laser tracks, different positions of laser tracks, and different lengths between supports. Detailed comparison of results of mechanical bend tests and computational modeling are summarized in Tables 3.12–3.15.

Table 3.12. Detailed comparison of results of mechanical bend tests and computational modeling Ex1

Deflection of samples of 0.5 mm				
Objects	Ex1 Case I	Ex1 Case II A	Ex1 Case II B	Ex1 Case II C
Calculated bending force, N	431	572	550	519
Measured bending force, N	417	560	531	511
Difference, %	3.24	2.09	3.45	1.54
Deflection of samples of 1 mm				
Objects	Ex1 Case I	Ex1 Case II A	Ex1 Case II B	Ex1 Case II C
Calculated bending force, N	732	808	798	776
Measured bending force, N	713	801	777	761
Difference, %	2.59	0.86	2.63	1.93
Deflection of samples of 1.5 mm				
Objects	Ex1 Case I	Ex1 Case II A	Ex1 Case II B	Ex1 Case II C
Calculated bending force, N	875	979	963	954
Measured bending force, N	852	950	936	909
Difference, %	2.62	2.96	2.81	4.71

End of Table 3.12

Deflection of samples of 2 mm				
Objects	Ex1 Case I	Ex1 Case II A	Ex1 Case II B	Ex1 Case II C
Calculated bending force, N	1033	1280	1217	1167
Measured bending force, N	986	1206	1167	1142
Difference, %	4.54	5.78	4.11	2.14

Table 3.13. Detailed experimental and modeled bending forces F_{exp} and F_{calc} , respectively, and their relative differences at different deflections w of Ex2

Bending forces, F_{exp} , F_{calc} and relative differences $d_{F,r} = (F_{exp} - F_{calc})/F_{calc}$	Ex2 Case I	Ex2 Case II A	Ex2 Case II B	Ex2 Case II C	Ex2 Case III A	Ex2 Case III B	Ex2 Case III C	Ex2 Case IV A	Ex2 Case IV B	Ex2 Case IV C
Deflection, 0.5 mm										
F_{exp} , N	200	226	228	242	220	221	236	209	211	230
F_{calc} , N	179	215	217	228	205	206	222	184	187	219
$d_{F,r}$, %	12	5	5	6	7	7	6	13	13	5
Deflection, 1 mm										
F_{exp} , N	261	365	368	387	352	356	376	333	336	370
F_{calc} , N	231	318	320	345	311	312	334	298	300	328
$d_{F,r}$, %	13	15	15	13	13	14	13	12	12	13
Deflection, 1.5 mm										
F_{exp} , N	282	425	426	455	412	413	437	402	403	431
F_{calc} , N	269	390	392	417	375	378	411	354	356	403
$d_{F,r}$, %	5	9	9	9	10	9	6	13	13	7
Deflection, 2 mm										
F_{exp} , N	296	445	447	475	439	440	463	421	423	455
F_{calc} , N	290	409	410	442	394	398	428	378	381	419
$d_{F,r}$, %	2	9	9	7	11	10	8	11	11	9

Table 3.14. Detailed comparison of results of mechanical bend tests and computational modeling Ex3

Bending forces, F_{exp} , F_{calc} and relative differences $d_{F,r} = (F_{exp} - F_{calc})/F_{calc}$	Ex3 Case I	Ex3 Case II A	Ex3 Case II B	Ex3 Case II C	Ex3 Case III A	Ex3 Case III B	Ex3 Case III C	Ex3 Case IV A	Ex3 Case IV B	Ex3 Case IV C
Deflection, 0.5 mm										
F_{exp} , N	1325	1760	1696	1745	1497	1569	1495	1517	1444	1493
F_{calc} , N	1446	1840	1845	1853	1591	1623	1584	1584	1524	1566
$d_{F,r}$, %	9	4	9	6	6	3	6	4	6	5
Deflection, 1 mm										
F_{exp} , N	1481	2029	1923	1991	1608	1658	1712	1686	1623	1607
F_{calc} , N	1576	2005	2033	2036	1742	1776	1771	1724	1684	1714
$d_{F,r}$, %	6	1	6	2	8	7	3	2	4	7
Deflection, 1.5 mm										
F_{exp} , N	1530	2145	2088	2042	1659	1744	1800	1798	1708	1723
F_{calc} , N	1701	2099	2171	2159	1852	1909	1875	1820	1802	1814
$d_{F,r}$, %	11	2	4	6	12	9	4	1	5	5
Deflection, 2 mm										
F_{exp} , N	1690	2263	2209	2237	2113	2024	2083	1943	1804	1864
F_{calc} , N	1898	2238	2295	2282	1954	2030	1998	1947	1895	1939
$d_{F,r}$, %	12	1	4	2	8	0.3	4	0.2	5	4

Table 3.15. Comparison of all obtained results of mechanical bend tests and computational modeling at 2 mm

Name of the specimen	Calculated bending force, N	Measured bending force, N	Difference, %
Ex1 Case I	1033	986	4.54
Ex1 Case II A	1280	1206	5.78
Ex1 Case II B	1217	1167	4.11
Ex1 Case II C	1167	1142	2.14
Ex2 Case I	290	296	2.07
Ex2 Case II A	409	445	8.8
Ex2 Case II B	410	447	9.02
Ex2 Case II C	442	475	7.46
Ex2 Case III A	394	439	11.42
Ex2 Case III B	398	440	10.55
Ex2 Case III C	428	463	8.17
Ex2 Case IV A	378	421	11.37
Ex2 Case IV B	381	423	11.02
Ex2 Case IV C	419	455	8.59
Ex3 Case I	1898	1690	12.31
Ex3 Case II A	2238	2263	1.11
Ex3 Case II B	2295	2209	3.89
Ex3 Case II C	2282	2237	2.01
Ex3 Case III A	1954	2113	8.13
Ex3 Case III C	2030	2024	0.29
Ex3 Case III B	1998	2083	4.25
Ex3 Case IV A	1947	1943	0.2
Ex3 Case IV B	1895	1804	5.04
Ex3 Case IV C	1939	1864	4.02

3.4.3.2. Comparison of the experimental and modeling tensile results

The FEA model was validated by comparing the results of tensile tests with the results of the real samples. Experimental results and tensile simulation results of laser-untreated samples were compared with the results of samples treated, applying the maximum force to break the specimens in real experiments and the maximal applied force of 3750 N at FEA modeling. A comparison of all obtained results of mechanical tensile tests and computational modeling is summarized in Table 3.16 and Fig. 3.29. The values of the maximum equivalent stresses can be determined as preliminary and cannot be predicted very accurately due to the large error (more than 20%) between the real experiment and the modeling values. An

error could have been influenced by existing laser processing micro-defects or sample structure, or other micro-defects obtained after preparing the samples for tensile tests. The most significant increase in the required tensile load and available stresses, according to the modeling results, was in the double-sided laser-treated samples with the positioning of ribs at 45 degrees with overlay 0.35 mm Ex4 Case III C (equivalent stress is 26% greater, 558.24 MPa compared to the laser-untreated sheet 410.57 MPa).

Table 3.16. Comparison of all obtained results of mechanical tensile tests and computational modeling

Name of the specimen	Real breaking stress, MPa	Calculated breaking stress, MPa	Difference, %
Ex4 Case I	400	410.57	2.57
Ex4 Case II A	414.5	525.26	21.09
Ex4 Case II B	422.3	523.05	19.26
Ex4 Case II C	440	532.83	17.42
Ex4 Case III A	426.3	540.12	21.07
Ex4 Case III B	426	545.4	21.89
Ex4 Case III C	433.5	558.04	22.32
Ex4 Case IV A	426.5	541.58	21.25
Ex4 Case IV B	428	539.14	20.61
Ex4 Case IV C	430.5	411.5	4.41

Tensile tests have also shown that the failure of laser-hardened samples does not occur only in the center of the sample (as it should be according to the standard) but also on the border and outside the laser-treated zone. This indicates that the central zone of the sample is significantly strengthened, and an even greater force must be applied to break it. A comparison of the results of FEA simulation tensile tests (modeled by using static structural and explicit dynamics analysis systems) with real experiments shows the possibility of using a 3D model to determine the best position of the reinforcing strips.

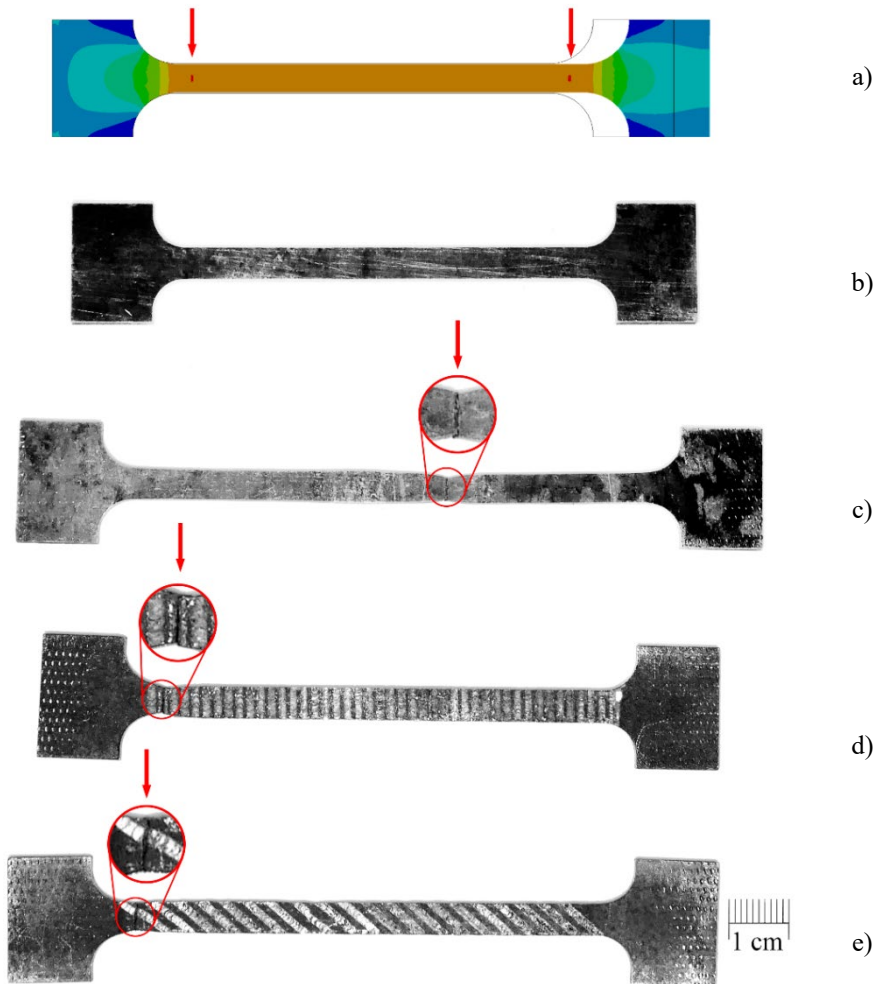


Fig. 3.29. Tensile testing results: (a) FEA modeling of Ex4 Case III B; (b) Ex4 Case I before tensile test; (c) Ex4 Case I after breaking; (d) Ex4 Case III B after breaking; (e) Ex4 Case III C after breaking

3.4.4. Analytical analysis of the axial stiffness of the laser-treated sheet

The results analysis is presented mainly in terms of relative quantities to make the analysis, discussion, and results valid not only for the particular considered cases

but also to extend the results and conclusions to other cases. Analysis of the effectiveness of various laser processing options is presented below.

3.4.4.1. Analysis of the effectiveness of various laser processing options

Fig. 3.30 shows the dependencies of the bounds of the cross-sectional area of the laser-treated metal, $A_{l,inf}$ and $A_{l,sup}$, as well as their ratios $A_l/(1/2b_lb_t)$, where $A_l \in \{A_{l,inf}, A_{l,sup}\}$ on the estimated number of laser-treated tracks, $\hat{n}_{tr}$, calculated by Eq. 2.10 or 2.14, and on the ratio d_c/d_t . The areas $A_{l,inf}$ and $A_{l,sup}$ were calculated by Eq. 2.8, 2.9, 2.11, 2.12, 2.13, and 2.14 of the sheet shown in Fig. 2.3, when the width of the laser-treated track was $d_t = 0.7$ mm and the width of the laser-treated area of the sheet under consideration was $b_l = 0.02$ m. The vertical dotted lines correspond to the minimum and maximum of $\hat{n}_{tr}$ or d_c/d_t and laser processing cases: Ex2 Case II when $d_c/d_t = 2/3$; Ex2 Case III when $d_c/d_t = 1.5$; and Ex2 Case IV when $d_c/d_t = 2$ based on data given in Table 2.8.

It should be noted that in the present calculations, the numbers of tracks, n_{tr} , for Ex2 Cases II–IV were evaluated by Eq. 2.10 or 2.14, i.e., n_{tr} was not taken from Table 2.8.

As shown in Fig. 3.30, $A_{l,inf}$ approaches $A_{l,sup}$ with increasing numbers of laser-treated tracks, $\hat{n}_{tr}$, or with a decrease in the ratio, d_c/d_t or d_c . Also, Fig. 3.12 demonstrates that the rate of area increase, $A_l \in \{A_{l,inf}, A_{l,sup}\}$, is practically constant with respect to increasing n_{tr} within the interval $n_{tr} \in [\min\{n_{tr}\}, 28, 57]$, corresponding to the interval, $d_c/d_t \in [1, \max\{d_c \setminus d_t\}]$, or when $d_c/d_t \geq 1$.

Remarkably, the rate of increase of $A_l \in \{A_{l,inf}, A_{l,sup}\}$ even increases with respect to decreasing d_c/d_t within the interval $d_c/d_t \in [\max\{d_c \setminus d_t\}, 1]$. However, as shown in Fig. 3.30, the increase in the areas $A_l \in \{A_{l,inf}, A_{l,sup}\}$ becomes slower with increasing n_{tr} or decreasing d_c/d_t or d_c at $d_c/d_t < 1$.

Finally, increasing $A_l \in \{A_{l,inf}, A_{l,sup}\}$ practically does not change at a very large $\hat{n}_{tr}$. It should be noted that the biggest difference $\max\{A_{l,sup} - A_{l,inf}\} = 0.1924$ mm², and the $(\max\{(A_{l,sup} - A_{l,inf})/A_{l,sup}\} \cdot 100 = 6.66\%)$ occurs at the largest value of the ratio $d_c/d_t = 2$, or at the smallest $\hat{n}_{tr} = 14.29$.

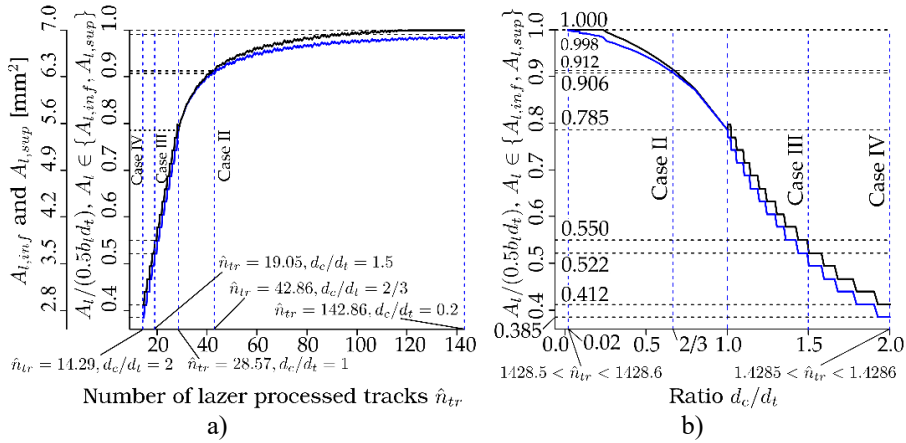


Fig. 3.30. Dependencies of the bounds of the cross-section of the laser-treated metal $A_{l,inf}$ and $A_{l,sup}$ and the ratios $A_{l,inf}/(1/2b_l d_t)$ and $A_{l,sup}/(0.5b_l d_t)$ on the number of tracks $\hat{n}_{tr}$ and ratio d_c/d_t of the considered sheet, see Fig. 2.3: (a) when $\hat{n}_{tr} \in [14.29, 142.86]$, corresponding to $d_c \in [1.4 \cdot 10^{-4}, 1.4 \cdot 10^{-3}]$ or $d_c/d_t \in [0.2, 2]$; (b) when $d_c/d_t \in [0.02, 2]$, corresponding to $d_c \in [1.4 \cdot 10^{-5}, 1.4 \cdot 10^{-3}]$ or $\hat{n}_{tr} \in [14.286, 1428.571]$

Fig. 3.13 shows the dependency of the ratio of the area of the remelted metal to the supremum bound of the area of the laser-treated metal $A_{l,rem}/A_{l,sup}$ as shown in Fig. 3.31a, and the dependency of the ratio of the overlapping area on the cross-sectional area of the single laser-treated track $A_{ov}/A_{tr,1}$ on the ratio d_c/d_t of the sheet under consideration (Fig. 2.3, where the total area of the remelted metal is calculated as follows: $A_{l,rem} = (n_{tr} - 1)A_{ov} = (b_l/d_c)A_{ov}$).

As shown in Figs. 3.31a and 3.31b, $A_{l,rem} = A_{ov} = 0$ as $d_c > d_t$ or $d_c/d_t > 1$, the rate of the increase of the ratio $A_{ov}/A_{tr,1}$ on d_c/d_t jumps sharply at $d_c/d_t = 1$, and this rate is almost constant within the interval $d_c/d_t \in [0.02, 1]$, since $A_{ov}/A_{tr,1}$ on d_c/d_t depends very similarly to the line. However, the dependence of the ratio of the total area of the remelted metal to the supremum bound of the laser-treated metal $A_{l,rem}/A_{l,sup}$ increases very slowly at $d_c/d_t = 1$, but becomes very steep with a higher ratio of d_c/d_t .

The behavior of $A_{l,rem}/A_{l,sup}$ with respect to d_c/d_t differs from $A_{ov}/A_{tr,1}$ due to the influence of the number of laser-treated tracks, n_{tr} . At relatively large d_c/d_t , the number n_{tr} is small. Therefore, the contribution of A_{ov} to $A_{l,rem}$ is also small. With decreasing d_c/d_t the number n_{tr} increases and, hence the contribution of increased A_{ov} to $A_{l,rem}$ increases also.

As shown in Fig. 3.31a, $A_{l,rem}/A_{l,sup} = 1$ as $d_c/d_t = 0.405$. Therefore, $A_{l,rem} > A_{l,sup}$ as $d_c/d_t < 0.405$, and the difference $A_{l,rem} - A_{l,sup}$ or the ratio $A_{l,rem}/A_{l,sup}$ increases very quickly with increasing $d_c/d_t \geq 1$. It should be noted that the cross-sectional area of the remelted metal, $A_{l,rem}$ can be ten or even twenty times bigger than the supremum bound of the cross-sectional area of the laser-treated metal $A_{l,sup}$ at small values of d_c/d_t . Throughout this subchapter, a decrease in d_c/d_t corresponds to increasing the number of laser-treated tracks, n_{tr} and vice versa, while increasing d_c/d_t corresponds to a decrease in n_{tr} .

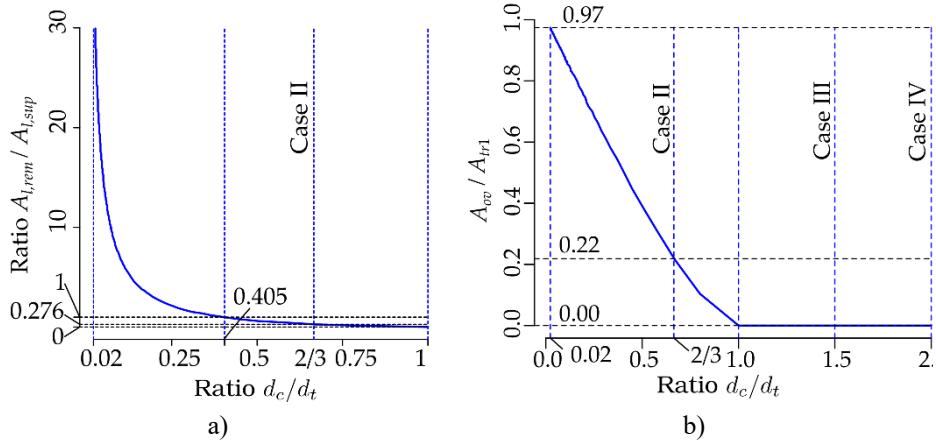


Fig 3.31. Dependencies of the ratios $A_{l,rem}/A_{l,sup}$ and $A_{ov}/A_{tr,1}$ on the ratio d_c/d_t of the considered sheet, see Fig. 2.3: (a) $A_{l,rem}/A_{l,sup}$ versus $d_c/d_t \in [0.02, 1]$; (b) $A_{ov}/A_{tr,1}$ versus $d_c/d_t \in [0.02, 2]$

Results of the above analysis established that making a laser-treated layer is very inefficient at small values of d_c/d_t or large values of n_{tr} , since a very large volume of the metal is melted repeatedly. For practical applications, it is reasonable to take $d_c/d_t = 1$. In this case, as seen in Fig. 3.30b, $A_l/(1/2b_l b_t) = 0.785$. This condition means an increase in the number of laser-treated tracks n_{tr} or decrease in the distance between the tracks, d_c or d_c/d_t the ratio can increase the cross-sectional area of the laser-treated metal only up to $(1 - 0.785) \cdot 100 = 21.5\%$. However, the cross-section of the remelted metal, or the ratio $A_{l,rem}/A_{l,sup}$, increases very quickly with decreasing d_c or increasing n_{tr} . Hence, the efficiency of laser processing can decrease suddenly.

For practical applications, the optimal limit of the d_c/d_t the ratio should be 0.405, since at this point $A_{l,rem}/A_{l,sup} = 1$ and $A_{l,inf}/(1/2b_l b_t)$ and $A_{l,sup}/(1/2b_l b_t)$ are about 0.96 and 0.97, respectively. Therefore, a further increase in n_{tr} or decrease in d_c/d_t can increase $A_l/(1/2b_l b_t)$ only up to 4%. To

increase the cross-sectional area of the laser-treated metal, A_l , it is better to increase the width, and hence the depth, of the laser-treated track d_t than to increase n_{tr} or decrease d_c/d_t .

The considerations are given above concerning the ratios $A_l/(1/2b_l d_t)$, $A_{l,inf}/(1/2b_l d_t)$, $A_{l,sup}/(1/2b_l d_t)$, $A_{l,rem}/A_{l,sup}$, $A_{ov}/A_{tr,1}$ and the corresponding cross-section areas $A_{l,inf}$, $A_{l,sup}$, $(1/2b_l d_t)$, A_{ov} , $A_{tr,1}$, $A_{l,upp} = 1/2b_l d_t$ are also valid for the corresponding ratios of the volumes $V_l/V_{l,upp}$, $V_{l,inf}/V_{l,upp}$, $V_{l,sup}/V_{l,upp}$, $V_{l,rem}/V_{l,sup}$, $V_{ov}/V_{tr,1}$ and the corresponding volumes $V_{l,inf}$, $V_{l,sup}$, V_{ov} , $V_{tr,1}$, $V_{l,upp}$ of the laser-treated metal, where V stands for the volume of the laser-treated metal and its indexes " l, inf ", " l, sup ", " l, upp ", " $V_{l,rem}$ ", " ov ", and " $tr, 1$ " means the same as the corresponding indexes of the cross-sectional areas denoted by A .

Since the above analysis, results, conclusions, and recommendations are expressed in relative terms, these considerations are also valid for other cases of sheets, laser-treated areas, their widths b_l , the laser-treated track widths d_t , the distances between the track centers d_c , and the number of laser tracks n_{tr} .

3.4.4.2. Axial stiffness and stress–strain behavior of the laser-treated sheet

The dependencies of the ratios of the axial forces of the laser-treated sheets (Fig. 2.3, Ex2 Cases II, III, and IV) to the untreated sheet, Ex2 Case I: $N_i/N_{\text{Case I}}$, $i \in \{\text{Case II, Case III, Case IV}\}$ on strain $\epsilon \in [0, \epsilon_{ul}] = [0, 302 \cdot 10^{-3}]$ are shown in Fig. 3.32. The axial forces N_i , $i \in \{\text{Case I, ... , Case IV}\}$ were calculated according to Eqs. 2.5 and 2.6 using the properties of the base and laser-treated metals given in Table 2.11. The cross-sectional areas of the laser-treated metal of the sheet A_l were calculated by Eqs. 2.7, 2.11, and 2.15 when the number of the laser-processed sides $n_s = 2$ and the number of the laser-treated tracks of one side of the sheet, corresponding to Ex2 Cases I, II, III, and IV $n_{tr} \in \{0, 14, 17, 38\}$ is given in Table 2.2. The following cross-sectional areas were obtained: $A_l = 0$ for Ex2 Case I, $A_l = 1.1504 \cdot 10^{-5} \text{ m}^2$ for Ex2 Case II, $A_l = 6.5423 \cdot 10^{-6} \text{ m}^2$ for Ex2 Case III, $A_l = 5.3878 \cdot 10^{-6} \text{ m}^2$ for Ex2 Case IV. The cross-sectional areas of the base metal of the sheet corresponding to Ex2 Cases I–IV, $A_b = A_{pl} - A_l$, where $A_{pl} = b_{pl} = 4 \cdot 10^{-5} \text{ m}^2$ is the cross-sectional area of the sheet (Fig. 2.3b).

As shown in Fig. 3.32, the influence of laser processing is almost infinitesimal when $\epsilon \in [0, \epsilon_{1,b}] = [0, 1.28 \cdot 10^{-3}]$ (section AB in Fig. 3.32). The maximum ratio $\max \{N_i/N_{\text{Case I}}, i \in \{\text{Case II, Case III, Case IV}\}, \epsilon \in [0, \epsilon_{1,b}]\} = 1.0015$. If the axial stiffness of the cross-section of the sheet is $B = N/\epsilon$, it means

that laser processing does not have any influence on the axial stiffness of the sheet when $\epsilon \in [0, \epsilon_{1,b}]$. However, the influence of laser processing on the ratio of the axial forces $N_i/N_{\text{Case I}}$ increases with increasing the strain within the interval $\epsilon \in [\epsilon_{1,b}, \epsilon_{1,l}] = [1.28 \cdot 10^{-3}, 1.962 \cdot 10^{-3}]$ and remains constant when $\epsilon \in [\epsilon_{1,l}, \epsilon_{ul}] = [1.962 \cdot 10^{-3}, 302 \cdot 10^{-3}]$, where hereafter $\epsilon_{ul} = \epsilon_{ul,b} = \epsilon_{ul,l} = 302 \cdot 10^{-3}$ (sections BC and CD in Fig. 2.9).

As shown in Fig. 3.32, laser processing increases the axial forces N_i and hence, the axial stiffness B_i , $i \in \{\text{Case II, Case III, Case IV}\}$, by about 17.5% for Ex2 Case II, 9.9% for Ex2 Case III, and 8.2% for Ex2 Case IV. For practical structural calculations, it is assumed that the sheet's bearing capacity corresponds to the axial force N_i at $\epsilon = \epsilon_{1,l}$, since the increase of the $N_i/N_{\text{Case I}}$ the ratio within the interval $[\epsilon_{1,l}, \epsilon_{ul}]$ is low, $1.179 - 1.175 = 2.5\%$ for Ex2 Case II, $1.102 - 1.009 = 0.9\%$ for Ex2 Case III, and $1.083 - 1.082 = 0.1\%$ for Ex2 Case IV. The dependencies of the ratios of the axial forces $\eta_{\epsilon, A_l/A_b} = N(A_l/A_b, \epsilon)/N(0, \epsilon)$, at $\epsilon \in \{\epsilon_{1,b}, \epsilon_{1,l}, \epsilon_{ul}\}$ with respect to the ratio of the cross-sectional areas of the laser-treated and base metals $A_l/A_b \in [0, 0.538]$ of the sheet (based on Fig. 2.3) are shown in Fig. 3.32. When $A_l = 0$, since $A_l/A_b = 0$ also corresponds to the laser-untreated sheet, i.e., Ex2 Case I, then $N(0, \epsilon) = N_{\text{Case I}}$. In these calculations, it was assumed that the cross-sectional area of the laser-treated metal attains values from the interval: $A_l \in [0, A_{l,up}] = [0, 2 \cdot 1/2b_l d_t] = [0, 1.4 \cdot 10^{-5}]$.

Since $A_b = A_{pl} - A_l$, where $A_{pl} = b_{pl} \cdot 2 \cdot 10^{-3} = 4 \cdot 10^{-5}$, then $\max\{A_l/A_b\} = 1.4/(4 - 1.4) = 0.5385$. Thus, $\max\{A_l/A_b\} = 0.5385$ corresponds to the upper bound of the cross-sectional area of the laser-treated metal when $A_{l,up} = n_s 1/2b_l d_t = 20 \cdot 10^{-3} \cdot 0.7 \cdot 10^{-3} = 1.4 \cdot 10^{-3}$ of the two-side laser-treated sheet, as shown in Fig. 2.3b. As shown in Fig. 3.33, the $\eta_{\epsilon, A_l/A_b}$ ratios on A_l/A_b do not change according to the linear law, as in the case of the dependence of the N on A_l when A_b is constant, according to Eq. 2.6. Ratios do not change since the cross-sectional area of the base metal $A_b = A_{pl} - A_l$, i. e. A_b also changes when A_l changes. In addition, it is visible that the ratio A_l/A_b affects the ratios $\eta_{\epsilon, A_l/A_b}$, especially when $\epsilon \in [\epsilon_{1,b}, \epsilon_{1,l}]$. Thus, when $\epsilon \in \{0, \epsilon_{1,b}\}$, the relative difference $\Delta_{\max} \eta_{\epsilon, A_l/A_b} = \max\{\eta_{\epsilon, A_l/A_b} - \eta_{\epsilon, 0, A_l/A_b} \in \{0, 0.538\}\} = \eta_{\epsilon, 0.538} - \eta_{\epsilon, 0} = 1.7\%$, while when $\epsilon \in \{\epsilon_{1,b}, \epsilon_{1,l}\}$, then $\Delta_{\max} \eta_{\epsilon, A_l/A_b} = 21.3\%$ and when $\epsilon \in \{\epsilon_{1,b}, \epsilon_{ul}\}$, then $\Delta_{\max} \eta_{\epsilon, A_l/A_b} = 21.8\%$. When the strain increases from $\epsilon_{1,l}$ to ϵ_{ul} and $A_l/A_b = 0.538$, the relative difference $\Delta_{\max} \eta_{\epsilon, A_l/A_b} = \eta_{\epsilon_{ul}, 0.538} - \eta_{\epsilon_{l}, 0.538} = 0.5\%$. Fig. 3.33 shows that the biggest possible increase of the axial force is when $A_l/A_b = A_{l,up}/(A_{pl} - A_{l,up}) = 0.538$ is $\eta_{\epsilon_{ul}, 0.538} - \eta_{\epsilon_{l}, 0.538} = 1.213 - 1.017 = 19.6\%$.

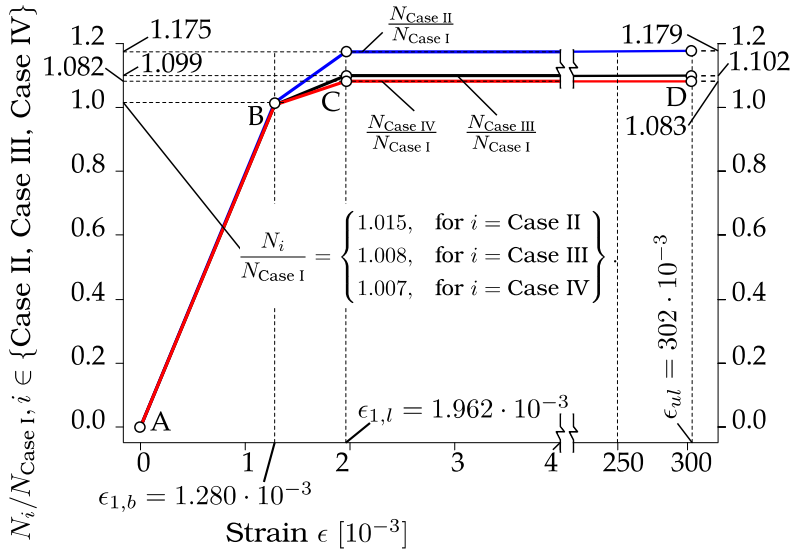


Fig. 3.32. Dependencies of the ratios of the axial forces of the laser-treated sheets, Ex2 Cases II, III, and IV, to the untreated sheet, Ex2 Case I: $N_i/N_{Case I}$, $i \in \{Case I, Case III, Case IV\}$ on strain $\epsilon \in [0, \epsilon_{ul}] = [0, 302 \cdot 10^{-3}]$ on strain ϵ

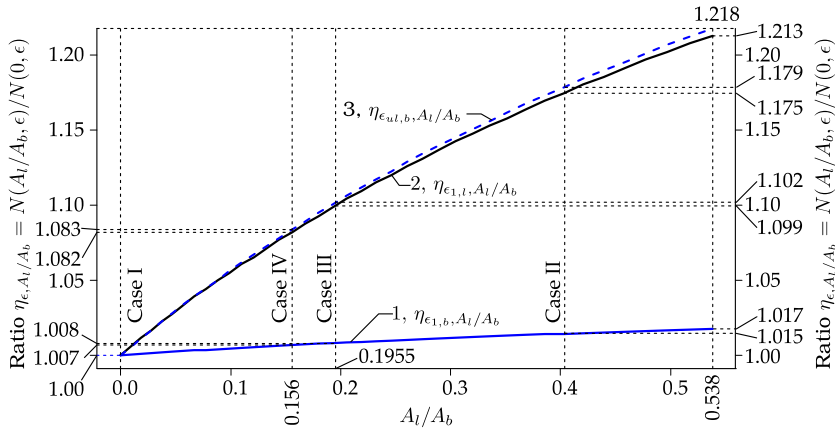


Fig. 3.33. Dependencies of the ratios of the axial forces $\eta_{\epsilon, A_l/A_b} = N(A_l/A_b, \epsilon)/N(0, \epsilon)$, at $\epsilon \in \{\epsilon_{1,b}, \epsilon_{1,l}, \epsilon_{ul}\}$ with respect to the ratio of the cross-section areas of the laser-treated and base metals $A_l/A_b \in [0, 0.538]$ of the sheet shown in Fig. 2.3

3.5. Conclusions of the Third Chapter

1. Results of the experiments and computer simulations of elastoplastic deformation established that local laser processing with surface melting can be used to strengthen the structural elements made from thin-sheet 1.1151 (EN 10083-2:2006) and 1.0402 (EN 10250-2:2022) steel with the carbon content 0.3% instead of the application of complex geometric shapes, additional strengthening elements or heat treatment. In this case, the stiffness and strength of metal sheet parts were improved due to local changes in the microstructure and properties of the steel. The thin sorbite structure was formed in the melted area, which allows for increasing the hardness of the steel samples in the treated areas from 39 to 50% compared to the laser-untreated areas for 1.1151 (EN 10083-2:2006) from 135 HV to 205 HV and for 1.0402 (EN 10250-2:2022) from 149 HV to 200 HV.
2. The formation of a sorbite structure with higher hardness in laser-treated areas led to an increase in strength in the laser-treated metal sheet and the maximum level of bending load, which could be endured without plastic deformation. Results of the experiments and computer simulations of elastoplastic deformation showed that local laser processing with the surface melting of thin sheet 1.1151 (EN 10083-2:2006) and 1.0402 (EN 10250-2:2022) steels increases the flexural stiffness from 5 to 8.4% and decreases the deflection under similar workloads from 13 to 24%.
3. The analytical modeling of the axial force strain behavior of the laser-treated sheets showed that the axial stiffness of the sheet cross-section increases up to 21.8% at the strain corresponding to the yield point of the laser-treated metal when the distance between the laser-treated tracks equals $2/3$ of their width.
4. This analytical and experimental study establishes that the stiffness and mechanical strength of laser-treated thin sheet steel depend on and can be altered by the parameters of the laser (the area and texture of the laser processing). The difference in spacing between laser tracks and their orientation affects the degree of mechanical strength increase of the thin sheet steel. The conducted analytical modeling of steel sheet samples showed that when the ratio of the distance between the centers of the laser-treated tracks and their width equals 1 (i.e., no gaps exist between the laser-treated tracks), the volume ratio of the laser-treated metal to its greatest possible volume is 0.785. For practical applications, the smallest reasonable ratio of the distance between the centers of the laser-treated tracks to their width is 0.405. In such a case, the volume of the repeatedly melted metal equals the volume of laser-treated metal, and the ratio of the volume of laser-treated metal to its greatest

possible volume is 0.97. Formation of a greater volume of laser-treated metal is available by increasing the width of the laser-treated metal track and by increasing the laser power instead of decreasing the distance between the laser-treated track centers by 0.405 of their width.

5. Comparing the calculations and experimental results showed that the finite element method and the proposed analytical model can be used for the prediction of the required laser processing area (the geometry and localization of the treated area, the depth of laser penetration, the orientation and quantity of required laser tracks) on particular steel. This can be done by using a numerical simulation instead of a complex and lengthy experimental selection of proper laser-treated layer depth and processing area to strengthen thin sheet steel. The modeling and bending test results correlated with each other. It was found that the maximum difference between the experimental and computational bending modeling results is less than 15%.

General conclusions

1. Results of the experiments and computer simulations of elastoplastic deformation established that local laser processing with surface melting can be used to strengthen the structural elements made from thin sheet 1.1151 (EN 10083-2:2006) and 1.0402 (EN 10250-2:2022) non-alloy steel with the carbon content of 0.3% instead of applying complex geometric shapes, additional strengthening elements or heat treatment, when optimal critical power for local laser processing of the steel surface is in the range from $2.5 \cdot 10^5$ to $4.5 \cdot 10^5$ W/cm². In this case, the stiffness and strength of metal sheet parts were improved due to local changes in the microstructure and properties of the steel.
2. The degree and effectiveness of hardening thin-sheet products not only depend on the parameters of laser processing but also the orientation and area of processing. Due to the transformation of the initial steel structure to a harder sorbite microstructure, the 1.1151 (EN 10083-2:2006) and 1.0402 (EN 10250-2:2022) steel hardness in the treated zones increased from 39 to 50% compared to the laser-untreated areas, which led to an increase of mechanical properties of thin-sheet products (flexural stiffness and allowed load-carrying capacity without plastic deformation).
3. The results of the experiments and computer modeling of elastoplastic deformation of 1.1151 (EN 10083-2:2006) steel sheet samples after local laser

processing with surface melting showed that through the creation and presence of strengthened surface layers and areas with sorbite structure, the flexural stiffness of sheet steel increased up to 8.4%. Its deflection, on the other hand, decreased under similar workloads by up to 17%. The results of similar experiments and modeling of 1.0402 (EN 10250-2:2022) steel sheet samples also showed that the flexural stiffness of such sheet steel after local laser processing increased by up to 10%.

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List of scientific publications by the author on the topic of the dissertation

Papers in the reviewed scientific journals

Kapustynskyi, O., & Višniakov, N. (2020). Laser treatment for strengthening of thin sheet steel. *Advances in Materials Science and Engineering*, 2020, 1–13.
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Papers in other editions

Kapustynskyi, O. (2021). FEA analysis of thin steel sheet with different locations of reinforcing ribs created by local laser treatment. In *METAL 2021 – 30th Anniversary International Conference on Metallurgy and Materials*.
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Kapustynskiy, O. (2022). FEA analysis under bending loads of thin steel sheet plate with double side reinforcing ribs created by laser treatment. In *METAL 2022 – 31st Anniversary International Conference on Metallurgy and Materials*.

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Summary in Lithuanian

Įvadas

Problemos formulavimas

Nepaisant to, kad įvairiose pramonės ir inžinerijos srityse yra galimybė naudoti daug patvarių ir lengvų medžiagų, plienas šiuo metu yra viena dažniausiai naudojamų konstrukcinių medžiagų. Pasaulinė plieno gamyba kasmet auga. Šiuo metu metalo gaminių rinkoje egzistuoja labai didelė konkurencija ir minimalus pelnas. Gamintojai stengiasi kurti inovatyvius gaminius ir įvairius taiko techninius sprendimus bei dizainą, leidžiančius sumažinti metalo konstrukcijų svorį ir taupyti žaliavą. Todėl plonasieniai gaminiai tampa vis populiarešni ir svarbūs metalo apdirbimo ir kitose pramonės šakose.

Plonasieniams gaminiams gaminti dažniausiai naudojamas nelegiruotasis konstrukcinis plienas, kurio vidutinis storis yra iki 2 mm. Tačiau nelegiruotųjų konstrukcinių plienų panaudojimas yra apribotas dėl nepakankamo mechaninio stiprumo ir standumo (Tylek & Kuchta, 2014a; 2014b).

Todėl, siekiant įvairinti ir plėsti plonasluoksnio plieno gaminių naudojimo mastą įvairiose pramonės srityse, būtina išspręsti tam tikras technologines problemas. Esant eksploatacinei apkrovai, didžiausia deformacija neturi viršyti tam tikrų leidžiamųjų verčių, nustatytų konstrukcijos projektavimo reikalavimuose.

Dabartiniai inžineriniai sprendimai, skirti plonasienio plieno standumui padidinti, daugiausia yra projektavimo metodai, pagrįsti konstrukcijos geometrijos ir jos standumo tarpusavio ryšiu (Liu, 2008; Jalilzadeh, 2019; Troina, 2020). Pavyzdžiui, naudojant standumo elementus ar pastorinimus, padidės gaminių standumas, bet tai privėda prie galutinio produkto matmenų, svorio padidėjimo ir formos sudėtingėjimo (Feschenko, 2016). Naujų plieno apdirbimo technologijų kūrimas leistų kontroliuoti ir pagerinti nelegiruotojo plieno mikrostruktūrą ir savybes (Yin, 2021). Naudojant lazerinį apdorojimą, galima sukelti ir kontroliuoti lokalius struktūros fazinius virsmus plonasienių gaminių iš nelegiruotojo plieno su anglies kiekiu iki 0,3 % (Ghorabaei, 2021). Vietinis lazerinis apdorojimas leistų sukurti zonas, kurių struktūra, kietumas ir kitos mechaninės savybės skirtųsi nuo likusios neapdoroto metalo struktūros (Elagina, 2009). Taigi ši lokalaus apdorojimo technologija galėtų pakeisti plieno gaminių savybes, pavyzdžiui, padidinti plieno gaminių standumą ir kietumą.

Darbo aktualumas

Disertacijoje atlikto tyrimo metu gauta naujų žinių apie plonasienių metalo gaminių, pagamintų iš dažnai vartojamo nelegiruotojo konstrukcinio plieno su anglies kiekiu iki 0,3 %, paviršiaus lokalaus apdorojimo lazeriu, specifiką. Sudaryta tokių plienų plonasienių gaminių apdorojimo ir analizės metodika.

Nustatytas ryšys tarp tinkamos lazerinio apdorojimo vietoje gautos mikrostruktūros ir apdorojimo parametrų leidžia reikšmingai paveikti tokių plonasienių plieno gaminių standumą ir kontroliuoti vidinių įtempių bei deformacijų pasiskirstymą ir reikšmes, kurios atsiranda plonasieniuose lakštinio plieno gaminiuose, apdorotuose lazeriu.

Tai labai pagerins gamybos technologiją ir pagerins plonasienių gaminių eksploatacines savybes. Eksperimentiniai duomenys yra aktualūs metalo apdirbimo pramonei ir plonasienių plieninių komponentų gamybai, taikant ekonomišką lokalų paviršiaus apdorojimą lazeriu, sustiprinant ir kietinant įvairius plonasienius gaminius iš nelegiruotojo plieno.

Tyrimo rezultatai svarbūs sprendžiant esamas technologines problemas įvairiuose pramonės objektuose (pavyzdžiui, slėginė įranga, indai, talpyklos, transportas ir laivų statyba), kur būtini plonasieniai metaliniai korpusai ir konstrukciniai komponentai iš nelegiruotojo plieno.

Tyrimo objektas

Naudojami ploni metalo bandiniai iš aukštos kokybės nelegiruotojo plieno 1.1151 (EN 10083-2:2006) ir 1.0402 (EN 10250-2:2022), kurių sudėtyje yra mažiau nei 0,3 % anglies, kurie buvo lokaliai apdoroti lazeriu (taikant skirtingą lazeriu apdoroto ploto dizainą).

Darbo tikslas

Šio darbo tikslas – sukurti naują vietinio lazerinio apdorojimo technologiją, kuri galėtų modifikuoti plonasluoksnių nelegiruotojo plieno gaminių vietinius paviršiaus plotus, kad pagerėtų tokių plieno gaminių eksploatacinės savybės (kietumas ir standumas), nekeičiant jų pradinio dizaino (pvz., matmenys, forma ir svoris).

Darbo uždaviniai

Norint pasiekti darbo tikslą, būtina išspręsti šiuos uždavinius:

1. Įvertinti lazerinio apdorojimo metodikos ir parametrų įtaką plieno mikrostruktūrai ir mechaninėms savybėms bei nustatyti optimalius lazerinio apdorojimo parametrus, užtikrinančius minimalias deformacijas ir maksimalų paviršiaus kietumo padidėjimą.
2. Įvertinti lazeriu apdoroto sluoksnio mechanines savybes ir vietinio lazerinio apdorojimo su paviršiaus lydymu efektyvumą, siekiant padidinti mechaninį stiprumą ir standumą nenaudojant sudėtingų formų konstrukcijų ar terminio apdorojimo.
3. Sumodeliuoti lenkimo ir tempimo apkrovų sąlygas ir išanalizuoti lazerinio apdorojimo su paviršiniu lydymu efektyvumą plonų lakštų komponentams stiprinti.
4. Palyginti eksperimentų ir modeliavimo rezultatus, įvertinti ir parinkti optimalų apdorojimo plotą, orientaciją ir lazerinio apdorojimo gylį, norint pasiekti maksimalų atsparumo eksploatacinėms apkrovoms efektyvumą.

Tyrimų metodika

Šiame darbe taikyti įvairūs analitiniai ir eksperimentiniai tyrimo metodai. Plonų lakštų nelegiruotojo plieno, kuriame yra mažiau nei 0,3 % anglies, pavyzdžiai buvo apdoroti lazeriu. Mikrostruktūra buvo analizuojama įvairiais šiuolaikinius tyrimo metodais: SEM, EDS, spalvine mikroskopija, XRD ir „Mössbauer“ spektroskopija. Lazeriu apdorotų plieno plonųjų lakštų savybės buvo įvertintos mechaninių savybių (lenkimo, tempimo, mikrokietumo) bandymais. Bandymų rezultatai buvo lyginami su plonasienių objektų deformacijų modeliavimo baigtinių elementų metodu rezultatais.

Disertacijos mokslinis naujumas

Mokslinis susidomėjimas lazerinio apdorojimo technologijomis pastaruoju metu tik auga. Paskelbta daug mokslinių publikacijų apie plieno ir kitų metalų apdorojimo lazeriu poveikį, apdorotų paviršių mikrostruktūrą ir savybes bei jų pritaikymą praktikoje įvairių metalo konstrukcijų gamybai. Pasaulinė plonasienių konstrukcinių komponentų, pagamintų iš tokio plieno, gamyba nuolat didėja. Todėl labai aktualu tirti ir gauti svarbių rezultatų, susijusių su galimybėmis pagerinti įvairių plonasienių nelegiruotojo plieno konstrukcinių komponentų, kurių anglies kiekis mažesnis nei 0,3 %, mechanines ir kitas charakteristikas. Šiame tiriamajame darbe gautos naujos žinios apie nelegiruotojo plieno, kuriame anglies kiekis mažesnis nei 0,3 %, sorbito struktūros susidarymo ypatumus naudojant vietinį lazerinį apdorojimą.

Remiantis gautais tyrimo rezultatais, patvirtinta hipotezė apie plonasienių elementų iš nelegiruotojo plieno su mažesniu nei 0,3 % anglies kiekiu, stiprinimo galimybės ir nustatyta, kad, naudojant tam tikrus lazerinio apdorojimo parametrus, galima gauti sorbitinę apdoroto paviršiaus mikrostruktūrą. Ši mikrostruktūra, palyginti su originalia plieno struktūra, pasižymi didesniu kietumu, mechaniniu stiprumu ir pakankamu plastiškumu, o tai teigiamai paveikia lazeriu apdorotų gaminių mechanines savybes. Nustatytos svarbiausios sąlygos ir paviršiaus lazerinio apdorojimo parametrai, leidžiantys lokaliai keisti nelegiruotojo plieno, kuriame anglies kiekis mažesnis nei 0,3 %, paviršinio sluoksnio struktūrą ir savybes, padidinti paviršinio sluoksnio kietumą ir viso plonasienio

gaminio lenkimo standumą. Nustatyta vietinio lazerinio apdorojimo parametrų, užtikrinančių maksimalų kietumą, įsiskverbimo į medžiagą gylį ir teisingą apdirbamo sluoksnio skerspjūvio geometriją, įtaka, kad būtų suformuoti veiksmingi struktūriniai standikliai, nekeičiant apdirbamų plonasluoksnių nelegiruotųjų plienų gaminių geometrijos. Taip pat buvo nustatyta sąsaja tarp lazerinio apdorojimo parametrų ir sorbitinės struktūros formavimo apdorotoje vietoje.

Darbo rezultatų praktinė reikšmė

Darbo rezultatai svarbūs sprendžiant esamų ir kuriamų plonasienių ir lengvųjų plieninių konstrukcijų, jų gamybos, apdorojimo technologines problemas. Tyrimo rezultatai leidžia parinkti ir pritaikyti racionaliausią, technologiškai paprasčiausią ir praktikoje patogiausią plonasienių plieninių konstrukcinių elementų apdorojimo lazeriu technologiją, parinkti ir optimizuoti apdorojimo parametrus, numatyti pagrindines lazeriu apdorotų paviršių ir produktų eksploatacines savybes.

Eksperimentiniais tyrimais patvirtinta, kad techniškai įmanoma atlikti lokalų nelegiruotųjų konstrukcinių plienų, kuriuose anglies kiekis yra mažesnis nei 0,3 %, apdorojimą lazeriu, kad būtų sukurta kietesnė plonasienių plieninių gaminių paviršiaus struktūra. Pasiūlytas optimalus lazerinio apdorojimo parametrų derinys plonasienių gaminių iš nelegiruotojo plieno lokaliai paviršiaus apdorojimui su struktūrinių standumo elementų formavimu. Siūlomo vietinio lazerinio apdorojimo tekstūra ir gylis padeda padidinti plonasienių gaminių iš aukštos kokybės nelegiruotojo plieno, kuriame anglies kiekis mažesnis nei 0,3 %, atsparumą darbo apkrovoms ir lenkimo standumą kaip sudėtingos geometrinės formos, papildomų standumo elementų arba terminio apdorojimo taikymo alternatyvą.

Siūlomos lazerinio apdorojimo technologijos parametrai gali būti parenkami atsižvelgiant į reikiamas gaminių mechanines savybes. Siūlomi technologiniai sprendimai gali padėti pagerinti plonasluoksnių konstrukcinių plienų, kuriuose anglies kiekis mažesnis nei 0,3 %, ir plonasienių gaminių, kuriuose šie plienai bus naudojami, mechanines savybes, sumažinant tokių plonų gaminių sudėtingumą ir supaprastinant gamybos technologiją. Tyrimo rezultatų pritaikymas leis Lietuvos ir Europos bei kitų užsienio šalių pramonės įmonėms sumažinti gaminamų plonasienių plieno gaminių projektavimo ir gamybos sąnaudas.

Ginamasis teiginys

1. Siūlomas lokalus plieno paviršių apdorojimas lazeriu dėl pradinės plieno struktūros transformacijos į sorbitinę mikrostruktūrą, pasižymintį geresnėmis mechaninėmis savybėmis, leidžia formuoti struktūrines armavimo briaunas arba sritis plonasienio metalo elementuose iš 1.1151 (EN 10083-2:2006) ir 1.0402 (EN 10250-2:2022) plienų, kuriuose anglies kiekis mažesnis nei 0,3 %, kai optimali kritinė galia naudojama lokaliai plieno paviršiaus apdorojimui lazeriu yra nuo $2,5 \cdot 10^5$ iki $4,5 \cdot 10^5$ W/cm². Po vietinio lazerinio apdorojimo plienų kietumas paveiktose padidėjo iki 50 %, o lenkimo standumas – iki 10 %.

Darbo rezultatų aprobavimas

Disertacijos tema paskelbti šeši straipsniai: du *Clarivate Analytics Web of Science* duomenų bazės leidiniuose, turinčiuose citavimo rodiklį (Kapustynskiy et al., 2020a, 2020b), vienas *Clarivate Analytics Web of Science* duomenų bazės „Conference Proceedings“ leidiniuose (Kapustynskiy et al., 2020), du – kitų tarptautinių duomenų bazių leidiniuose (Kapustynskiy et al., 2022, 2021), vienas – kitame recenzuojamame mokslo leidinyje (Kapustynskiy et al., 2019). Disertacijoje atliktų tyrimų rezultatai buvo paskelbti devyniose mokslinėse konferencijose Lietuvoje ir užsienyje:

- Tarptautinė mokslinė konferencija *Mechanika 2019, 2022* Kaunas, Lietuva.
- Tarptautinė konferencija *Metalurgija ir medžiagos Metal 2020, 2021, 2022*, Brno, Čekijos Respublika.
- Tarptautinė konferencija - mokykla *Pažangios medžiagos ir technologijos, 2019, 2020*, Palanga, Lietuva.
- 3-iasis Virtualus kongresas *Medžiagų mokslas & Inžinerinės medžiagos, 2021*, Oregonas, JAV.
- 6-asis Baltarusijos-Baltijos forumas *Bendradarbiavimas yra inovacijų vystymosi katalizatorius*, Minskas, Baltarusija.

Disertacijos struktūra

Darbą sudaro įvadas, trys pagrindiniai skyriai, išvados, literatūros sąrašas, autoriaus publikacijų disertacijos tema sąrašas ir trys priedai. Disertacijos apimtis (be priedų) – 118 puslapių, 18 sunumeruotų formulių, 53 iliustracijos ir 34 lentelės.

Padėka

Autorius dėkoja mokslo vadovui dr. Nikolajui Višniakovui už kantrų vadovavimą, entuziastingą skatinimą ir naudingą šio tiriamojo darbo kritiką. Taip pat dėkojama dr. Remigijui Juškėnui ir dr. Kestučiui Mažeikai iš Fizinių mokslų ir technologijų centro už pagalbą atliekant struktūrinę rentgeno difrakcinę analizę ir Mossbauerio spektroskopijos duomenų analizę, taip pat dr. Jelenai Škamat už pagalbą atliekant skenuojančios elektroninės mikroskopijos vaizdų analizę. Galiausiai didžiausia padėka autoriaus tėvams ir žmonai už palaikymą ir padėsinimą visų studijų metu.

1. Nelegiruotųjų plienų apdorojimo technologijų, struktūros ir fizikinių savybių apžvalga

Šiame skyriuje nagrinėjami plonasienių plieninių gaminių iš nelegiruotųjų plienų su anglies kiekiu iki 0,3 % ypatumai, galimi jų tobulinimo technologiniai sprendimai, gaunama metalo struktūra ir pasiekiamos mechaninės savybės priklausomai nuo terminio apdorojimo ar kitokio alternatyvaus paviršiaus apdirbimo metodo. Taip pat analizuojamos techninės šių apdirbimo metodų taikymo galimybės, lazerinio apdorojimo procesų specifika.

Remiantis literatūros analizės rezultatais prieita prie tokių hipotezių ir išvadų:

1. Šiuolaikinės lazerinės technologijos, palyginti su kitais ne visada racionaliais, efektyviais ar sunkiai pritaikomais metalo apdirbimo būdais (projektiniais sprendimais, terminiu, termocheminiu ar mechaniniu apdirbimu), gali būti labai naudingos didinant plonasienių konstrukcijų, pagamintų iš konstrukcinio nelegiruotojo plieno, standumą ir kitas eksploatacines savybes.

2. Lazerinio apdorojimo technologijos užtikrina vietinį šildymą, aukštus temperatūros gradientus ir pasiekiamą aušinimo greitį (10^4 – 10^6 °C/sek) dėl didelio šilumos laidumo. Todėl apdirbant lazeriu galima pasiekti mikrostruktūrinių pokyčių, dėl kurių pagerėja nelegiruotojo konstrukcinio plieno, kuriame yra mažiau nei 0,3 % anglies, mechaninės savybės. Tačiau lazerinio transformacinio grūdinimo be lydymo taikymas nelegiruotajam konstrukciniam plienui, kuriame yra mažiau nei 0,3% anglies, apdoroti ribojamas dėl mažo grūdinto sluoksnio storio, nes turi būti paveiktas labai didelis paviršiaus plotas. Apdirbant lazeriu lydant gaunamas didesnis paveikto sluoksnio storis, todėl plonasieniams plieno gaminiams sukieinti labiau tinka vietinis apdorojimas lazeriu su paviršiaus lydymu.

Apibendrinus atliktos literatūros analizės rezultatus, suformuluoti pagrindiniai darbo uždaviniai.

2. Analizės metodika ir medžiagos lazeriniam apdorojimui

Skyriuje pateiktos sukurto analitinės ir eksperimentinės tyrimų metodikos, leidžiančios išsiaiškinti taikomų lazerinio apdorojimo procesų technologinių parametrų įtaką plonasienių plieno gaminių su anglies kiekiu iki 0,3 %, paviršiaus mikrostruktūrai ir svarbiausioms savybėms. Aprašyta lazerinio apdorojimo parametrų skaičiavimo ir lazerinio apdorojimo metodika, apdorotų lazeriu sričių struktūros ir fazinės sudėties analizės metodikos, mechaninių bandymų atlikimo ir modeliavimo metodikos.

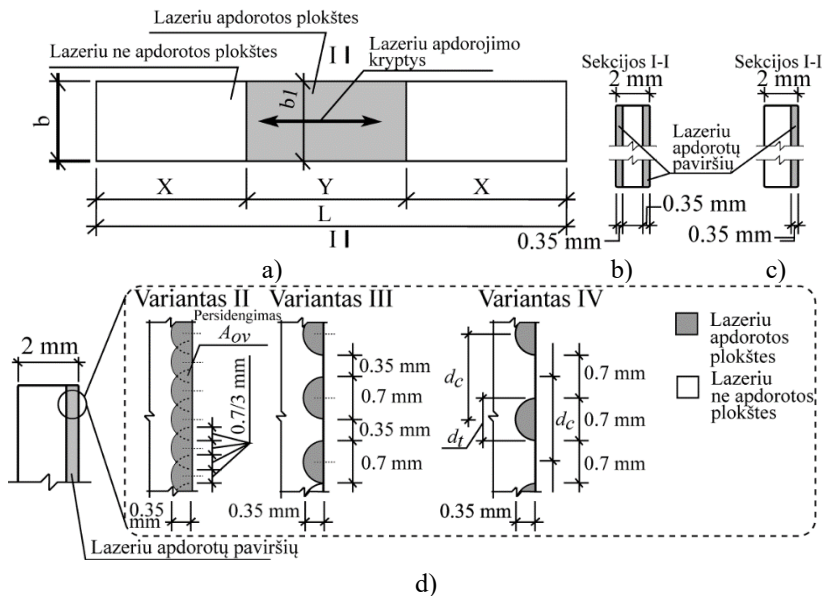
Tyrimuose buvo naudoti nelegiruotojo konstrukcinio plieno 1.1151 (EN 10083-2:2006) ir 1.0402 (EN 10250-2:2022) pavyzdžiai, plačiai taikomi gaminant įvairius plonasienius metalo gaminius (lakštus, kampuočius, vamzdžius ar kitokius profilinius elementus) ir kitus mažo atsparumo lenkimui komponentus bei sudėtingesnės formos gaminius (cisternas, membranas). Visų 2 mm storio pavyzdžių struktūra, savybės ir paviršiaus paruošimas prieš apdorojant lazeriu buvo identiški. Po mechaninio apdirbimo paviršiaus šiurkštumas Ra buvo ne didesnis kaip 5 μm . Apdirbti plieniniai bandiniai buvo lokaliai apdoroti lazeriu taikant įvairius parametrus. Impulsinis lazeris (impulso trukmė – 1–5 μs) įkaitino plono lakšto paviršių iki temperatūros, kurioje įmanomi plienų faziniai virsmai arba lydymas. Pasiekiami temperatūros gradientai sukelia vėlesnį spartų paviršiaus aušinimą 10^3 – 10^4 °C/s greičiu dėl šilumos išsklaidymo į pagrindinį metalą. Toks aušinimo režimas skatino sukieintų zonų formavimą, kurių mikrostruktūrą galima nustatyti naudojant CCT diagramas.

Lazerinis paviršiaus apdorojimas atliktas Nd:YAG 4 ašų lazerinio suvirinimo sistema BMM400 (Kinija). Šio impulsinio lazerio 400 W vidutinės galios pakanka išlydyti minimaliai reikalingą metalo paviršiaus sluoksnį ir sukelti fazinius virsmus plono lakštinio plieno pavyzdžio apdorotoje srityje. Atsižvelgus į naudojamos lazerinės įrangos charakteristikas ir plieno savybes, buvo atliktas reikiamų lazerinio apdorojimo režimų skaičiavimas ir parametrų optimizavimas.

Skaiciuojamais metodais ir eksperimentiškai pasirinkti optimalūs apdorojimo parametrai (lazerio dėmės skersmuo, lazerio judėjimo greitis, impulso trukmė, impulsų dažnis, impulso energija) išliko pastovūs visų eksperimentų metu. Keičiami parametrai yra lazerio takelių skaičius, atstumas tarp jų (perdengimas), takelių orientacija ir apdorojamų sričių skaičius. Atstumas tarp lazerinio apdorojimo takelių visuose technologiniuose eksperimentuose buvo 0,35 mm ir 0,7 mm. Apdorojimo kryptys, lazeriu apdorotų takelių skaičius, apdorotų paviršių vieta ir kiekiai (vienpusis arba dvipusis apdorojimas) pavaizduoti S2.1 paveiksle.

Plieno bandinių Nd:YAG lazeriniam apdorojimui buvo naudojamas apsauginių dujų mišinys iš Ar-CO₂ (20 % CO₂) ir tipinis apsauginių dujų srautas 20 l/min.

Taikyto plieno ir lazeriu apdoroto paviršiaus sluoksnio mikrostruktūros cheminė sudėtis ir mechaninės savybės buvo tirtos, siekiant nustatyti teisingus įvesties duomenis baigtinių elementų (BE) modeliavimui.



S2.1 pav. Bandinių lazerinio apdorojimo schema: a – bendras bandinio su apdorota sritimi vaizdas; b – iš dviejų pusių lazeriu apdorotos plokštės skerspjūvis; c – iš vienos pusės lazeriu apdorotos plokštės skerspjūvis; d – lazerinių takelių išsidėstymo variantai

Makroskopinis ir mikroskopinis lazeriu apdorotų bandinių tyrimas atliktas pagal ISO 17639:2003. Plieno ir lazeriu apdoroto sluoksnio metalografinis tyrimas bei lazeriu apdoroto sluoksnio geometrijos ir matmenų analizė atlikta optiniu mikroskopu „Eclipse MA200“ („Nikon“, Japonija) su „Lumenera Infinity 2-2“ vaizdo kamera ir JEOL JSM-7600 (Japonija) skenuojančiuoju mikroskopu su energijos dispersiniu spektrometru (EDS) „INCA Energy X-Max20“ („Oxford Instruments“, JK) įvairiai didinant (iki $\times 1500$). Makroskopiniam ir mikroskopiniam tyrimui ėsdinimo priemonės buvo parinktos pagal

ISO/TR 16060:2003. Plieno bandiniams ėsdinti buvo naudojamas „Nital“ tirpalas. Be to, papildomai fazinės sudėties tyrimui buvo taikoma spalvotosios mikroskopinės analizės technika, naudojant keturis skirtingus specialių reagentų receptus ėsdinimui: A) pikrino rūgšties tirpalas etilo alkoholyje; B) pikrino rūgšties ir nitalio ėsdiklių derinys; C) ėsdiklis natrio metabisulfito pagrindu; D) ėsdiklis natrio tiosulfato pagrindu.

Plieno bandinių cheminė sudėtis buvo nustatyta naudojant „PMI Master PRO“ („Oxford Instruments“, JK) optinės emisijos (OES) spektrometrą su CCD detektoriais ir optika, apimančia visą spektrinį diapazoną nuo 170 iki 420 nm (nustatant C, P, S, B, Sn koncentraciją pienuose ppm). Atlikta medžiagų fazinės sudėties kokybinė rentgeno difrakcijos (XRD) analizė. Buvo pritaikyti du skirtingo tikslumo ir skirtingos aptikimo ribos difraktometrų modeliai: DRON-7 (Rusija) ir „SmartLab“ (Japonija). „Mössbauer“ spektroskopija atlikta apdoroto lazeriu sluoksnio fazinei sudėčiai apibūdinti. Tam tikslui naudotas „Mössbauer“ spektrometras („Wissenschaftliche elektronik GMBH“, Vokietija). Bandinių dydis – iki 10×10 mm². Matematinei spektrų analizei buvo taikomas programinės įrangos paketas „WinNormos“.

Kietumas buvo nustatomas naudojant „ZwickRoell“ ZHμ kietumo testerį (Šveicarija):

- Plieno kietumas buvo nustatytas Vikerso metodu pagal EN ISO 6507-1, taikant apkrovą 9,807 N.

- Lazeriu apdorotų paviršių kietumas buvo nustatytas Vikerso metodu paviršiuje ir skerspjuvyje pagal EN ISO 4516, taikant apkrovą 2,942 N.

Lenkimo bandymai buvo atliekami įvairiomis sąlygomis, t. y. buvo atliekami pagal ISO 7438:2016 reikalavimus arba naudojant nestandartines apkrovos sąlygas, kurios imituoja metalinių apvalkalo konstrukcijų lenkimo nuo atsitiktinių apkrovų sąlygas (S2.1 lentelė). Plonos plokštelės elastoplastinis lenkimas atliktas naudojant trijų taškų lenkimo įrenginį. Lenkimo bandymai buvo atliekami taikant universalią bandymo mašiną „TIRAtest 2300“ (Vokietija) su „Katman-Express“ programine įranga. Lenkimo bandymui buvo naudojamas apkrovos matuoklis iki 2 kN. Bandyme naudotų apkrovos ir deformacijų matavimo jutiklių tikslumas buvo $\pm 0,03$ %. Bandymai buvo atliekami taikant pastovų deformacijos greitį nuo 1 iki 1,5 mm/s. Apkrova svyravo nuo 0 N iki didžiausios apkrovos 2000 N, atitinkančios didžiausius eksperimento įlinkius, kurie yra lygūs 2 mm. Įlinkiai buvo matuojami plokštės tarpatramio viduryje.

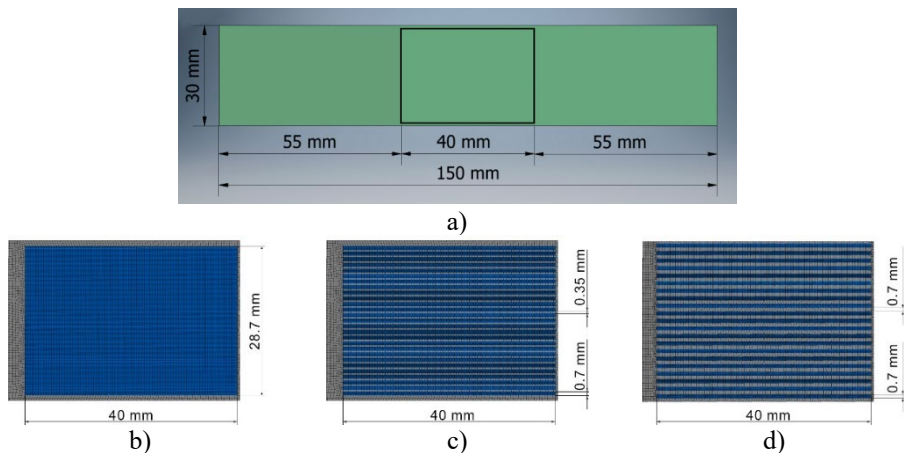
Papildomai buvo atlikti tempimo bandymai su skirtingu lazeriu apdorotų takelių išsidėstymu (S2.2 lentelė). Tempimo bandymuose buvo naudojama universali tempimo bandymo mašina 2055 P-5 („Tochpribor“, Rusija) su „Labview“ (versija 2020, „National Instruments“, JAV) programine įranga ir PXI sistemos technine įranga (moduliu platforma NI PXIe-1073). Tempimo bandymui taikytas apkrovos matuoklis iki 5 kN.

S2.1 lentelė. Lenkimo bandymams taikytų lazeriu apdorotų takelių geometrijos ir išsidėstymo variantai

Eksperimento pavadinimas	Takelių skaičius (iš viso)	Atstumas tarp lazeriu apdorotų takelių	Lazeriu apdoroto sluoksnio padėtis ir įtemptas būvis	Lazeriu apdorotų takelių orientacija	Plienai
Ex1 Variantas I	0				1.1151
Ex1 Variantas II A	56	Persidengimas	Viršus, gniuždymas	Horizontaliai	
Ex1 Variantas II B	27	0,35			
Ex1 Variantas II C	21	0,7			
Ex2 Variantas I	0				1.1151/ 1.0402
Ex2 Variantas II A	38	Persidengimas	Viršus, gniuždymas	Horizontaliai	
Ex2 Variantas II B	38		Apačia, tempimas		
Ex2 Variantas II C	76		Dvipusis		
Ex2 Variantas III A	17	0,35	Viršus, gniuždymas		
Ex2 Variantas III B	17		Apačia, tempimas		
Ex2 Variantas III C	34		Dvipusis		
Ex2 Variantas IV A	14	0,7	Viršus, gniuždymas		
Ex2 Variantas IV B	14		Apačia, tempimas		
Ex2 Variantas IV C	28		Dvipusis		
Ex3 Variantas I	0				1.0402
Ex3 Variantas II A	76	Persidengimas	Dvipusis	Horizontaliai	
Ex3 Variantas II B	76			Vertikalčiai	
Ex3 Variantas II C	108			45 laipsnių	
Ex3 Variantas III A	34	0,35		Horizontaliai	
Ex3 Variantas III B	34			Vertikalčiai	
Ex3 Variantas III C	52			45 laipsnių	
Ex3 Variantas IV A	28	0,7		Horizontaliai	
Ex3 Variantas IV B	28			Vertikalčiai	
Ex3 Variantas IV C	40			45 laipsnių	

S2.2S lentelė. Tempimo bandymams taikytų lazeriu apdorotų takelių geometrijos ir išsidėstymo variantai

Ekspimento pavadinimas	Takelių skaičius (iš viso)	Atstumas tarp lazeriu apdorotų takelių	Lazeriu apdoroto sluoksnio padėtis ir įtemptas būvis	Lazeriu apdorotų takelių orientacija
Ex4 Variantas I	0	–	–	–
Ex4 Variantas II A	16	Persidengimas	Dvipusis	Horizontaliai
Ex4 Variantas II B	236	Persidengimas	Dvipusis	Vertikaliai
Ex4 Variantas II C	178	Persidengimas	Dvipusis	45 laipsnių
Ex4 Variantas III A	8	0,35	Dvipusis	Horizontaliai
Ex4 Variantas III B	114	0,35	Dvipusis	Vertikaliai
Ex4 Variantas III C	86	0,35	Dvipusis	45 laipsnių
Ex4 Variantas IV A	6	0,7	Dvipusis	Horizontaliai
Ex4 Variantas IV B	84	0,7	Dvipusis	Vertikaliai
Ex4 Variantas IV C	64	0,7	Dvipusis	45 laipsnių



S2.2 pav. Mėginių paviršiaus vaizdai „Ansys“ programinėje įrangoje:

a – bendras metalinės plokštės vaizdas su apdoroto ploto matmenimis; b – Ex1 Case II A; c – Ex1 Case I B; d – Ex1 Case II C

Lazeriniu būdu apdorotų plonų bandinių tempimas ir lenkimas buvo modeliuojami baigtinių elementų metodu (BE). „Ansys workbench“ programinės įrangos paketas (16.0 versija) buvo naudojamas mechaniniams įtempimams ir deformacijoms modeliuoti ir analizuoti. Kiekvienai eksperimentų serijai buvo sukurtas skaitinis lenkimo ir tempimo bandymo modelis, identiškas eksperimentinių bandymų sąlygoms. Bendrieji skaitmeninių

modelių vaizdai pateikti S2.2 paveiksle. Lenkimo modeliuose atstumas tarp atramų kaip ir realiuose lenkimo bandymuose svyravo nuo 14 iki 70 mm, imituojant skirtingas lakštinio gaminio lenkimo sąlygas arba standartų reikalavimus.

3. Mikrostruktūros analizės, mechaninių savybių bandymų, procesų modeliavimo rezultatai ir aptarimas

Apskaičiuotos kritinės lazerio galios reikšmės, priklausančios nuo impulso trukmės ir lazerio prasiskverbimo į medžiagą gylio. Remiantis šiais rezultatais galima daryti išvadą, kad turint 3 mm skersmens lazerio dėmę lazerio kritinė galia takeliams formuoti turi būti nuo $2,5 \cdot 10^5$ iki $4,5 \cdot 10^5$ W/cm², o lazerio spindulio judėjimo greitis – nuo 20 iki 50 mm/min diapazone. Mažas lazerio spindulio judėjimo greitis (mažiau nei 20 mm/min) lemia metalo pjovimą dėl didelės kritinės galios, veikiančios medžiagą, o labai didelis judėjimo greitis (daugiau nei 50 mm/min) labai sumažina pralydimo gylį. Tinkamiausias režimas iš visų galimų lazerinio apdorojimo parametrų variantų pateiktas S3.1 lentelėje.

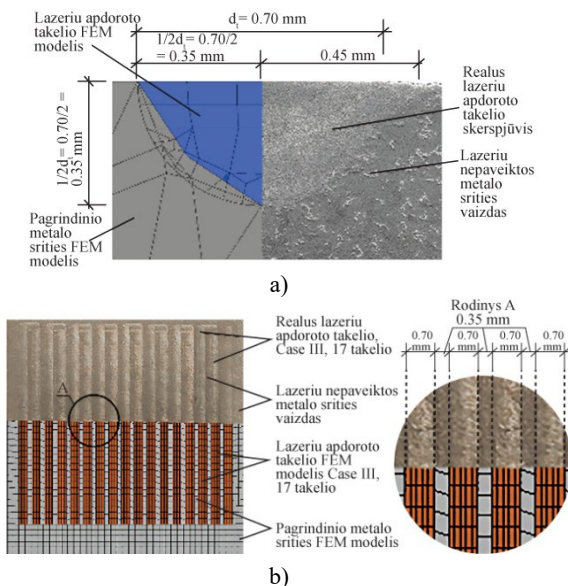
S3.1 lentelė. Nd:YAG lazerinio apdorojimo parametrai

Pralydimo gylis h , mm	Greitis v , mm/min	Dažnis f , Hz	Pulso trukmė t_p , ms	Vieno impulso energija E_p , J	Taško dydis d , mm	Didžiausia galia P_p , kW	Persidengimo koeficientas P_{sr} , %	Kritinė galia P_{dl} , W/cm ²	Tikra kritinė galia P_{d2} , W/cm ²
0,346	240	10	5	14,4	3	2,8	97– 98,6	$4,11 \cdot 10^5$	$3,98 \cdot 10^5$

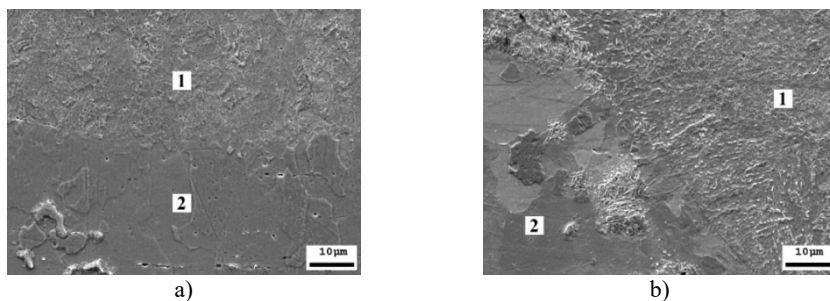
Plieno kristalinės gardelės struktūra įkaitintoje ir perlydytoje zonose pakinta, iš ferito-perlito struktūros (būdingos plienui 1.1151 ir 1.0402 po grūdinimo ar normalizavimo) ir virsta sorbito struktūra, kurio tekstūra yra smulkesnė nei perlito. Grūdelių dydis paveiktoje zonoje sumažėjo nuo G8 (vidutinis grūdelių skersmuo apie 20 μm) iki G11 (vidutinis grūdelių skersmuo apie 7 μm).

Lazeriu paveiktą 1.1151 ir 1.0402 plieno bandinių SEM analizė parodė, kad išmatuotas atstumas tarp lamelių gautoje dispersinėje sorbito struktūroje yra mažesnis nei 0,3 μm (S3.1 pav.). Šis atstumas būdingas sorbitui, nes perlito atstumas tarp lamelių yra apie 0,6–0,7 μm, trostito – apie 0,1 μm, martensito ir bainito – apie 0,2 μm, o liekamojo austenito lamelių storis – 0,05–0,2 μm (Gulyaev, 1986; Vorobeva et al., 2013).

Šiuo atveju sorbito struktūra turi daug privalumų, nes jo tekstūra yra smulkesnė, o dispersiškumas ir stipris didesnis nei perlito. Lazerio paveiktame (perlydytame) sluoksnyje arba išilgai išlydytų zonų krašto nesusidaro jokių labai kietų ir trapių grūdinimo struktūrų ar kitų nepageidaujamų intarpų ir vidinių defektų (S3.2 pav.).



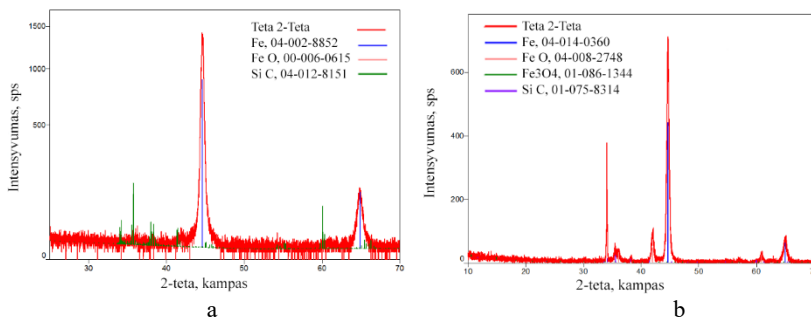
S3.1 pav. BE ir tikrojo bandinio lazeriu paveiktos srities skerspjūviai (a) ir bendras tikrojo bandinio ir jo BE modelio (Ex2 Varianto III) lazeriu paveiktų sričių paviršių vaizdas (b)



S3.2 pav. Lazeriu apdorotų sričių mikrostruktūra (padidėjimas $\times 1000$):
a – apdorota zona; b – takelių persidengimo sritis; 1 – paviršiaus sritis po apdorojimo lazeriu;
2 – lazerio nepaveikta zona

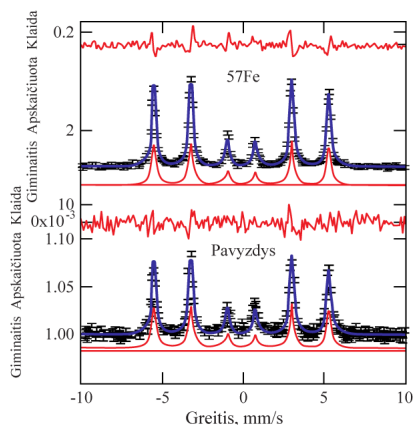
Cheminių elementų pasiskirstymo paveiktuose (perlydytuose) sluoksniuose rezultatai parodė, kad šioje srityje nėra didelės cheminės įvairovės. Cheminių elementų pasiskirstymo ir koncentracijos SEM-EDS sudėties analizė, linijinis skenavimas ir taškinė analizė parodė, kad C, Mn ir Si pasiskirstymas bandinyje yra gana tolygus.

Remiantis XRD duomenų analize, lazeriu paveikto sluoksnio rentgeno spindulių difrakcijos spektras būdingas ferito mikrostruktūros grupei (įskaitant sorbitą ir troostitą) su kubine centruoto tūrio kristaline struktūra. XRD analizė patvirtina tik tai, kad lazerio paveiktoje zonoje nėra nestabilaus liekamojo austenito, nes austenitas turi kubinę centruoto paviršiaus kristalinę struktūrą ir kitokias XRD difrakcijos smailes (S3.3 pav.).



S3.3 pav. Lazериu paveikto sluoksnio plieno 1.1151 XRD spektras: a – pagrindinio metalo paviršius; b – lazериu paveikto sluoksnio plotas

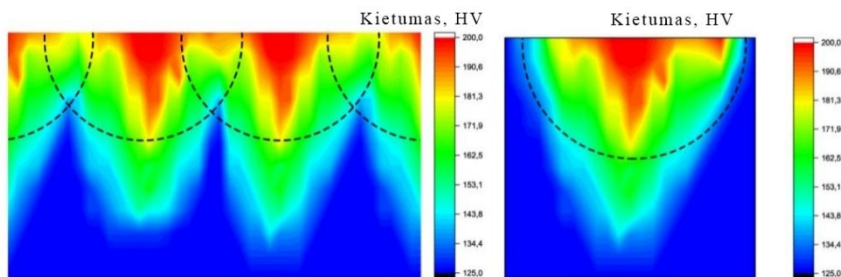
Mossbauerio spektroskopijos, taikytos lazериu paveiktų paviršių bandiniams, rezultatai parodė, kad pagrindinė fazė yra Fe (S3.4 pav.). Kitų fazių (karbidų) koncentracija lazериu paveiktame bandinyje neviršija matavimo 2 % paklaidos.



S3.4 pav. Lazериu paveikto sluoksnio Mossbauerio spektras

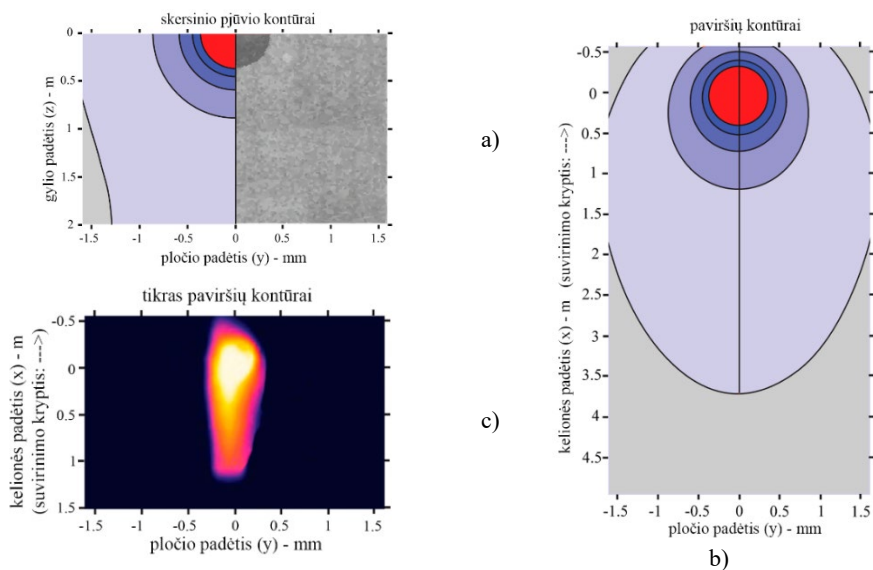
Remiantis gautų diagramų analizės rezultatais, tinkamiausiu lazериu paveikto paviršiaus aušinimo būdas gali būti aušinimas ore arba naudojant suslėgtojo oro (arba apsauginių dujų) srovę, nes šiose aušinimo terpėse užtikrinamas sorbito struktūrai susidaryti būtinas aušinimo greitis (apie 10 °C/s).

Išmatuotas lazериu paveiktų sluoksnių kietumas atitinka tipinį sorbito kietumą, kuris yra 200–205 HV intervale (S3.5 pav.) (Jianjun et al., 2019). Kad būtų pasiektas maždaug 200 HV kietumas šiame mažangliame pliene, greitai atvėsus išlydytos srities mikrostruktūrai, būtina pasiekti bent 25 % bainito arba martensito struktūrą. Priešingu atveju šio plieno bandinio mikrostruktūra turėtų būti sustiprinama smulkinant grūdelių dydį ir sukuriant smulkiadisversę perlito (sorbito, troostito) struktūrą.



S3.5 pav. Kietumo pasiskirstymas apdoroto lazeriu bandinio skerspjūvyje (pavyzdys Ex1 Variantas IIA)

Sumodeliavus šilumos pasiskirstymą lazerinio apdorojimo metu buvo nustatyta, kad išlydytos vonelės forma ir pasiektas lydymo gylis yra labai artimas lazerinio apdorojimo eksperimentų metu gautiems duomenims. Temperatūrinių laukų modeliavimo rezultatai buvo patvirtinti naudojant infraraudonųjų spindulių termovizorių „Optris PI450i“ (S3.6 pav.).



S3.6 pav. Šilumos perdavimas lazerinio apdorojimo metu: a – sumodeliuotas temperatūros pasiskirstymas lakšto skerspjūvyje ir lydymo zonos ribos realiaame bandinyje; b – sumodeliuotas lazerinio apdorojimo temperatūrinių laukų vaizdas iš viršaus; c – lazerinio apdorojimo metu užfiksuotų temperatūrinių laukų vaizdas iš viršaus (vaizdas gautas naudojant „Optris Infrared Camera PI450i“)

Modeliuojant skirtingai lazerių apdorotų bandinių deformavimo procesą BE metodu, buvo gauti duomenys, reikalingi lyginamajai analizei ir lazerinio apdorojimo efektyvumui

įvertinti. Baigtinių elementų modeliavimo rezultatai koreliuoja su realių bandinių deformavimo rezultatais. Lazериu nepaveiktų bandinių lenkimo ir tempimo eksperimentiniai rezultatai ir deformacijų lenkiant modeliavimo rezultatai buvo palyginti su lazериu apdorotų bandinių analogiškų bandymų rezultatais (S3.3 ir S3.4 lentelės). Eksperimentiniai ir modeliavimo duomenys patvirtino, kad bandinių paviršiaus suketinimui ir bendram atsparumui lenkimui turi lazерио paveiktos zonos padėtis, atstumas tarp lazерио takelių, kietesnės fazės tūris ir jo santykis su lazерио nepaveiktos medžiagos tūriu. Tempimo bandymai taip pat parodė, kad lazериu apdorotų bandinių irimas įvyksta ne tik bandinio centre (kaip turėtų būti pagal standartą), bet ir lazериu apdorotos srities pakraščiuose (kurie yra už bandinio skaičiuojamosios dalies ribų). Tai rodo, kad centrinė bandinio zona yra gerokai stipresnė ir jai suardyti reikia panaudoti dar didesnę jėgą. Baigtinių elementų metodu modeliuotų bandinių tempimo rezultatų palyginimas su realių eksperimentų duomenimis rodo, kad, norint nustatyti geriausią lazериu apdorotų sričių ir takelių išsidėstymą, reikia naudoti 3D modelį.

S3.3 lentelė. Pavyzdžių lenkimo bandymų ir modeliavimo rezultatų palyginimas (kai įlinkis 2 mm)

Pavyzdžio pavadinimas	Apskaičiuota lenkimo jėga, N	Išmatuota lenkimo jėga, N	Skirtumas, %
Ex1 Variantas I	1033	986	4,54
Ex1 Variantas II A	1280	1206	5,78
Ex1 Variantas II B	1217	1167	4,11
Ex1 Variantas II C	1167	1142	2,14
Ex2 Variantas I	290	296	2,07
Ex2 Variantas II A	409	445	8,8
Ex2 Variantas II B	410	447	9,02
Ex2 Variantas II C	442	475	7,46
Ex2 Variantas III A	394	439	11,42
Ex2 Variantas III B	398	440	10,55
Ex2 Variantas III C	428	463	8,17
Ex2 Variantas IV A	378	421	11,37
Ex2 Variantas IV B	381	423	11,02
Ex2 Variantas IV C	419	455	8,59
Ex3 Variantas I	1898	1690	12,31
Ex3 Variantas II A	2238	2263	1,11
Ex3 Variantas II B	2295	2209	3,89
Ex3 Variantas II C	2282	2237	2,01
Ex3 Variantas III A	1954	2113	8,13
Ex3 Variantas III C	2030	2024	0,29
Ex3 Variantas III B	1998	2083	4,25
Ex3 Variantas IV A	1947	1943	0,2
Ex3 Variantas IV B	1895	1804	5,04
Ex3 Variantas IV C	1939	1864	4,02

S3.4 lentelė. Pavyzdžių tempimo bandymų ir modeliavimo rezultatų palyginimas.

Pavyzdžio pavadinimas	Realų stiprumo riba, MPa	Apskaičiuota stiprumo riba, MPa	Skirtumas, %
Ex4 Variantas I	400	410,57	2,57
Ex4 Variantas II A	414,5	525,26	21,09
Ex4 Variantas II B	422,3	523,05	19,26
Ex4 Variantas II C	440	532,83	17,42
Ex4 Variantas III A	426,3	540,12	21,07
Ex4 Variantas III B	426	545,4	21,89
Ex4 Variantas III C	433,5	558,04	22,32
Ex4 Variantas IV A	426,5	541,58	21,25
Ex4 Variantas IV B	428	539,14	20,61
Ex4 Variantas IV C	430,5	411,5	4,41

Bendrosios išvados

1. Aprašytas lokalaus lazerinio apdorojimo metodas leidžia plonasienėse konstrukcijose iš 1.1151 (EN 10083-2:2006) ir 1.0402 (EN 10250-2:2022) nelegiruotojo plieno, kuriame anglies kiekis yra mažesnis nei 0,3 %, sukurti struktūrines standumo briaunas arba sritis, kai optimali kritinė galia lokaliai plieno paviršiaus apdorojimui lazeriu yra nuo $2,5 \cdot 10^5$ iki $4,5 \cdot 10^5$ W/cm². Tai tapo įmanoma dėl to, kad tam tikromis lazerinio apdorojimo sąlygomis susiformuoja palankios sorbitinės mikrostruktūros kietesnis sluoksnius, kurio kietumas, stiprumas ir plastiškumas yra geresni, palyginti su pradine šių plienų struktūra ir analogiška chemine sudėtimi.
2. Plonasienių plieno gaminių sustiprinimo efektyvumas priklauso ne tik nuo lazerinio apdorojimo parametrų, bet ir nuo apdorojimo ploto ir takelių orientacijos. 1.1151 (EN 10083-2:2006) ir 1.0402 (EN 10250-2:2022) plieno kietumas apdorotose zonose dėl pradinio plieno struktūros transformacijos į kietesnę sorbito mikrostruktūrą, palyginti su lazeriu neapdorotomis vietomis, padidėjo nuo 39 iki 50 %. Dėl to pagerėjo svarbios plonasienių gaminių mechaninės savybės (lenkiamasis standumas ir leidžiamoji darbinė apkrova be plastinės deformacijos).
3. Lokaliai apdorotų lazeriu, lydant paviršių 1.1151 (EN 10083-2:2006), plieno lakštų bandinių elastoplastinės deformacijos eksperimentų ir kompiuterinio modeliavimo rezultatai parodė, kad dėl stipresnių paviršiaus sluoksnių ir plotų su sorbitine struktūra suformavimo lakštinio plieno lenkimo standumas padidėjo iki 8,4 %. Kita vertus, esant panašiai darbo apkrovai, jo įlinkis sumažėjo iki 17 %. Analogiškų eksperimentų su 1.0402 (EN 10250-2:2022) plieno lakštų pavyzdžiais ir modeliavimo rezultatai taip pat parodė, kad tokio lakštinio plieno lenkiamasis standumas po lokalaus apdorojimo lazeriu padidėjo iki 10 %.

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RESEARCH OF IMPROVEMENT OF NON-ALLOY
STEEL SURFACE HARDNESS AND STIFFNESS
BY LASER TREATMENT

Doctoral Dissertation

Technological Sciences,
materials engineering (T 008)

NELEGIRUOTOJO PLIENO PAVIRŠIAUS KIETUMO IR
STANDUMO DIDINIMO LAZERINIO APDOROJIMO
METODU TYRIMAI

Daktaro disertacija

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