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Mathematical modelling of continuous laser welding and local heat treatment of welded pipes of stainless and heat-resistant chromium-nickel steels

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Abstract. The method of mathematical modeling has been used to study the features and regularities of the processes of shaping the tube billet, laser butt welding and local laser heat treatment of straight-seamed pipes from stainless austenitic steels. It is shown that for laser radiation with a power of 6 kW it is possible to weld workpieces up to 10 mm thick. The applicability of local laser heat treatment for a welded seam is estimated. It is established that at a welding speed of up to 3 m/min for a laser with a power of up to 6 kW, a local surface laser heat treatment of the seam with a width of up to 2 mm is possible up to a depth of 3 mm. This treatment meets the requirements of minimizing the tensile stresses generated in the pipe on the external surface during its shaping and thermal stresses during the solidification of the weld melt.

1. Introduction
Currently, research and industrial developments in the field of laser technologies, in particular, laser welding of pipes for various purposes, are actively developing [1-3]. Modern laser butt welding of sheet material from stainless and heat-resistant alloys puts forward increased requirements to the quality of the edges of welded joints [4], especially for pipe blanks with a wall thickness of more than 3 mm [5]. For successful laser welding, the butt clearance between the ends of the pipe blank should not normally exceed 0.1*δ, where δ is the thickness of the sheet [6]. At the same time, the realized welding speed is limited by the technological capabilities of the speed of forming the pipe billet and depends essentially on the type of the welding mill. In addition, the speed of forming the pipe blank must necessarily be optimized, both from the point of view of the energy-force parameters of the molding process and the elasto-deformational state that arises in the material of the tube billet [7]. In modern production, this is often done with the help of software packages that can be integrated into the process control system and having strict limitations when implementing new processes and developments [8].
2. Methods

Today, most of the world's manufacturers of welded-seam welded pipes use the program package of the German company Data M Software GmbH "COPRA RF" (https://sapr.ru/article/20659), which provides the development and evaluation of the pipe welding line tool. Russian university NUST MISIS (www.misis.ru) also created a computer program "GNUT" for the calculation of roll calibrations for the production of bent symmetrical and asymmetric profiles of practically any real configurations with the issuance of a complete set of drawings [9-11]. The software to date has no analogues in Russia and successfully competes with the software product "COPRA" in the market of Russian manufacturers of various types of curved profiles.

The software product and a computer program complex has been created in the form of a Web-application in Visual Studio in C# with a modern interface has been developed within the framework of the Russian's Federal Target Programme project on the topic: "The organization in Kaliningrad region of a new ecologically balanced high-tech innovative industrial production of welded special-purpose pipes from stainless steels, titanium and heat-resistant alloys using high-speed laser welding and subsequent high-performance thermal and chemical-thermal processing" (unique identifier: RFMEFI57817X0252). The complex is located in the educational environment "Dist" on the portal http://econom.misis.ru [12]. This makes it possible to make the selection of the profiling route as quickly as possible and perform calculation of the roll calibrations for the production of bent symmetrical and asymmetric profiles of virtually any real configurations with the issuance of a complete set of drawings. The algorithm of the program is based on the mathematical model of the strip profiling process [13], it allows calculating the geometric and energy-force parameters of the process. To create an algorithm for designing roll calibrations for the production of bent profiles, a unified description of the shape of the profile was proposed [12]. The left and right halves of the cross section of the profile are treated as separate sets of alternating straight sections and rounds. The configuration of each of them for one and the other half of the profile is entered separately, starting from the middle. For each point of conjugation (the beginning and end of the section), the coordinates, the radius of curvature and the angle of rotation are specified (or will be calculated in the future). The accepted description of the shape of the profile makes it possible to compile a general algorithm for calculating the roll calibrations of virtually any profiles, and not to develop an algorithm for each profile or group of profiles. The software package can be recommended for use in the development of technological processes for a new profile and brand assortment. The software has been registered by the Russian's Federal Service for Intellectual Property No. 2018614644 and 2018614645.

3. Results and discussions

The developed methodology and software were tested in the calculation of the process for the production of welded, straight-seamed pipes on the Olimpia 80 production line, which consists of an uncoiler, a roll opening machine, a sheet straightening machine, a dock splitter, a spiral tape drive and a main deforming section that includes melding and calibration mill. Welded pipes with a diameter up to 320 mm and wall thickness up to 10 mm can be obtained at the mill [14].

The research and analysis of the process of production of tubular billets of the assortment with a maximum diameter (up to 325 mm) and thickness (up to 10 mm) has been performed. The results of calculating the stress-strain state showed that the maximum level of longitudinal tensile deformations and stresses lies in the region of the elastic state, which indicates that there is no danger of corrugation at the edges of the strip. The prediction of residual stresses also showed that they are at a sufficiently low level. This allowed us not to take into account their influence during modeling of the welding process and to consider the tube billet in the form of a butt joint with a given sheet thickness and an infinite surface.

Such a simplification for pipes of increased diameter can be considered justified and permissible. The assumptions made do not fundamentally affect the relevance and practical significance of the problem being solved: the choice of acceptable modes of laser welding and local laser heat treatment in relation to a given rolling mill forming a pipe blank.
The studies of the influence of energy and technological parameters of laser action on the dimensions of the weld pool in the process of continuous laser welding of pipes (108 ÷ 325) mm in diameter from stainless austenitic steels and heat-resistant chromium-nickel alloys has been carried out by methods of mathematical modeling. For the emerging weld, assessments were made of the applicability of the local heat treatment using a laser energy source in a continuous process for the production of welded pipes.

Experimental studies have shown that to interpret the results of the study, it is necessary to apply mathematical simulation modeling that will allow optimizing the welding process both in the deep (dagger) and surface melting modes. This agrees well with the data of [15].

In order to determine the optimal parameters of the laser source (power and speed of movement), a mathematical simulation of the heating of a metal plate by a moving laser source was performed using the ANSYSCFX software package.

The nonstationary temperature distribution \( T(x, y, z, t) \) in a metallic sample is described by a nonlinear heat equation:

\[
c\rho \left( \frac{\partial T}{\partial t} + v \frac{\partial T}{\partial y} \right) = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right),
\]

(1)

Where \( c(T) \) – The value of the heat capacity of the material, taking into account the presence of phase transitions and the structure of the coating \( J/(kg\cdot K) \); \( \rho(T) \) – density of the material, \( kg/m^3 \); \( \lambda(T) \) – effective value of thermal conductivity, \( W/(m\cdot K) \).

The following initial and boundary conditions were used to solve the thermal problem. At the initial time \( t = 0 \), the body temperature \( T = T_0 \), where \( T_0 \) is the body temperature before the onset of laser action. On the surface of the body at \( z = 0 \), where the absorption of laser radiation takes place

\[
\lambda \frac{\partial T}{\partial z} = -q + \alpha(T - T_0),
\]

where \( q \) is the power density of the laser radiation absorbed by the material, \( \alpha \) is the coefficient of heat exchange with the surrounding medium having a temperature \( T_c \). We assume that on the surfaces \( y = 0 \) and \( y = l_y \) the value \( \frac{\partial T}{\partial y} = 0 \). Accordingly, on the surfaces \( x = \pm 0.5l_x \) and \( z = 1 \) the value of \( T = T_0 \).

The paper adopted the normal law of the distribution of the power density of laser radiation along the radius \( r \):

\[
q(r) = q_0 e^{-\left( \frac{r}{r_0} \right)^2},
\]

(2)

where \( q_0 = \frac{AP}{\pi r_0^2} \), \( W/m^2 \); \( A = (1 - R) \) – absorptivity, where \( R \) – reflection coefficient; \( P \) – total power of laser radiation, kW; \( r_0 \) – radius of the focusing spot, m.

In the work modes of welding with deep penetration (keyhole welding) and surface melting (conduction limited) were considered. Such regimes can be easily implemented by using fiber optic lasers with a power (2 ÷ 10) kW [16]. The use of deep penetration welding is more preferable for thick plates. However, in this case, there may be problems in the stability of the penetration of the joint, which reduce the quality of the welded seam [17]. The use of surface melting for high-power lasers is complicated by the difficulties of formation of a large-size spot [1].

Calculations of the thermal state of metal preforms were carried out, the thickness of which was varied within the range (2 ÷ 10) mm with a step \( \Delta = 2 \) mm, when irradiated with a focused source of laser radiation, whose power was varied from 1 kW to 6 kW in 1 kW increments and spot diameter \( d = 2 \cdot 10^{-4} \) m. The value of the speed of movement of the laser beam relative to the surface of the workpiece was selected in accordance with the speed of movement of the pipe blank during molding, which could reach up to 3.0 m/min for a pipe with a wall thickness of 10 mm in the Olimpia 80 mill.
The weld area and its parameters were determined from the 1813 K isotherm, which corresponds to the melting temperature of the sample material (Figure 1).

![Figure 1. The temperature field of the welded plate at a radiation power P = 1 kW and the speed of the laser beam V = 0.5 m/min: a - on the upper surface of the plate; b - on the lower surface of the plate; c - in the longitudinal plane passing through the central line (line 1); d - in the transverse plane along the line of maximum heating of the plate (line 2).](image)

Based on the calculations performed, optimal values of the radiation power density and the speed of the workpiece motion relative to the heat source are determined for each thickness of the billet. Optimum technological modes of penetration of plates of different thicknesses are presented in Figure 3.

Heat treatment for stainless steels of austenitic class consists of heating and subsequent high-speed cooling from a temperature above 1050 °C into water [18]. Under conditions of local laser heating by a moving source, subsequent cooling followed by sufficiently high speeds of the process being realized [15]. They are commensurate with quenching, so it is advisable to investigate the possibility of using laser radiation to conduct local heat treatment by mathematical modeling.
Figure 2. Plots of the temperature variation of the lower surface of the plate: a, c - along the central line; b, d - along a transverse line passing through the point of maximum heating of the plate. Determination of the length (c) and width (d) of the zone of the liquid phase on the lower surface. Radiation power $P = 1$ kW; speed $V = 0.5$ m/min.

Figure 3. The graph of the optimal region of the correspondence between the laser radiation power, the speed of the workpiece movement and the thickness of the blanks that meet the requirements for laser welding of tube blanks, based on the calculation of the thermal field and the hydrodynamic state of the medium of the weld pool.
One of the difficulties in carrying out the process of laser heat treatment is to ensure uniformity of heating across the thickness of the weld. We call it locally volumetric, since we need to talk about some local volumes of the product, where the temperature gradient does not exceed 25 °C/mm during the heating process. Therefore, a locally-volumetric laser thermal treatment for a full cycle of heat treatment under conditions of simple rectilinear motion of a laser beam can be carried out for welded structures with a thin wall.

**Figure 4.** Temperature distribution on the surface of the billet under thermal treatment by laser radiation with a power $P = 0.2$ kW: 

- a - $d = 3.0$ mm; $W = 3.1 \times 10^8$ W/m$^2$; $V = 0.12$ m/min; 
- b - $d = 3.4$ mm; $W = 2.3 \times 10^7$ W/m$^2$; $V = 0.12$ m/min; 
- c - $d = 4.2$ mm, $W = 1.5 \times 10^7$ W/m$^2$; $V = 0.09$ m/min; 
- d - $d = 4.2$ mm, $W = 1.5 \times 10^7$ W/m$^2$; $V = 0.06$ m/min; 

1 – upper (workpiece) surface; 2 – lower (opposite to the treated surface).

In this approximation, the temperature field was calculated in the course of thermal treatment by a laser source of a straight-seam butt weld in moving tube billets 2 mm thick with a change in the velocity of the workpiece ($V$) and the diameter of the laser spot ($d$). The results of the investigations are shown in Figure 4.

The results of the studies show that simultaneous increase in the diameter of the spot of the laser beam and an increase in the speed of motion of the workpiece leads to a decrease in the temperature of heating of the workpiece, and also influences the temperature gradient between the upper and lower surfaces of the plate in the direction of its decrease.
At large thicknesses for welded seams of products from stainless steels, to which high requirements of intercrystalline corrosion are not required, one can speak of surface heat treatment. In this case, only the surface layer of the welding seam is exposed to the thermal influence, in order to eliminate possible welding defects or to carry out surface structural and phase changes in the weld material and the weld zone. It is advisable to increase the efficiency of such heat treatment in the following ways. First, by controlling the sign of the elastic stresses arising in the tube blank on its outer and inner surfaces during shaping. Secondly, the formation of thermal elastic stresses, which are partially compensated by the already existing deformation elastic stresses on the outer surface of the welded pipe. Thirdly, by applying non-through (surface) heating of the weld, we keep the compressive elastic stresses on the inner surface of the welded pipe, as a positive factor for a welded pipe operating under pressure. Fourth, surface heat treatment should allow local surface overheating (with respect to optimal heat treatment) to the temperature that facilitates the removal (healing) of defects in the form of surface microcracks and pores (caverns) with a highly developed surface ("torn" edges).

To form a through laser thermal treatment on pipes with a thickness of more than 5 mm, it is necessary to proceed to the regime of complex scanning with elements of reciprocating and rotational motion of the beam along the surface being treated [1, 16] and special methods that significantly increase the absorbing capacity of the surface being treated [19] and thermal conductivity of the processed material [20].

For the realization of the through heat treatment of the weld and the weld zone pipes with a larger wall thickness, it is necessary to use more complex reciprocating and rotational scanning schemes with overlapping of the treated surface with a laser beam, including using multibeam laser heads and various degrees of defocusing of the incident beam.

To achieve the required level of properties, improve quality and reliability laser tubes working under pressure, in certain cases it is permissible to apply surface laser thermal treatment that allows healing of surface defects and retaining compressive elastic stresses on the inner surface of the welded pipe.

4. Conclusions
Mathematical modeling and theoretical calculations of the thermal field and hydrodynamic state of the weld puddle of the medium, formed by laser irradiation of a planar continuous translationally moving butt preform stainless austenitic steel or a superalloy based on nickel, have shown that for realization of continuous welded longitudinal laser welding the plates (round billets) with a thickness of up to 10 mm at a speed up to 3 m/min, technological solid-state fiber-optic lasers with a power of up to 6 kW can be used.

The calculated technological parameters of laser heat treatment make it possible to state that the achieved temperature field in the zone of action of laser radiation is completely within the range of the recommended heat treatment for austenitic stainless steel.

The principal possibility of realization in the production cycle conditions for continuous locally bulk laser heat treatment at a speed of 3 m / min direct butt weld (width 3 mm) on the tubes of stainless austenitic steels and superalloys based on nickel having a diameter of 320 mm and a thickness of 3 mm has been demonstrated

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To achieve the required level of properties, improve quality and reliability laser tubes working under pressure, in certain cases it is permissible to apply surface laser thermal treatment that allows healing of surface defects and retaining compressive elastic stresses on the inner surface of the welded pipe.
A computer program complex for calculating parameters technological processes, including calibration rolls for the new profile and Grades in the form in Visual Studio Web-based applications in C# with a modern interface, which is placed in the educational environment "Dist" on econom.misis.ru portal has been developed. The developed methodology and programs were tested when calculating the process of production of welded straight-through pipes on the production line of Olimpia 80.

The results of the calculation of the stress-strain state showed that the maximum level of longitudinal tensile deformations and stresses lies in the region of the elastic state, which indicates that there is no danger of corrugation at the edges of the strip.

The use of the software package allows you to control the amount of residual stresses in the pipe billet and purposefully form a residual total stress in the welded pipe that is inhomogeneous in thickness. This allows us to develop a process of continuous surface laser heat treatment of the welded joint and the weld zone, which can reduce the tensile stresses of the outer surface and preserve the compressive stresses of the internal surface of the laser welded pipe. For pipes operating under pressure, this treatment should improve their quality and reliability.

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