LASER WELDING OF ROOT WELDS OF THICK JOINTS OF HEAT-RESISTANT STEEL

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Technology of laser welding of root welds from heat-resistant steel is described. Optimum conditions for sound formation of root welds with complete penetration and smooth transition from the back bead to the base metal were determined.

Keywords: *laser welding, heat-resistant steel, power, beam, filler wire, welded joint, root pass, weld*

Ensuring the reliability and operability of critical components of turbounits, for instance rotors of powerful steam turbines, is a challenge. One of the most urgent problems here is sound performance of root welds of the rotor joints. Considering the structural features, welding is performed under complicated conditions and performance of NDT is difficult. On the other hand, item geometry, its service life and reliability as a whole depend on welding the root welds. At present, root welds of rotors of low pressure cylinders are made by nonconsumable-electrode argon-arc welding in the gravity position or on a permanent steel backing (for low pressure cylinders of slow-speed turbines). With such a welding process, however, it is difficult to ensure a stable 100 % penetration of weld root around the entire joint perimeter, particularly in manufacturing large-sized rotors of powerful turbines. A significant drawback of making the root welds on a backing ring is formation of structural-technological lack-of-penetration, which, being a potential stress raiser, promotes lowering of the level of fatigue strength and increase of brittle fracture susceptibility. Therefore, finding a method to make the root weld with 100 % penetration and ensuring back bead formation, is a technological priority.

The objective of this work was investigation and determination of optimum conditions to produce sound root welds with back bead formation in laser welding of thick metal of heat-resistant steel. This required solving a number of procedural and technological problems, related to laser type selection, determination of its optimum power, selection of shielding gas and groove geometry, establishing laser welding parameters and optimization of welding technique.

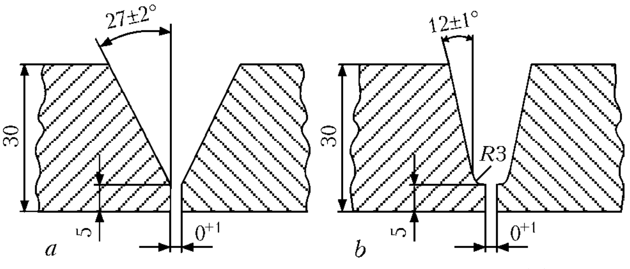


Figure 1. Schematic of edges for laser welding of V- (*a*) and U-shaped (*b*) groove

Investigation procedure envisaged application of 25Kh2NMFA rotor steel 30 mm thick as the base material, as well as steel 20, 5 mm thick, for preliminary experiments on optimization of individual parameters of the mode of welding the root face of 25Kh2NMFA steel butt joint (Figure 1). Root face thickness equal to 5 mm was selected on the grounds of convenience of assembly and minimum section of the root weld, meeting the strength requirements.

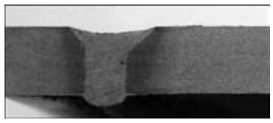
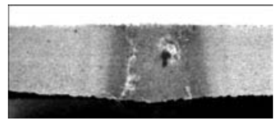
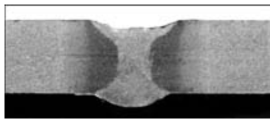
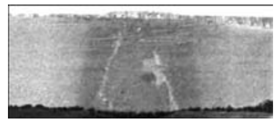
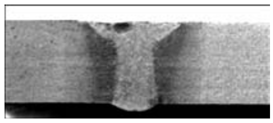
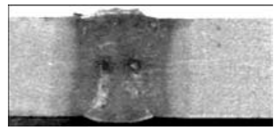
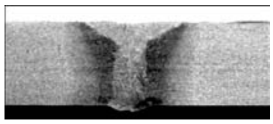
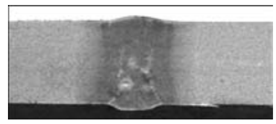
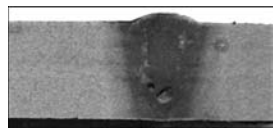
Used as the radiation source was solid-state laser of DY 044 type (Rofin Sinar, Germany). Radiation power is known to have an essential influence on the penetrability and nature of weld formation [1]. Increase of radiation power improves both the effectiveness of beam action, and penetration depth and weld width. Experiments on determination of welding mode parameters were conducted on butt samples of 300 × × 150 × 5 mm size from steel 20 (wt.%: 0.196 C; 0.2 Si; 0.49 Mn; 0.019 S; 0.017 P) without edge preparation at different radiation power from 2.5 up to 4.0 kW. Radiation was focused by a lens with focal distance of 200 mm. Welding was conducted with three-axis manipulator [2]. As a rule, shielding by a gas jet aimed into the zone of laser radiation action on the metal is used in laser welding. Shielding weld metal from oxidation, the gas jet deflects the vapour flow and spatter from the axis of laser radiation propagation and lowers the screening action of plasma, present in the crater and above the irradiated surface. CO_2 gas and CO_2 + + 18 % Ar mixture were used as shielding gases.

Welded joint quality was the main criterion for establishing the optimum conditions and parameters of laser welding. Quality control was performed by studying the macrostructure in the cross-section of templates cut out of welded joints. Joint quality was considered to be satisfactory in the absence of pores, cracks, lacks-of-fusion, slag inclusions, as well as in case of correspondence to standards of concavity and convexity of weld root from the reverse side.

It is seen from Table 1 that carbon dioxide gas provides the best shielding of weld metal. In welding in the mixture at the selected welding speed pores were formed.

Table 2 gives the data on the influence of radiation defocusing on penetration geometry in shielding with

Table 1. Influence of radiation power and shielding gas on macrostructure and geometry of welded joint of steel 20, 5 mm thick

Power, kW	CO_2	CO_2 + 18 % Ar mixture
4.0		
3.5		
3.0		
2.8		
2.5		

carbon dioxide gas and CO_2 + Ar mixture. The surface of welded parts was located above or below the lens focal plane, where the focused beam has the smallest diameter. Focused beam diameter has direct influence on power density and on penetration geometry, respectively. The best results are achieved at lowering of the focal point under the sample surface for 2 mm. In all the variants it is rational to shield the radiation zone with carbon dioxide gas. When gas mixture and selected welding speed were used pores formed practically in all the cases. Therefore, in further experiments the main shielding was performed with carbon dioxide gas (feeding to pool head). For additional shielding of the solidifying metal, argon was fed to the pool tail part.

The main features of welding heat-resistant steels of the pearlitic class are their high sensitivity to the rate of cooling below austenitization temperatures and need to preserve structural stability, as well as mechanical properties, the level of which is achieved largely by thermal strengthening of steel before welding [3]. Considering the high susceptibility of these steels to formation of brittle hardening structures in the HAZ metal, welding should be performed with preheating and concurrent heating, and welded joints should be treated by high tempering. In addition, in order to reduce the risk of cold cracking in multipass welding of more than 20 mm thick metal, it is recommended to weld the weld root by a more ductile material than when filling the groove (in nonconsumable-electrode argon-arc welding Sv-08G2S or Sv-08GS

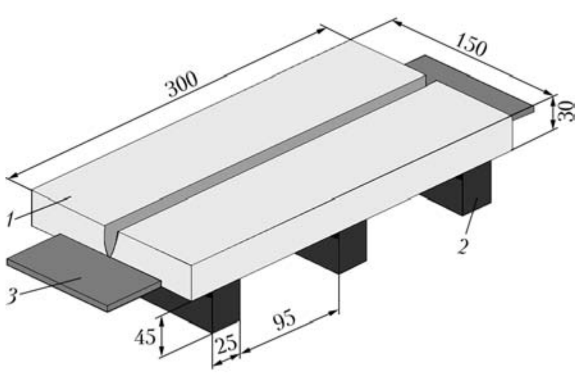


Figure 2. Schematic of rigid sample from 25Kh2NMFA steel: *1* — plate; *2* — stiffener; *3* — run-off tab

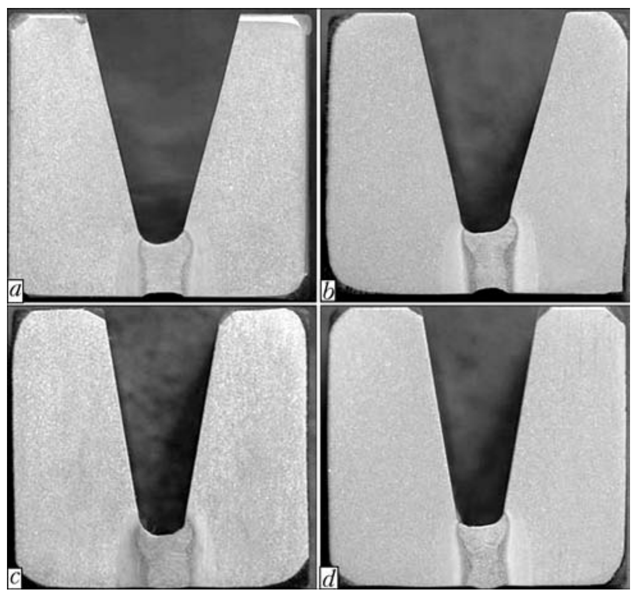
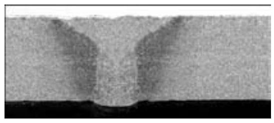
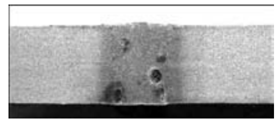
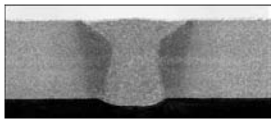
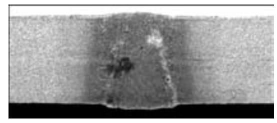
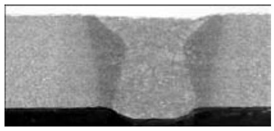
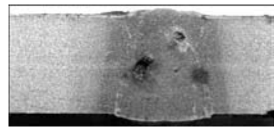
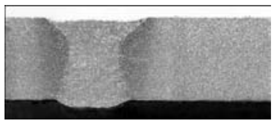
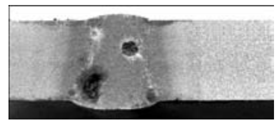
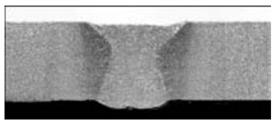
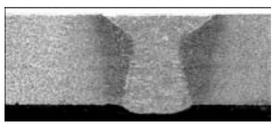
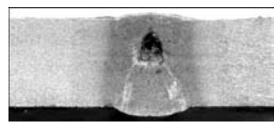
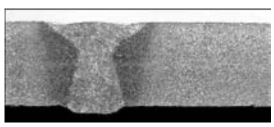
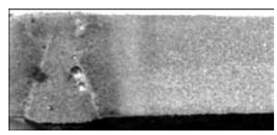
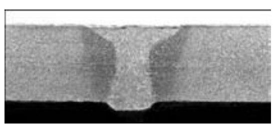
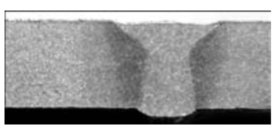
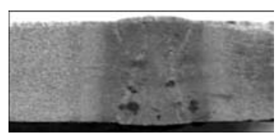


Figure 3. Macrosections of the root weld made by laser welding with V- (*a, b*) and U-shaped (*c, d*) groove and 5 mm root face

Table 3. Influence of radiation defocusing and shielding gas on macrostructure and geometry of welded joint of steel 20, 5 mm thick

Lowering	CO_2	CO_2 + 18 % Ar mixture
+5		
+3		
+2		
+1		
0		
−1		
−2		
−3		
−5		

wire is used). In this connection subsequent experiments on making the root welds of 25Kh2NMFA rotor steel joints (wt.%: 0.22 Cr; 0.3 Si; 0.44 Mn; 1.87 Cr; 1.38 Ni; 0.36 Mo; 0.04 V; 0.009 S; 0.008 P) were conducted with preheating to 250–300 °C and using ductile filler wire.

Optimisation of the technology of laser welding of root welds of butt joints on 25Kh2NMFA steel 30 mm thick was conducted on rigid samples (Figure 2) with and without filler wire feed. Sv-08G2S wire of 1.2 mm diameter was used as filler material. Several geometries of rigid butt edge preparation were studied for making the root welds (see Figure 1). U-shaped groove turned out to be the best (Figure 1, *b*). Root face was 5 mm in all the cases. Selection of groove type was aimed at obtaining a welded joint with a good weld root penetration at minimum consumption of deposition metal, while keeping the groove shape simple to produce. U-shaped edge preparation compared to V-shaped groove required a smaller amount of deposited metal, and owing to a wide gap in the weld root, it facilitates the process when making the first root weld. In welding with a V-shaped groove without filler wire, the weld has a weaker section, is drawn inside from the groove reverse side (Figure 3, *a*), and the probability of fracture of such a weld is quite high. In welding with a V-shaped groove with application of filler wire (Figure 3, *b*) the section is somewhat larger, but back bead formation in unacceptable, in view of the presence of a kind of concentrator (groove instead of the root bead).

Processing and generalization of the results of investigation of welded joint quality showed that selection of laser welding parameters and filler wire feed rate allows achieving the optimum geometry, satisfactory formation and required reinforcement of the weld root.

Conducted studies showed that radiation of Nd:YAG laser of 4.4 kW power at welding speed of 16 m/h allows making in the butt joint a root weld with complete penetration and good formation of the back bead.

Optimum mode of welding the root welds in the joints of 25Kh2NMFA steel with U-shaped groove (Figure 3, *c, d*) is as follows: radiation power of 4 kW; welding speed of 16 m/h; focal distance of 200 mm; focal point deepening to 2 mm; gas flow rate: CO_2 — 20 l/min (to pool head), Ar — 10 l/min (pool tail part); feed rate of 1.2 mm wire — 38.4 m/h.

Thus, results of experiments on laser welding of root welds in the downhand position showed that with the appropriate fit-up and following the welding modes complete penetration of the weld root without defects (pores or cracks) with good formation of the back bead is ensured.

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OPTIMAL CONTROL OF FORMATION OF WELD REINFORCEMENT

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Method is proposed for development of the optimal system for automatic control of formation of the weld reinforcement with transportation lag in the feedback loop under MAG welding conditions. A dynamic model of formation of the weld reinforcement was developed to build the optimal controller. Mathematical modelling was performed by using the MATLAB software package. The developed control system provides a minimal duration of the process at preset limitations of dynamics of the adjustment actions.

Keywords: *MAG welding, dynamic model, weld reinforcement formation, mathematical modelling, optimal control system, transportation lag*

Achieving the optimal weld shape is one of the key tasks in fabrication of welded structures. This is explained by the fact that at the optimal shape of the weld reinforcement it is possible to decrease values of the stress concentration factor and improve performance of welded structures. Moreover, the required weld sizes allow minimising overuse of welding consumables under mass production conditions. Up to now, formation of the weld has been controlled by using an open circuit, through setting the welding process parameters. Peculiarities of design of the open systems to control formation of the welds, based on regression models, are considered in study [1]. Also, the weld shape can be controlled by using mechanical oscillations of the welding tool and magnetic control of the weld pool [2]. All open methods for control of the weld formation share one drawback, which is related to the absence of the mechanism to compensate for external disturbances, which affect a workpiece during the arc welding process and may lead to deviations of geometric parameters of the weld from the preset values. For example, such disturbances include ambient parameters, state of the surface and deviations of geometric parameters of a welding object. One of the methods to compensate for the external disturbances is to use the closed feedback systems for automatic control of the weld formation. A promising area of further advancement of the arc welding control systems is development and investigation of optimal and adaptive systems, the main advantages of which are considered in studies [3–5]. The necessity of applying the optimal control theory methods to welding is associated with high requirements for reliability and durability of welded structures [6].

The purpose of this study was to develop a system to control formation of the weld in MAG welding by using a laser TV sensor (LTS) in the feedback circuit to measure geometric parameters of the weld reinforcement bead.

Formalise the control problem, i.e. replace the control object by a mathematical model that describes essential peculiarities of the control problems and goals. The process of formation of the weld bead is a multidimensional connected control object, the behaviour of which can be described in first approximation by a system of first-order differential equations. In the state space, the object equations have the following forms:

$$\mathbf{x} = \boldsymbol{A}\mathbf{x} + \boldsymbol{B}\mathbf{u} + \boldsymbol{V}_0, \quad (1)$$

$$\mathbf{y} = \boldsymbol{C}\mathbf{x} + \boldsymbol{V}_o, \quad (2)$$

where $\mathbf{x}$ is the vector of state variables of the bead formation process $(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_n)^T$; $\mathbf{u}$ is the vector of control actions of the welding process $(\mathbf{u}_1, \mathbf{u}_2, \ldots,$