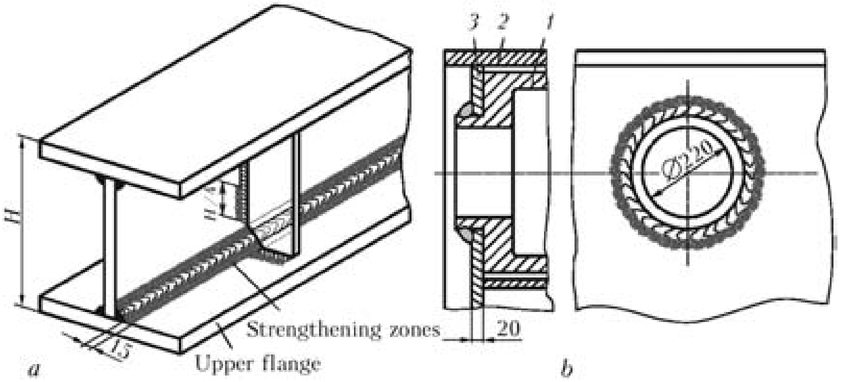

Figure 6. Strengthening zones of welded joints (darkened) of crane beams (*a*) and balance beam of well cranes (*b*): *1* — bushing; *2* — upper flange; *3* — web

Another critical welded structure subjected to cyclic loading and formation of fatigue fractures is a balance beam of well crane «Slabing-1150». It was found by the service of master mechanic together with authors that effect of alternating loads caused service life of a balance beam to be not more than three months before initiation of crack along the weld or HAZ metal at the distance of 5–10 mm from the fusion line in the zone of welding-on of a bushing to the body of a balance beam (Figure 6, *b*).

At the beginning of 2007, basing on the results represented in this article, two balance beams of well cranes were treated using a ball-rod strengthener. Nowadays the life of balance beams after such strengthening treatment reached 15-times increase. The operation of balance beams is continuing, thus proving high technical and economic efficiency of strengthening treatment using the ball-rod strengthener.

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LASER WELDING OF THIN-SHEET STAINLESS STEEL

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Peculiarities of laser welding of the 0.15 and 0.20 mm thick austenitic stainless steel sheets were studied. It was shown that at a certain power of the laser beam the experimentally measured width of the weld could be satisfactorily described by the model of a linearly moving source in a homogeneous approximation. Increase in power of the laser beam results in formation of a hole on the surface being welded, through which part of the beam power goes away, thus leading to violation of correlations with the model. Based on the peculiarities revealed, a procedure is proposed for determination of optimal welding parameters to provide the maximal effective efficiency of the process.

Keywords: *laser welding, stainless steel, thin sheet, effective efficiency, quality criteria, weld width and shape, weld metal structure, strength*

Butt laser welding of thin (δ = 0.1–0.2 mm) stainless steel sheets is applied for manufacture of tubular billets to produce bellows. A prompt selection of optimal welding parameters is required under the small-scale production conditions because of a large number of different types of the billets.

Domestic and foreign literature comprises an insignificant amount of publications dedicated to estimation and effect of the laser welding parameters on properties of the butt joints on thin stainless steels, and disclosing methods for selection of optimal technological modes [1–6].

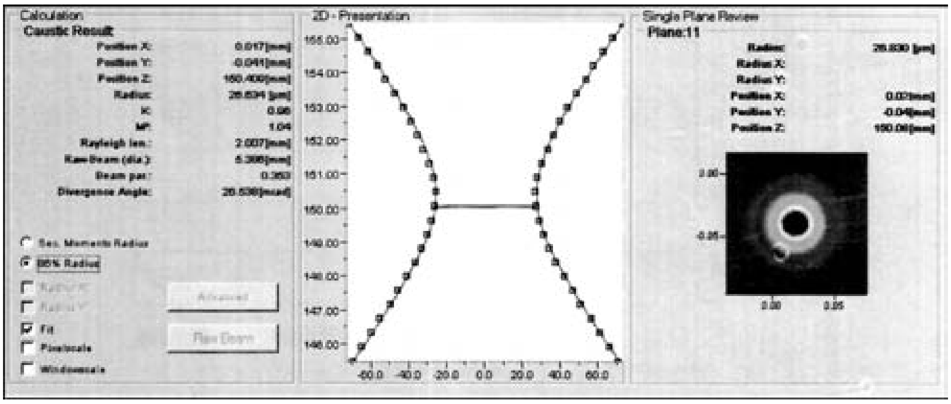

Figure 1. Characteristics of the beam of laser LS-01-B determined by using software «Primes Laser Quality Monitor»

The purpose of this study was to determine relationship between parameters of laser welding of thin-sheet stainless steel and quality criteria of the welded joints, as well as to develop a procedure for selection of the welding parameters in the manufacturing environment.

Experimental materials and equipment. Strips with δ = 0.15 and 0.20 mm, made from steels 12Kh18N10T and 1.4541 (according to DIN EN 10028-7:2000, the latter being a close analogue of steel 08Kh18N10T) were welded.

The samples were welded by using three-coordinate laser system ARMA-100M (manufacturer — E.O. Paton Electric Welding Institute) equipped with the 100 W single-mode ytterbium fiber laser of the LS-01-B type (manufacturer — Research and Production Company IRE-Polus, Fryazino, Russian Federation), the generating core of which had a diameter of 10 μm. Characteristics of the laser beam are shown in Figure 1 [7]. The laser radiation was focused on metal into a 40 μm diameter beam.

Helium (from the top of the welded joint) and argon (from below) were used as shielding gases. The following data on consumption of some shielding gases and their mixtures were obtained experimentally, m^3/s: He $(50-60)\cdot10^{-5}$, He + 50 % Ar $(45-55)\cdot10^{-5}$, and Ar $(15-20)\cdot10^{-5}$.

Both butt welded joints and penetration welds on a whole metal sheet were investigated. The sheets for butt welding were cut by sheet shears with electric drive MHSU 1000×2.0 (Schroeder Maschinenbau, Germany). The device in which the sheets to be welded were abutted provided minimal deplanation of edges.

Strength of the welded joints was tested by using tensile testing machine FP10/1. Width of the welds was measured in a region produced under the steady-state thermal conditions of welding by using small toolmaker's microscope MMI-2. Geometry of the weld and strength of the joint were chosen as key criteria of quality of the welded joints.

Main requirements to geometry of the weld on tubular billets of bellows were verticality of the fusion line and absence of rolls and sags. With these requirements it is possible to investigate only the relationship between the welding process parameters and width of the weld.

Effect of welding speed on weld (penetration) width. Samples of steel 12Kh18N10T with thickness of 0.15 mm were welded and penetrated at constant laser power $P = 65$ W, and those of steel 1.4541 with thickness of 0.15 and 0.20 mm were welded and penetrated at $P = 55$ and 60 W, respectively. Welding speed v_w was varied from 0.8 to 2.5 cm/s. Dependencies of the weld width and effective efficiency on the welding speed for the samples of the above steel grades are shown in Figure 2.

Curve *1* in Figure 2 (experimental data) shows variations in width of the welds on steel 12Kh18N10T with thickness of δ = 0.15 mm depending on the weld-

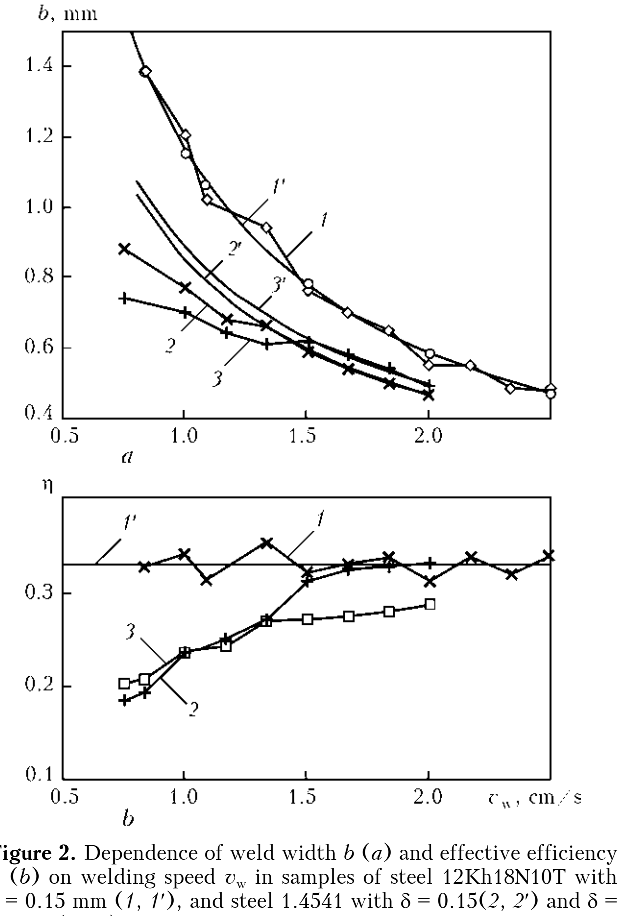

Figure 2. Dependence of weld width b (*a*) and effective efficiency η (*b*) on welding speed v_w in samples of steel 12Kh18N10T with δ = 0.15 mm (*1*, *1'*), and steel 1.4541 with δ = 0.15(*2*, *2'*) and δ = = 0.20 (*3*, *3'*) mm

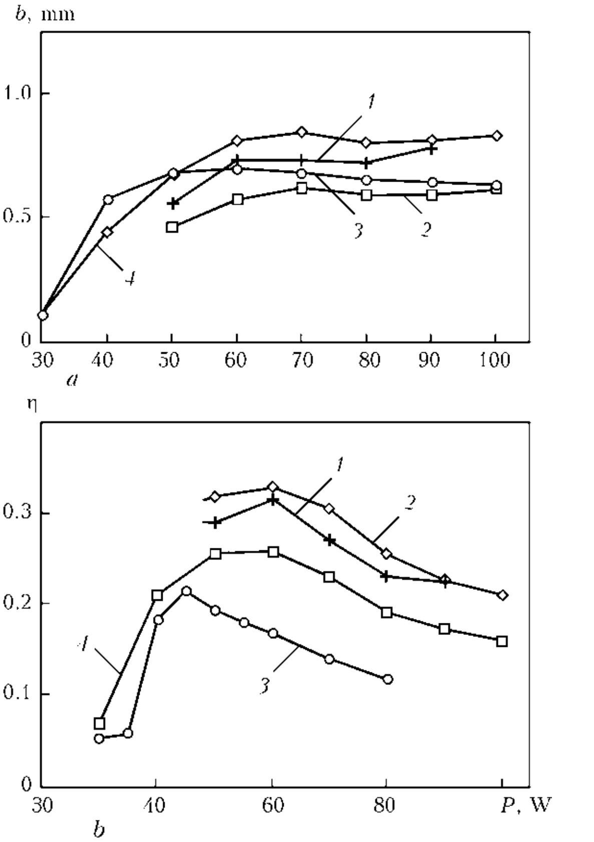

Figure 3. Dependence of weld width b (a) and effective efficiency η (b) on the beam power in samples of steel 12Kh18N10T with δ = = 0.15 mm at v_w = 1.5 (*1*) and 2.0 (*2*) cm/s, and steel 1.4541 with δ = 0.15 (*3*) and 0.20 (*4*) mm at v_w = 0.8 cm/s

ing speed, whereas curve *1'* was calculated by the least square method as $b = f(v_w)$. As seen from the Figure, all of the experimental points fit well the hyperbolic curve described by expression

$$b = 2.981 \cdot 10^{-3} + 1.163/v_w. \quad (1)$$

For steel 1.4541 the hyperbolic dependence takes place only at a high welding speed (compare curves *2*, *2'* and *3*, *3'* in Figure 2, *a*). Moreover, for the steel strip with δ = 0.20 mm this dependence holds at a somewhat lower speed than for the strip with δ = = 0.15 mm. At both values of the strip thickness and a low welding speed the weld width is smaller than it follows from the hyperbolic dependence determined from the experimental data at a high welding speed.

Dependence of weld width on laser radiation power. The experiments were carried out at constant welding speeds v_w = 0.8, 1.5 and 2.0 cm/s and at a power varied from 30 to 100 W. The results obtained are shown in Figure 3, *a*.

In the samples of steel 12Kh18N10T with δ = = 0.15 mm and at a welding speed of 1.5 and 2.0 cm/s the weld width grows with a power increased to 60 W (curves *1* and *2* in Figure 3, *a*), whereas the weld width hardly depends on it at higher values of P.

The samples of steel 1.4541 with δ = 0.15 and 0.20 mm were welded at welding speed v_w = 0.8 cm/s. At a power of 30 and 40 W the weld width was almost the same as in the samples of steel 12Kh18N10T with δ = 0.15 mm. The growth of the weld width slowed down with increase in the P values, and at $P \geq 60$ W the value of b remained almost unchanged (see curves *3* and *4* in Figure 3).

Strength characteristics of welded joints. The joints were made by using argon (from below of a welded joint) and helium (from the top) as shielding gases. The Table gives results of tensile tests of the welded joints. Comparison of these results shows that the strongest joints most fully meeting the specification requirements were produced at a laser beam power of 50–65 W and welding speed of 1.0 to 1.8 cm/s.

Metallographic examinations of weld metal. The samples of the 1.4541 steel strip (base metal had austenitic structure with precipitated carbonitrides) were examined. The samples were welded at laser beam power P = 40, 50, 60 and 70 W and v_w = 1 cm/s. The samples were etched by the electrolytic method in 20 % solution of chromic acid. Hardness was measured with LECO microhardness meter M-400 under a load of 0.98 N. The content of ferrite was determined by using ferrite meter «Ferritgehaltmesser 1,053» (Germany).

The following conclusions can be made based on the metallographic examinations of the said samples:

- at a laser beam power of 40–70 W and welding speed of 1 cm/s the fusion lines are located almost vertically, and there are no rolls and sags (Figure 4);
- columnar crystalline grains are located at the end of the cast zone, and equiaxed crystals are at the centre;
- hardness of the weld metal increases insignificantly (by 13–17 %) compared to the base metal (hardness of the base metal is *HV*01 156–165, hardness in the central part of the weld is *HV*01 176–193, and that in the heat-affected zone is *HV*01 165–181);
- content of the ferrite phase increases from 0 (in the base metal) to 0.15 vol.% (in the weld metal) with increase in the laser beam power.

Results and discussion. The model of a moving linear concentrated source in a homogeneous approximation with Gaussian distribution of the radiation intensity, at which the temperature at any point of a sheet is the same or thickness-averaged, was taken as a scheme for calculation of metal heating [8].

Comparison of practical results (see Figure 2) with the calculated ones showed that the speed values coincided in a certain range. Besides, maximal temperature T_{max}, which is achieved at distance y_0 from the weld axis, can be determined by the following expression [9]:

$$T_{max} = \frac{0.484q}{v_w c\gamma 2y_0}\left(1 - \frac{\beta y_0^2}{2a}\right)^2, \quad (2)$$

where q is the thermal power of the laser beam; $c\gamma$ is the volumetric heat capacity; β is the heat transfer coefficient; and a is the thermal diffusivity coefficient. At T_{max} equal to the melting point of the investigated steel, $2y_0 \equiv b$. As welding is performed at a high speed, it can be assumed that the surface heat transfer is negligible ($\beta = 0$). Then dependence of the weld width on the welding speed can be described by the hyperbolic dependence.

Approximation function (1) differs from dependence (2) in a free term. However, its value is so low that it can be neglected. Good agreement of dependencies (1) and (2) in some regions of the weld is indicative of low and stable heat losses taking place during dwelling of such a region at the melting point.

It is a common practice to characterise efficiency of the welding process by the value of effective efficiency η, which is usually determined by the calorimetry method. However, this method fails to give reliable results in welding of thin sheets with a low-power laser source. The calculated value of η can be used for qualitative estimation of the efficiency of the welding process. We use formula (2) to calculate the thermal power required for penetration of the sheet to a width whose values were determined experimentally. The ratio of the calculated value of the thermal power to the laser beam power gives us the value of the coefficient of utilisation of the laser beam power or effective efficiency η.

The following thermal-physical characteristics of stainless steel were used to calculate η: thermal conductivity coefficient $\lambda = 0.25$ W/(cm·K) (for high-alloy steels the values of λ grow with increase in temperature approximately up to 1100 K, above which the values of λ for different steel grades in the austenitic state are close to each other and do not exceed 0.25–0.33 W/(cm·K) [9], the lowest value of λ out of the probable ones was taken because of its increase at a low temperature); specific heat $c = 3.97$ J/(m^3·K) (0.46 kJ/(kg·K)); thermal diffusivity coefficient $a = 0.063$ cm^2/s; and melting point $T_{max} = 1673$ K [10]. Dependence of the coefficient of the effective efficiency on the welding speed and laser beam power is shown in Figures 2, *b* and 3, *b*, respectively.

According to expression (2), the weld width is directly proportional to the thermal power of a linear source. However, as evidenced by the experimental data, this dependence for steels 12Kh18N10T and 1.4541 holds only in the initial region of the curve (at a low power value), with increase in the power the weld width depends just insignificantly on P. For steel 1.4541 the weld width at a low welding speed is smaller than that following from the hyperbolic dependence (see Figure 2, *b*). It is shown in this Figure that in the regions of the hyperbolic dependence of the weld width on the welding speed the value of the calculated effective efficiency is constant and equal to $\eta = 0.33$ or close to it. In the regions where the experimental value of η deviates from the hyperbolic dependence, $\eta < 0.33$, the higher the deviation, the lower being this value.

Strength characteristics of welded joints produced at different welding parameters and using different shielding gases

Sample No.	P, W	v_w, cm/s	Tensile force F, MN	Elongation δ, %	Shielding gas
1	65	1.82	65.8	25.0	Helium
2	50	1.00	81.6	25.0	Same
3	60	1.25	86.7	28.0	»
4	65	1.67	45.0	12.5	Argon
5	50	1.00	57.3	16.3	Same
6	60	1.25	60.0	22.0	»
Base metal	–	–	63.6	32.4	–
Specification	–	–	≥54.0	≥20.0	–

As seen from Figure 3, *b*, $\eta < 0.07$ at the lowest values of the power ($P < 40$ W), while with increase in power the effective efficiency grows to the values close to 0.33, and then decreases. The lowest values of η correspond to incomplete penetration of the sheet. The resulting $\eta = f(P)$ dependence can be explained as follows. The metal surface melts with increase in the beam power, the coefficient of absorption of laser radiation growing. This is followed by formation of a crater and keyhole, resulting in increase of the radiation absorption and effective efficiency. This mechanism works until the values of the beam power, at which the keyhole depth becomes equal to the sheet thickness, are achieved and until η amounts to the maximal value. Further increase in the beam power causes formation of a hole in the crater bottom, via which part of the laser radiation passes through the sheet transferring no energy to the metal edges. In this case the effective efficiency dramatically decreases. As in our case the diameter of the neck of the focused beam is approximately 0.04 mm, the calculated diameter of the linear source and temperature of its side surface should insignificantly depend on the power [11]. Growth of the laser radiation power

Figure 4. Macrosection (×200) of the joint on sheet steel 1.4541 with $\delta = 0.20$ mm welded at $v_w = 0.8$ cm/s and $P = 60$ W

Figure 5. Appearance of three-coordinate system of the ARMA-100M type for laser welding

leads to increase in the diameter of the hole formed inside the linear source and, hence, to the energy losses. With this the weld width is many times in excess of the diameter of the linear source and remains almost unchanged.

It can be concluded on the basis of estimates of the efficiency of the welding process that the technological parameters of welding can be selected from the maximal value of the effective efficiency.

Based on the above-said, formulate the procedure for determining the optimal technological parameters of laser welding of thin-sheet stainless steel billets: it is necessary to set the weld width required from the technological standpoint; experimentally determine dependence of the weld width on the welding speed, $b(v_w)$ at P = const; calculate the maximal value of the welding speed, $v_{w\ max}$, at which the rectangular weld geometry is provided; experimentally determine dependence $b(P)$ at $v_w = v_{w\ max}$; and find the inflection point, at which the value of the weld width, b, remains unchanged with further increase in laser radiation power P. The obtained values of the welding speed are optimal in terms of the maximal efficiency of the welding process.

This procedure was used for the development of the technology for laser welding of small batches of different-diameter longitudinal thin-walled stainless steel pipes intended for manufacture of bellows. The designed three-coordinate laser welding systems of the ARMA-100M type (Figure 5) were applied at Joint Stock Company «Kiev Central Design Bureau of Armature Engineering» (Kiev) and SRIC ARMATOM Ltd. (Kiev). Application of the developed procedure together with the ingenious technological fixture allowed achieving the monthly productivity of one such system equal to 5000 tubular billets for the manufacture of bellows. The bellows (Figure 6) were certified according to the OIT (Certification of Equipment, Products and Technologies for Nuclear Plants, Radiation Sources and Storage Facilities) certification system to correspondence to the requirements of the Russian codes, as well as other regulation documents that set requirements to ensuring safety in the field of utilisation of atomic energy in the Russian Federation.

Figure 6. Samples of multilayer bellows manufactured by laser welding of tubular billets of steel 1.4541 with δ = 0.15 mm

The products manufactured are used in different types of stop valves operating in increased-pressure pipelines and under constant high- and low-frequency vibrations, and in locking assemblies requiring precise adjustment of position of a locking element.

CONCLUSIONS

1. As experimentally established, the sound welded joints meeting the corresponding specification requirements can be provided at a laser beam power of 50–65 W, welding speed of about 1 cm/s, and helium (from the top) and argon (from below) used as shielding gases.

2. The procedure was developed for determination of optimal technological parameters to provide the maximal efficiency of the welding process under production conditions.

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