TECHNOLOGICAL PECULIARITIES OF LASER WELDING OF MEDIUM-CARBON ALLOYED STEEL

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Technological peculiarities of 4.4 kW Nd:YAG laser welding of medium-carbon steel of the Fe–Cr–Mn–Si alloying system, 3.0 to 10.4 mm thick, in one pass with through penetration have been studied. Compared with argon-arc welding, the present welding method provides 6–12 times reduction of time of machine welding, 2.5–4.5 times decrease in power consumption and 12 times decrease in consumption of filler metal.

Keywords: *laser welding, medium-carbon alloyed steel, penetration, welded joint, hardness, efficiency*

A-TIG arc welding with through penetration without backing is successfully used for joining of steel of up to 6 mm thickness and multipass A-TIG + TIG welding with bevel edges is applied at higher steel thickness though filling the groove by filler material. However, argon-arc welding is a low efficiency process and characterizes by higher heat input in the metal.

Laser welding with deeper penetration [1] is proposed for widening a nomenclature of welded parts and increase a quality of their joining. Therefore, obtaining of new experimental data on evaluation of technological peculiarities of laser welding of alloyed steels is of the interest.

Peculiarities of formation of butt joints from S = = 3.0, 6.0 and 10.4 mm thick medium-carbon steel of the Fe–Cr–Mn–Si alloying system (KhGS) using Nd:YAG laser DY 044 (Rofin Sinar, Germany) of up to 4.4 kW power including in combination with TIG welding were studied in the work. Lens with focal length F = 300 mm was used for irradiation focusing. Ar, He, CO_2, Ar + 17 % CO_2 + 1 % O_2 and N_2 were applied as shielding gas.

Single pass welding of alloyed steel of 3 mm thickness with $v_w \geq 150$ m/h speed at $p/v_w \leq 29$ W·h/m linear consumption of electricity and $q/v_w \leq$ ≤ 105 J/mm heat input (Table 1, Figure 1) was carried out using the laser of indicated power. Reduction of power of laser irradiation up to 3 kW (1.47 times) necessitates the 5 times reduction of welding speed and 3.4 times increase of p/v_w and q/v_w. Welding speed should be reduced up to 60 and 48 m/h, p/v_w and q/v_w are to be risen up to 73.3 and 91.6 W·h/m and to 264 and 330 J/mm, respectively, for through penetration of 6 mm thick steel at 4.4 kW laser power in atmosphere of various shielding gases (CO_2, Ar and Ar + 17 % CO_2 + 1 % O_2. v_w = 10.5–12.5 m/h, p/v_w = 419–352 W·h/m and q/v_w = 1509–1207 J/mm were used for CO_2 welding with through penetration without baking of 10.4 mm thick steel. The values of the latter parameters are not character for laser welding. Extrapolation of experimental data indicates the possibility of through penetration of alloyed steel of 11.0–11.5 mm thickness at reduction of welding speed up to 6–8 m/h.

Machine DU-044 is appropriate for welding of 6–7 mm thick steel. Laser welding of alloyed steel of

Table 1. Possibility of laser through penetration of alloyed steel

Thickness of steel, mm	P, kW	Shielding gas	v_w, m/h	q/v_w, J/mm	Width, mm	
					Weld*	HAZ
3.0	3.0	CO_2 Ar Ar + 17 % CO_2 + 1 % O_2	30 30 30	360 360 360	3.0/2.5 2.6/2.8 2.5/3.0	– – –
3.0	4.4	CO_2 Ar Ar + 17 % CO_2 + 1 % O_2	150 150 150	105.6 105.6 105.5	1.1/1.3 1.1/1.3 1.4/1.1	0.4–0.6 0.4–0.5 0.4–0.6
6.0	4.4	CO_2 Ar Ar + 17 % CO_2 + 1 % O_2	60 48 48	264 330 330	2.8/1.0 3.6/3.3 4.1/3.7	0.3–0.4 0.4–0.8 0.5–0.7
10.4	4.4	CO_2	10.5 12.5	1267.2–1508.6	5.6/4.6	2.0–4.0

*Values of width from the face are given in the numerator and from the back side — in the denominator.

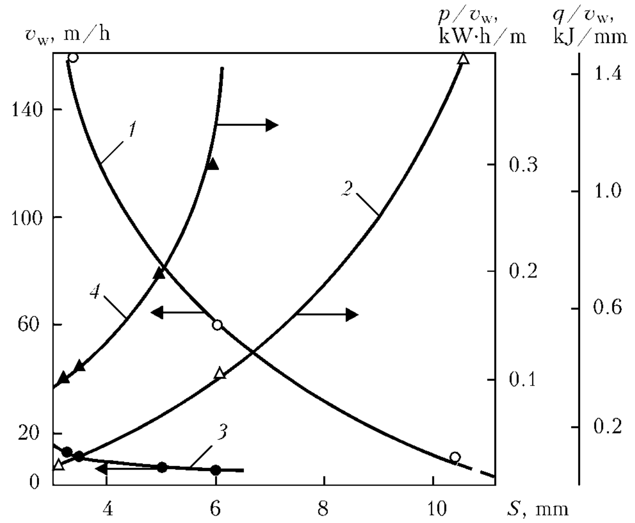

Figure 1. Comparison of welding speed, specific consumption of electricity p/v_w and heat input q/v_w in single pass welding using 4.4 kW power laser (*1*, *2*) and A-TIG method (*3*, *4*) depending on thickness of alloyed steel being welded

3–6 mm thickness is carried out with increased (8–12 times) speed, lower (3.5–4.5 times) consumption of electricity and metal heat saturation, reduced (4.5–7.5 times) consumption of shielding gas in comparison with A-TIG method. Speed of welding of 10.4 mm thick steel with square bevel increases approximately 2 times and number of passes reduces 3 times in comparison with argon-arc welding of the same steel with bevel edges, that result in 6 times reduction of time of machine welding. At that total consumption of shielding gas reduces 3–3.5 times and 2.5–3.5 times for electricity.

Welds made on 3.0, 6.0 and 10.4 mm thick steel using laser in one pass with through penetration have width 1.0–3.0, 1.5–3.5 and 3.5–6.0 mm, respectively. At that lager values refer to face of the weld (Figure 2). The narrower weld can be formed in the middle at 0.3–0.8 mm depth of steel thickness. The weld made on 10.4 mm thick steel can have sagging up to 2–3 mm and 1–2 mm deflection. Common increase of speed and power of laser irradiation is necessary for their reduction.

Additional welding passes with incomplete penetration and autoshaping of the welded joint are reasonable. Application of shielding gases including mixture with CO_2 promotes improvement of formation of penetration surface. Width of HAZ visually deter-

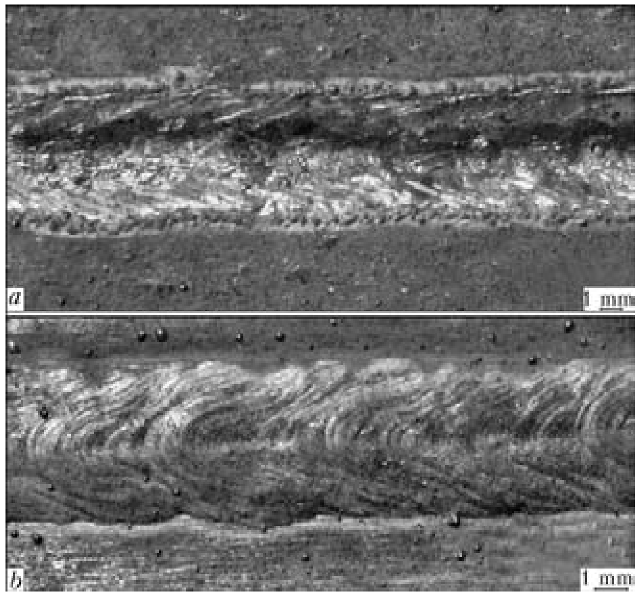

Figure 3. Appearance of surface of the butt joint from alloyed steel after laser welding without (*a*) and with (*b*) melting of filler wire

mined from the both sides of the joints of 3.0, 6.0 and 10.4 mm thick steel makes 0.2–0.5 and 1.5–3.0 mm and have inverse relation on speed of welding. Attached drops of molten metal take place on the surface of welded joints (Figure 3). Frequency of their location increases with rise of power density and energy of laser spot.

Incomplete laser penetrations of 10.4 mm thick steel have mushroom shape (Figure 4). Extrusion and displacement of the melt from under the laser beam to a tail and sides of the pool, rejection of liquid and solid particles, formation of narrow gas-metal channel of the depth equal to penetration depth take place under the effect of reactive pressure forming in the laser spot of metal vapor. Penetration beyond the bounds of gas-metal channel takes place through heating and melting with overheated melt and high temperature vapor-gas mixture.

Parameters of penetration depend on applied shielding gases (Ar, He, Ar + 17 % CO_2 + 1 % O_2, N_2 and CO_2). Ionized gas-metal flow (welding plume) is sufficiently transparent for laser irradiation of 1.06 μm wave length [2]. In this connection virtually similar depth of penetration (8.4–8.6 mm) takes place in application of such inert gases as argon and helium with ionization potentials U_i, differing 1.56 times,

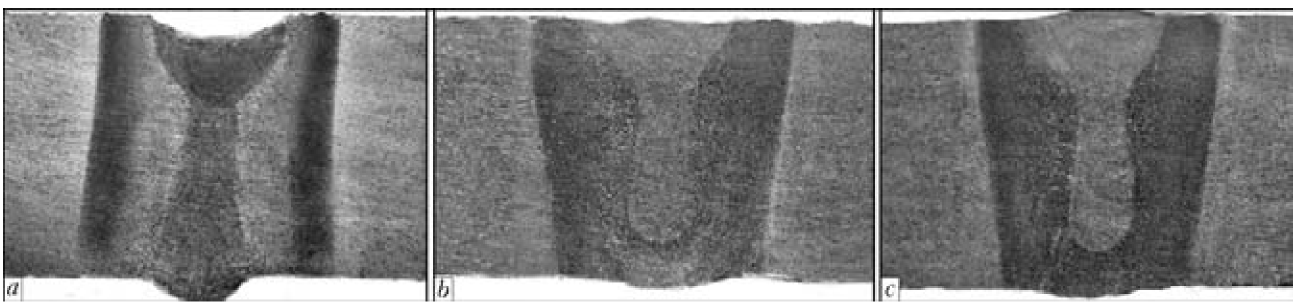

Figure 2. Cross section of butt joints from 10.4 mm thick steel of KhGS system with square bevel obtained using 4.4 kW power laser in one pass (*a*) and several (*b*, *c*) passes without (*a*, *b*) and with (*c*) melting of filler wire

Table 2. Chemical composition of metal after laser penetration of alloyed steel in different shielding gases

Shielding gas	C	Si	Mn	Cr
Ar	0.33–0.34/0.33	1.05–1.10/1.07	0.75–0.87/0.82	0.85–0.97/0.91
CO_2	0.33–0.34/0.33	1.02–1.10/1.05	0.71–0.77/0.74	0.81–0.90/0.87
Ar + 17 % CO_2 +1 % O_2	0.27–0.32/0.30	0.97–1.04/1.01	0.70–0.73/0.72	0.80–0.86/0.81
He	0.31–0.33/0.32	0.92–1.05/1.01	0.68–0.77/0.74	0.84–0.93/0.87
N_2	0.28–0.33/0.30	1.06–1.10/1.03	0.75–0.77/0.76	0.80–0.86/0.82

Notes. 1. Data on limits of value of chemical element weight fractions obtained after four analyses on height of penetration are given in the numerator and averaged values are in the denominator. 2. The base metal contains, wt.%: 0.33 C; 1.1 Si; 1.0 Mn; 0.98 Cr.

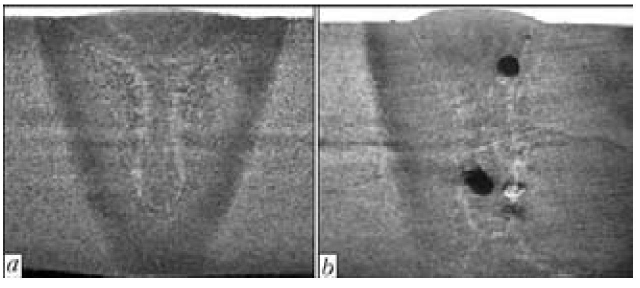

Figure 4. Incomplete laser penetrations in CO_2 (*a*) and argon (*b*) of 10.4 mm thick steel 30KhGSA

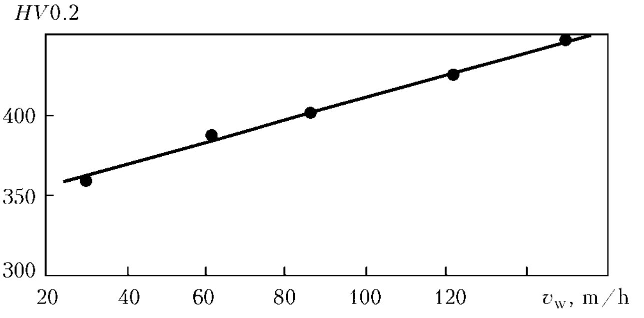

Figure 5. Dependence of metal hardness of weld made on steel 30KhGSA 3 mm thick on speed of laser welding

and which increases during application of CO_2 separately or in composition of Ar + 17 % CO_2 + 1 % O_2 mixture.

Laser welding of 30KhGSA steel in CO_2, Ar, He, Ar + 17 % CO_2 + 1 % O_2 and N_2 is accompanied by reduction of a content of carbon, silicon, chromium, manganese (Table 2) which remains (except for manganese) in the limits of requirements of GOST 4543–71, i.e. wt.%: 0.28–0.35 C; 0.9–1.2 Si; 0.8–1.1 Mn and Cr. Pores which are absent after welding in CO_2 and N_2 (see Figure 4) can be formed in the welds made with application of inert gases. CO_2 welding is recommended to be applied for alloyed steels.

Metal of the joint from alloyed steel welded by laser has higher hardness in comparison with the base metal. It increases from *HV*0.2-375 to *HV*0.2-450 with rise of v_w from 30 to 150 m/h at reduction of q/v_w from 360 to 106 J/mm (Figure 5) in the welds made on 3 mm thick steel. Reduction of metal hardness up to *HV*0.2-240–340/305 and *HV*0.2-230–280/265 after one and three passes is promoted by decrease of speed of welding and increase of its heat input in performance of the weld on 10.4 mm thick steel. There are no cold cracks appeared after laser welding of medium-carbon alloyed steel regardless increased hardness of metal of the joint.

Vertical and double-sided laser welding are characterized by obtaining of quality butt joint from alloyed steel of increased thickness using higher speed. Width of the weld makes 5–6 mm (from the face), 2.5–3.0 mm (from the back) and 1.6–1.8 mm (Figure 6, *a*) at a depth of 2.0–2.1 mm in vertical welding of alloyed steel of 10.4 mm thickness at v_w = = 15.6 m/h. Shape and structure of the joint after double-sided welding remain, particularly, the same as in single-sided downhand welding. There are no need in using of welding wire and forming device for obtaining of the quality joint.

Double-sided 6 mm depth laser penetration of the joint with overlap of the layers can be realized with v_w = 48 m/h when q/v_w reduces up to 330 J/mm.

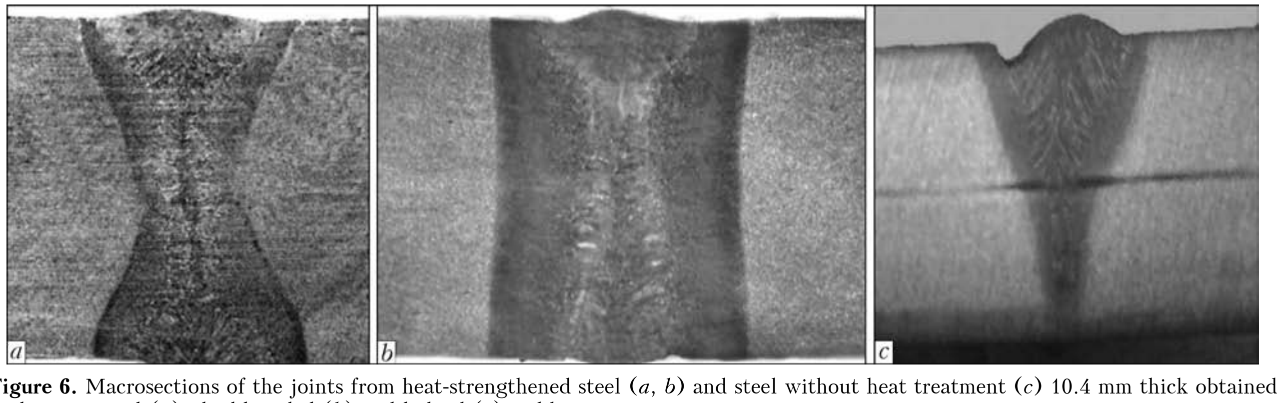

Figure 6. Macrosections of the joints from heat-strengthened steel (*a*, *b*) and steel without heat treatment (*c*) 10.4 mm thick obtained by laser vertical (*a*), double-sided (*b*) and hybrid (*c*) welding

At that time of machine welding, total consumption of electricity and shielding gas reduce 2–2.2 times in comparison with downhand welding. Absence of concavities, presence of small reinforcements and insignificant width of the weld (3.5 mm from both sides and 1.2–2.0 mm in the middle part), reduced width of visually identifying HAZ of thermostrengthened steel (from 0.5 to 1.2 mm near the surface up to 1.4–1.6 mm at a depth of 2–3 mm) (Figure 6, *b*) are character for the obtained joints.

Flat sample from alloyed steel in the as-welded condition with $\sigma_{0.2}$ = 830–850 MPa and σ_t = 940–970 MPa carries 34,900 cycles of tensile loading up to σ_l = 550 MPa and failures outside the joint in the place of transfer from working part to grip one.

It is well-known fact that the depth of penetration and speed of welding can be increased combining the laser beam and arc of consumable electrode [3]. Combining of two heat sources in one weld pool provides the greatest effect. Speed of hybrid welding with through penetration of 10.4 mm thick steel can make 35–40 m/h (Figure 6, *c*). Depth of penetration using these heat sources with the same parameters of welding equals 2.5–3.0 and 5.0–5.5 mm separately, i.e. in total less than 10 mm. Naturally, the through penetration of steel of higher thickness is possible at lower speed of hybrid welding.

CONCLUSIONS

1. It is determined that the butt joints of alloyed steel of up to 10.4 mm thickness can be performed in downhand position using though penetration of square bevel edges with 4.4 kW power laser.

2. Quality of the joint formation is improved through regulation of speed and rate of heat input, performance of additional passes and realization of double-sided and vertical welding.

3. 6–12 times reduction of time of machine welding, 2.5–4.5 times decrease of electricity consumption, 3–7.5 times decrease of shielding gas and 12–13 times reduction of filler wire consumption in comparison with tungsten electrode argon-arc welding are observed using laser irradiation of 4.4 kW power. Content of the main alloying elements and carbon remains at satisfactory level and manganese reduces by 18–28 %.

1. Grigoryants, A.G., Shiganov, I.N. (1988) *Laser welding of metals*. Moscow: Vysshaya Shkola.
2. Shcheglov, P.Yu., Gumenyuk, A.V., Retmajer, M. et al. (2011) Examination of welding plume in high-power fiber laser welding. In: *Abstr. of 5th Int. Conf. on Laser Technologies in Welding and Materials Processing*. Kiev: PWI, 50–51.
3. Krivtsun, I.V., Shelyagin, V.D., Khaskin, V.Yu. et al. (2007) Hybrid laser-plasma welding of aluminium alloys. *The Paton Welding J.*, **5**, 36–40.

INVESTIGATION OF STRUCTURAL TRANSFORMATIONS AND STRESS-STRAIN STATES OF PARTS OPERATING AT CYCLIC THERMOMECHANICAL LOADS AND ESTABLISHMENT OF FUNDAMENTALS FOR SURFACING PARTS WITH HIGH FATIGUE CHARACTERISTICS

Research work on this subject was finished in 2011 at the E.O. Paton Electric Welding Institute (Subject Manager – Prof. I.A. Ryabtsev)

Basing on the modern models of tough-plastic non-isothermal flow, thermokinetic diagrams of decay of austenite of deposited and base metal using a numerical method of finite elements, the method of calculation has been developed which makes it possible within the frame of only single model to calculate the stress-strain and structural state of parts at single- and multi-layer surfacing and their effect on fatigue life at cyclic thermomechanical loads after surfacing and in the process of service.

The new method has been developed and experimentally confirmed for improving the thermal strength of deposited parts due to surfacing of a sublayer of low-carbon low-alloy steel, which has a high ductility and fatigue strength. Calculation of stress-strain and structural state in the process of surfacing and service cyclic thermal loads of parts of mill rolls type, deposited by a tool steel without and with a ductile sublayer, showed that due to relaxation of stresses the surfacing with a ductile sublayer provides the reduction of stresses by 25–30 % in the most loaded external working layer, thus resulting in 30–35 % increase in thermal strength of the deposited part. Calculations were confirmed by experimental investigations of thermal and mechanical fatigue life of the deposited parts.

The investigation allowed us to develop the new surfacing materials and technologies of surfacing the parts which operate under conditions of wear and cyclic mechanical or thermomechanical loads: driven shaft-gears and geared rim of autogenous mill; steel rolls of pipe rolling mills TPA 30-102 and sheet-rolling mills; dies, parts of crane MKT-250, etc.