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USE OF LASER WELDING AND SURFACING TECHNOLOGIES FOR REPAIR AND MANUFACTURE OF THIN-WALLED WELDED JOINTS OF HIGH-ALLOY STEELS

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ABSTRACT

Thin-walled welded joints of corrosion-resistant high-alloy steels are used in various industries for the manufacture of critical structures. The tendency to reduction in the mass of products in order to save costs and energy resources makes it relevant to find the ways to solve the problem of welding such joints, including also the use of concentrated power sources such as laser radiation. The use of laser technologies in welding thin-walled joints of high-alloy steels may be applied not only at the manufacturing stage but also at the stage of repair. The high cost of treatment of such materials makes the problem of finding the ways to avoid the formation of defects in such welded joints relevant. At the same time, it is urgent to develop technologies for repair of thin-walled welded joints made of high-alloy steels. The article is devoted to the solution of this task namely by using laser welding and surfacing technologies. According to the results of visual, radiographic testing and metallographic examinations, the parameters of thin-walled welded T-joints of AISI 321 steel were evaluated, namely: geometry, ripple, presence of craters, pores, their quantity, sizes, mutual position and other parameters provided by DSTU EN ISO 13919-1:2015 standard. The analysis of the obtained data made it possible to find the presence of individual defects of welded T-joints in the form of single pores, chain of pores, lacks of fusion, depression of the weld, lacks of penetration, shrinkage cavities and cavities in the crater, undercuts, excess of convexity. The procedure for their elimination and prevention of their formation was developed. It was established that thin-walled welded T-joints of AISI 321 steel after repair according to the proposed procedure have mechanical characteristics at the level of defect-free welded joints and amount to 670–717 MPa. This allows recommending the proposed procedure to perform the operation of repair of such joints when eliminating defects in the form of burn-outs.

KEYWORDS: laser welding, high-alloy steels, welded T-joints, repair, procedures of defects elimination, critical structures

INTRODUCTION

In many industries, structures of corrosion-resistant high-alloy steels of small thickness (0.1–2.0 mm) are widely used [1–3]. Butt, T-joint and fillet welded joints of thin metal are used by developers and manufacturers of all kinds of devices for delivery, redistribution of flows, measurement of pressure and flow rate of liquids and gases used in the nuclear industry, automotive industry and rocket construction [4–6]. Their specific requirements are specified to the aim and conditions of service of these products. Quite often, a welded joint should not only have a sufficient strength, but also be sealed. The operation in an aggressive environment at high temperatures requires an increased corrosion resistance. In addition, these products should have an increased reliability. This is caused by the fact that they are usually used in critical assemblies, which, first of all, applies to aviation, space and nuclear power engineering [7–9].

Welded joints of such parts may be produced using different welding methods. The main among them are argon-arc [6], microplasma, contact-roller, electron beam and laser welding [10–12]. The latter refers to the most acceptable methods to solve the tasks of producing small thickness joints. Laser welding does not require vacuum chambers as electron beam welding, it allows producing narrower welds compared to arc methods, allows carrying out precision adjustment of technological parameters, it is distinguished by a high stability and allows receiving satisfactory service characteristics of the weld during welding of thin metal.

However, when producing welded joints of thin-sheet steels, certain technical problems arise. In the case of excessive heat input, that occurs while welding thin-walled parts or producing sufficiently wide welds, residual deformations of welded structures arise [11]. This is especially clear when welding austenitic corrosion-resistant steels, that have a low thermal conductivity and a high linear expansion ratio [1, 3, 7]. This enhances the curvature and deformation of edges of thin-walled parts during welding. As a result, the gaps between the welded surfaces increase, and, as a consequence, in welding, defects in the form of burn-outs, lacks of fusion, lacks of penetration arise and the geometry of the welded joint becomes unstable.

A high cost of treatment of such materials makes the problem of finding the ways to avoid the formation of defects in such welded joints relevant. At the same time, the urgent problem is to develop technologies for repairing thin-walled welded joints of high-alloy

Table 1. Chemical composition of AISI 321 steel, wt.%

Grade of steel	C	Si	Mn	Ni	S	P	Cr	Ti	Fe
AISI 321	< 0.1	< 0.8	1–2	10–11	< 0.2	< 0.035	17–19	< 0.6	Base

steels. The article is devoted to the solution of this task namely by using laser welding and surfacing technologies.

MATERIAL AND PROCEDURES OF RESEARCH

The research material (Table 1) was high-alloy AISI 321 steel. The specimens were made from a sheet of 1.2 mm thickness. The size of the billet of a T-joint stiffener is 320×100 mm; the size of the billet of a T-joint flange is 300×200 mm.

OPTIMIZATION MODE OF REPAIRING WELDED JOINTS

Laser welding of welded T-joints of AISI 321 steel with the thickness of the flange and stiffener of 1.2 mm was performed "uphill" in a vertical position in a one pass with a slot weld in a pulsed mode of laser radiation generation in the laboratory bench, shown in Figure 1.

The parameters of welding modes were as follows: maximum laser radiation power P_{max} = 4.4 kW; average laser radiation power P_{av} = 3.2 kW; pulse duration T = 75 %; frequency of passing laser radiation pulses is 250 Hz; focal length of the lens F = 300 mm; lifting of laser radiation focus over the welded surface ΔF = +2 mm; welding speed V_w = 4000 mm/min. The choice of this mode is predetermined by the most stable formation on both sides of fillets between the flange and stiffener of the T-joint, while providing the required geometry of the welded joint and a high level of mechanical characteristics.

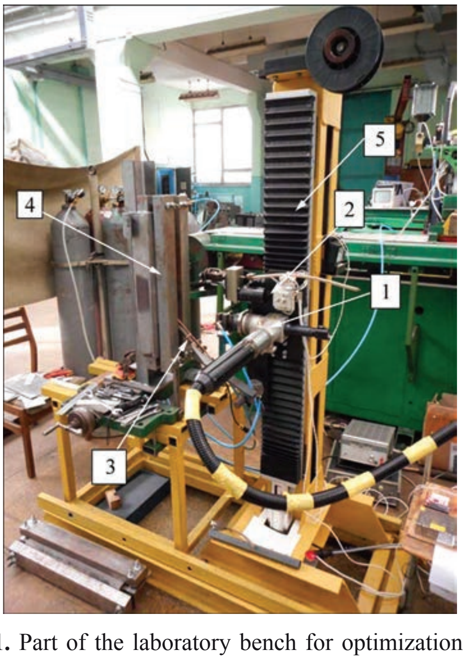

Figure 1. Part of the laboratory bench for optimization technological techniques of laser welding in a vertical spatial position: 1 — head for laser welding; 2 — manipulator carriage; 3 — gas shielding; 4 — clamp; 5 — manipulator beam (*Z* axis)

Typical defects of welded joints are normalized by DSTU EN ISO 13919-1:2015 standards "Welding. Joints made by electron beam and laser welding. Guidelines on quality level assessment depending on defects. Part 1. Steel" and DSTU EN ISO 6520-1:2015 "Welding and related processes. Classification of geometric defects in metal materials. Part 1. Fusion welding". According to these standards, three levels of joint quality are recommended: moderate "D", average "C" and high "B".

According to the results of visual and radiographic testing, the parameters of thin-walled welded joints of AISI 321 steel were evaluated, namely: geometry, ripple, presence of craters, pores; their quantity, sizes, mutual position and other parameters provided by DSTU EN ISO 13919-1:2015 standard.

The evaluation of the obtained data made it possible to establish the probability of forming individual defects in welded T-joints, namely, single pores, chain of pores, lacks of fusion, depression of the weld, lacks of penetration, shrinkage cavities and cavities in the crater, undercuts, excess of convexity. The procedure of their elimination and prevention of their formation was developed, which has the following content:

- to eliminate defects in the form of pores, chain of pores, lacks of fusion, depression of the weld, lacks of penetration – rewelding of the weld with the addition of filler material (if necessary);
- to prevent the formation of shrinkage cavities and cavities in the crater — run off tabs; software control of smooth growth of laser radiation power at the beginning of welding and smooth drop at the end of welding were used;
- to eliminate undercuts, excess of convexity — additional remelting with a defocused beam was performed.

The studies on consideration of options for repair of defects in the form of burn-outs (melt-through) and cracks were conducted. The options of using filler materials in the form of powder and a thin strip are considered. During repair, as a filler material, a strip of 0.25 mm thick of AISI 321 steel and a surfacing powder with a fraction "150 + 53" of grade "16316" produced by the Castolin Eutectic Company with the following chemical composition, %: Fe — base; 0.03 C; 17.5 Cr; 13 Ni; 2.7 Mo were used.

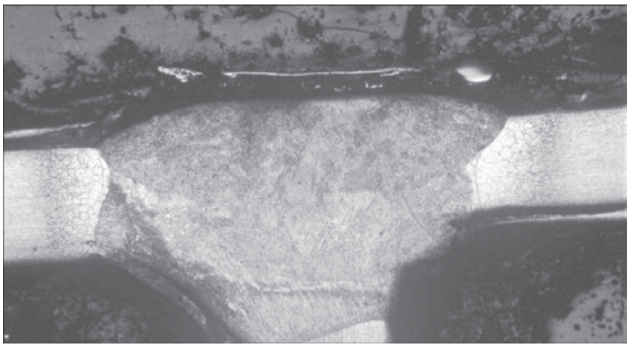

Figure 2. General appearance of welded T-joint after repair welding (×25)

Below, the procedure of repair treatment on the example of eliminating a defect in the form of a burn-out in the T-joint was considered. Defective areas of the specimen were subjected to repair.

As a result of the carried out works, it was established that at the presence of defective areas with burn-outs at the welding area, welded joints should be repaired by the following procedure, namely (the given data for repairing the defect of 1.5×1.5 mm, as for such that is most often encountered in visual testing of produced welded joints):

● mechanical treatment (cleaning) of repair place;

● cleaning with acetone immediately before repair;

● putting of repair patch of AISI 321 steel (δ = = 0.25 mm thick) with an area by 30–50 % larger than a defect area;

● laser repair spot welding on the mode: laser radiation defocusing ΔF = 30 mm, laser radiation power P = 1 kW, exposure time is 0.5 s;

● mechanical treatment (cleaning) of the repair place after welding;

● cleaning with acetone immediately before the next operation of repair;

● applying the required volume of filler material in the form of powder (powder with "150 + 53" fraction of 16316 grade, produced by the Castolin Eutectic Company is used; it is admitted to use the analogue of powder close to the base material as to its composition and properties);

● performance of repair surfacing for elimination of the weld depression (formation of a sufficient reinforcement of the upper bead) on the mode: laser radiation defocusing ΔF = +30 mm, laser radiation power P = 1 kW, exposure time is 0.5 s.

Performance of repair operation according to the abovementioned procedure allows: eliminating discontinuities in welded T-joints; forming fillets on both sides of a stiffener in the T-joints; forming the required reinforcement of the upper weld bead.

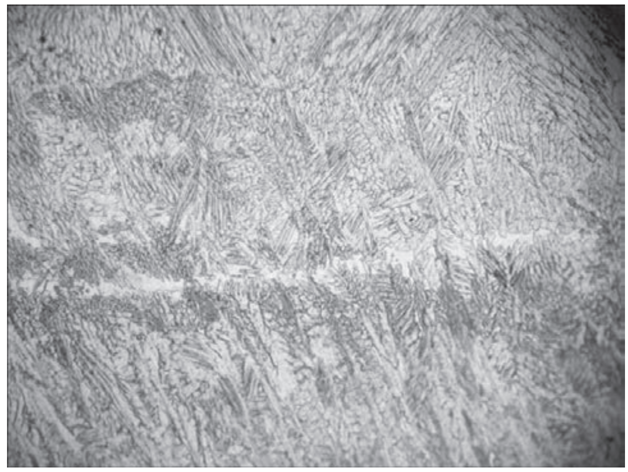

Figure 3. Fusion line of weld metal of T-joint after repair welding (×200)

METALLOGRAPHIC EXAMINATIONS OF PRODUCED WELDED JOINTS AFTER REPAIR

The structure in the welded T-joint after the repair was examined according to the abovementioned sequence of operations. From the repaired T-joint with a rewelded defect in the form of a burn-out, a template was cut out, which was fixed in a metal frame by filling latacryl. After mechanical treatment (grinding and polishing), the specimen was studied by the methods of optical microscopy and microdurometric analysis.

The studied joint represents a T-joint, consisting of a stiffener and a flange (Figure 2).

The cast structure of the weld is almost uniform throughout the whole area of the joint both in the base weld, as well as in the repaired part (Figures 3 and 4).

At the boundary of the weld of repair welding, a zone was revealed, that was still bright after etching having a hardness in the upper part $HV1$ — 3090–3510 MPa, and on the side of the flange — $HV1$ — 4010–4210 MPa. Whereas the hardness of the repair welding metal is on average $HV1$ —

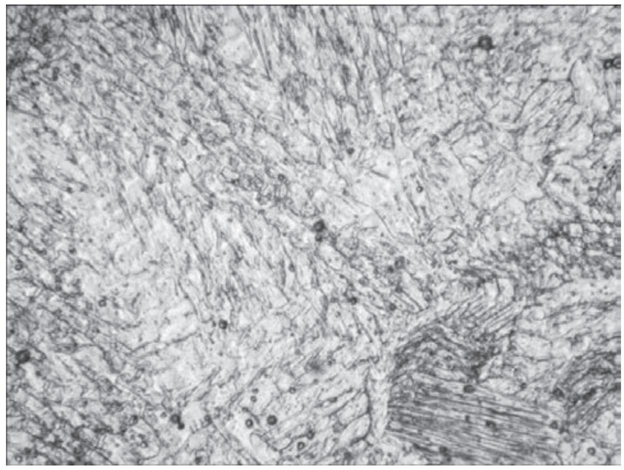

Figure 4. Microstructure (×500) of cast weld metal in the T-joint with repair welding, general appearance

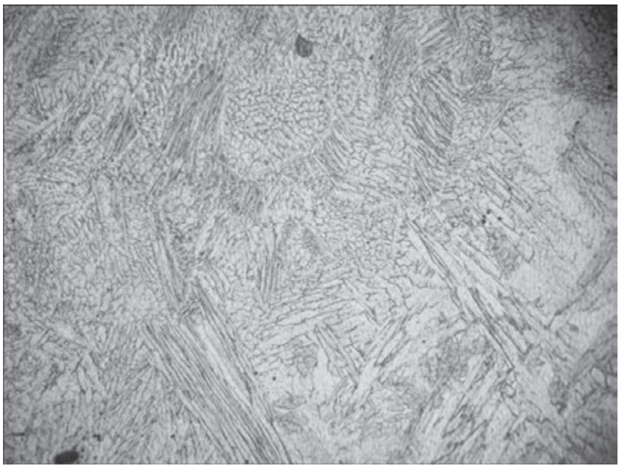

Figure 5. Microstructure (×200) of repair welding metal

Figure 6. Microstructure (×200) of initial weld and HAZ metal in the stiffener of welded T-joint after repair welding

3510–3830 MPa with separate areas where it is reduced to *HV*1 — 3140–3362 MPa and increased to *HV*1 — 4010 MPa.

The structure of the base weld and the weld after repair welding is austenitic with δ-ferrite, probably contains martensite (Figures 5 and 6).

The presence of martensite is evidenced by an increased hardness and the presence of relief in the body of crystallites (Figure 7). This assumption requires verification by local research methods.

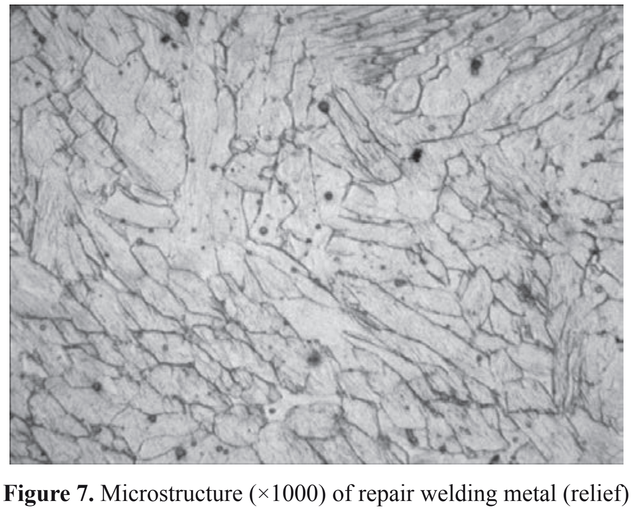

Figure 7. Microstructure (×1000) of repair welding metal (relief)

Figure 8. Microstructure (×500) of initial weld and HAZ metal in the stiffener of welded T-joint after repair welding

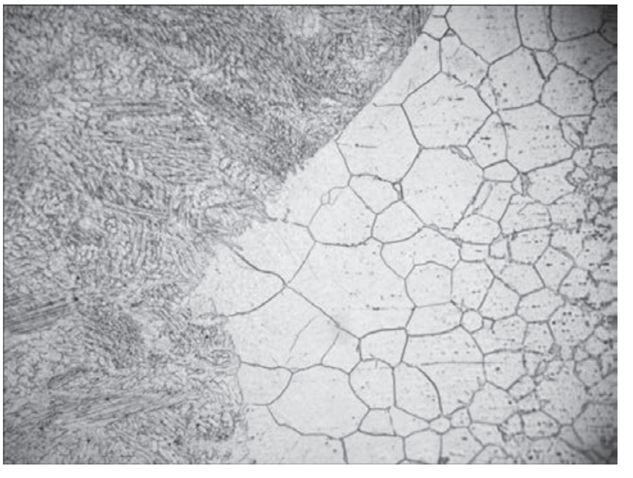

Figure 9. Microstructure (×200) of HAZ metal and fusion line with the flange of welded T-joint after repair welding

The structure of the weld near the fusion line with the stiffener is smaller compared to the rest of the weld (Figure 8) and represents austenite and δ-ferrite, the width of this area is ~ 100 μm. The hardness here

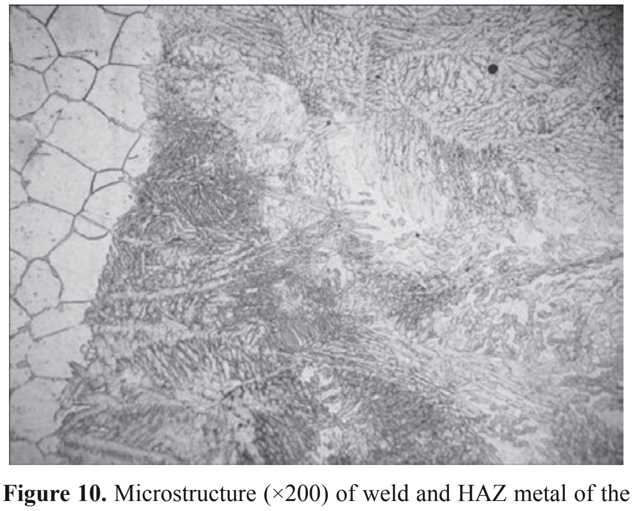

Figure 10. Microstructure (×200) of weld and HAZ metal of the flange of welded T-joint after repair welding

Table 2. Results of tests of specimens on static tension with repaired spot defects

Number	Width, mm	Thickness, mm	σ_t, MPa	Fracture place
1	25.3	1.2/1.2	717	Fracture along BM
2	25.5		670	Fracture along weld
3	25.2		684	
4	25.1		672	Fracture along BM
5	24.9		694	
6	25.3		715	

is slightly lower than in other areas of the weld — *HV*1 — 2740 MPa.

The structure of HAZ of the stiffener metal represents austenite and δ-ferrite. The size of the austenite grain in HAZ did not change compared to the base metal (Figure 8). At a distance of up to 50 μm from the fusion line, the amount of δ-ferrite increased. The hardness in this area is *HV*1 — 2450 MPa.

The structure of HAZ of the flange also consists of austenite and δ-ferrite (Figure 9), but differs by a coarser grain of austenite — grain size No. 4.5 (GOST 5639–82). At the boundary of the grains of austenite (Figure 10), δ-ferrite is precipitated, the width of the overheating area of a coarse grain is ~ 400 μm. HAZ hardness in the overheating area is *HV*1 — 2740–3090 MPa.

After repair welding, no defects in the areas of base and repair welds and HAZ were detected. The structure of the base metal is two-phase austenitic-ferritic. Along the direction of rolling, δ-ferrite is precipitated, the hardness is *HV*1 — 2060–2580 MPa.

MECHANICAL TESTS OF SPECIMENS OF WELDED T-JOINTS AFTER REPAIR ON STATIC TENSION

The tests of welded specimens on static tension were performed after repair. The tests were performed on the specimens of T-joints in a quantity of 6 pieces cut out from different tested joints. To simulate defects in the form of burn-outs, drills (from 1 to 3 pieces at a length of 20 mm) were performed in the specimens prepared for tests on static tension. Defects simulated in such a way were repaired by the spot powder laser surfacing (Figure 11).

The results of testing the specimens with repaired spot defects on static tension are given in Table 2.

According to the results of carried out tests of the specimens with repaired spot defects on static tension, the values of the tensile strength σ_t for all the tested repaired welded joints are not lower than the indices obtained for the base welded joints without repair and the base material of the specimens (tensile strength σ_t of the base welded joints is 665–712 MPa; tensile strength σ_t of the base material of the specimens is

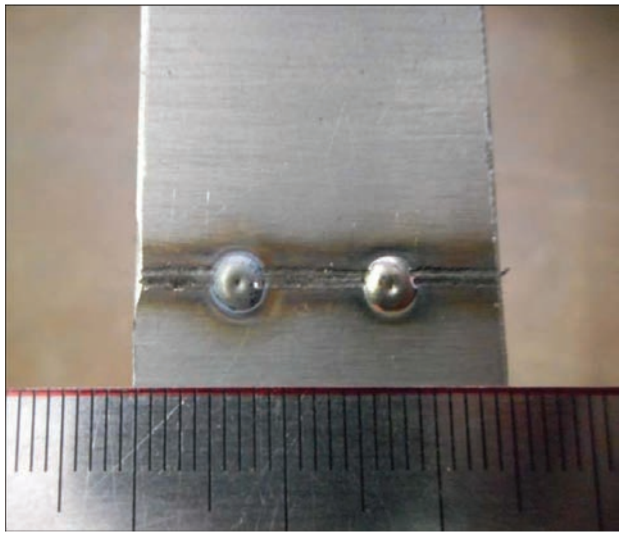

Figure 11. Photo of specimen for tests on static tension with repaired two spot defects

685–725 MPa). These results allow suggesting that mechanical properties of welded joints produced after repair by the proposed procedure meet the standards DSTU EN ISO 13919-1:2015 and DSTU EN ISO 6520-1:2015, specified to welded joints produced by fusion welding.

CONCLUSIONS

According to the results of visual, radiographic testing and metallographic examinations, the parameters of thin-walled welded T-joints of AISI 321 steel were evaluated, namely: geometry, ripple, presence of craters, pores; their quantity, sizes, mutual position and other parameters provided by DSTU EN ISO 139191:2015 standard. The analysis of the obtained data made it possible to establish the presence of individual defects of welded T-joints in the form of single pores, chain of pores, lacks of fusion, depression of the weld, lacks of penetration, shrinkage cavities and cavities in the crater, undercuts and excess of the convexity. The procedure for their elimination and prevention of their formation was developed.

It was established that thin-walled welded T-joints of AISI 321 steel after repair by the proposed procedure have mechanical characteristics at the level of defect-free welded joints and amount to 670–717 MPa. This allows recommending the proposed procedure to perform the operation of repairing such joints while eliminating defects in the form of burn-outs.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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