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Laser welding of stainless steel

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ABSTRACT

Purpose: of this paper was to analyze the influence of the basic parameters of laser welding (i.e. laser beam power and welding speed, as well as energy input) of butt joints of the 2.0 mm thick stainless steel AISI 304 sheets on the weld shape and joint quality.

Design/methodology/approach: The preliminary trials of simulated laser welding by melting the austenitic stainless steel sheets (the so called bead-on-plate welding), as well as the welding of the test butt joints, were carried out using the high-power diode laser (HPDL) ROFIN DL 020, without the additional material (the technique of autogenous welding). A crucial parameter that determines both the mechanical properties and the corrosive resistance of a joint (the region of a weld and HAZ - heat affected zone) in the case of stainless steels with austenitic structure is energy input, which should be kept at a minimum, and at the same time full penetration and a proper shape of the fusion zone should be ensured. The investigations included the macrostructure and microstructure observations by light microscopy, researches of mechanical properties in a static tensile test and also microhardness measurements made by Vickers method.

Findings: The results have shown that it is possible to provide a proper shape of the weld of fine-grained structure and narrow heat affected zone, but it requires careful selection of the welding parameters, especially a low energy input. The microhardness measurements showed that the in case of welding the butt joints using the high-power diode laser in HAZ area a slight increase in microhardness to approx. 185HV0.2 compared to base material (160-169HV0.2) and a decrease in microhardness in the fusion zone (FZ) to approx. 140-150HV0.2 have been observed. All welded sample broke from the joint during the testing at tensile stress between 585 MPa and 605 MPa with corresponding percentage elongation in the range of 45-57%. It can be found that the joints strength is not less than the strength of the base metal of 2.0 mm thick AISI 304 austenitic stainless steel sheet.

Research limitations/implications: Studies of the weldability of stainless steels indicate that the basic influence on the quality of welded joints and reduction of thermal distortions has the heat input of welding, moreover the highest quality of welded joints of austenitic stainless steel sheets are ensured only by laser welding.

Practical implications: The laser welding technology can be directly applied for welding of austenitic steel AISI 304 sheets 2.0 mm thick.

Originality/value: Application of high power diode laser for welding of austenitic stainless steel AISI 304.

Keywords: Laser welding, AISI 304 steel, High-power diode laser (HPDL)

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MANUFACTURING AND PROCESSING

1. Introduction

The wide used kinds of stainless alloys are austenitic steels, well-known as 18-8 types. Contain, according to the standard, from 16 to 18% Cr, 6-8% Ni and 0.03-0.1% C. Austenitic stainless steels (ASS) are widely used materials because of their excellent corrosion resistance in various aggressive environments, mainly: air atmosphere, damp and salt water and some oxidizing solutions of the salt as well as inorganic and organic acids, combined with high mechanical and plastic properties [1-2]. Compared to low-alloy steels, such as: BH type steels (Bake Hardening – grade 11180B, 11260B), steels with ferritic-bainitic structure with residual austenite, TRIP (Transformation Induced Plasticity) steels – TRIP700 grade, steels with ferritic-austenitic structure type DS (Duplex Steel – grade 1.4462) and high strength micro-alloy steels type HSLA (High Strength Low Alloy – grade H320LA), as well as steels with ferritic-martensitic structure type DP (Dual Phase – grade H300X) or also some Al and Mg alloys, the tested Cr-Ni austenitic steel shows a clearly better ratio of strength to plastic properties (Fig. 1) [1-5].

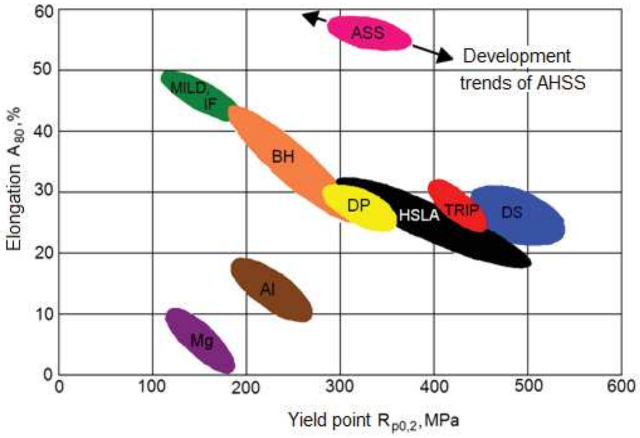

Fig. 1. Comparison of mechanical properties of various group of constructional materials [6]

Stainless steels are iron alloys that have a durable chrome oxide passive layers on the surface, which ensure them a corrosion resistance. The corrosion resistance of stainless steels depends on various metallurgical and processing variables (i.e.: chemical composition of material, occurrence of other phases – delta (Feδ) ferrite; stress state, temperature, rate of deformation etc.). Corrosion resistance of those type of steel increase with increasing chrome content in the alloy [2,5-9]. Stainless steels have a large range of applications, mainly: in the chemical, petrochemical, automotive and food industries. They are also applied in nuclear energy industries, for the production of decorative products or ships equipment and etc. [6].

According to the classical definition, welding is a process of joining two metals through localized coalescence resulting from a suitable combination of temperature, pressure and metallurgical conditions [7]. Whereas the laser welding is accomplished when the light energy emitted from a laser source is focused upon a workpiece to fuse materials together. According to those definitions can be say that austenitic stainless steels type 18-8 are well welded and the problem of hot cracking of welded joints is limited thanks to high metallurgical purity of steel and also consumables and applying minimal heat input of welding. Similarly reduction of carbon content in austenitic steels and consumables below 0.01% prevents the phenomenon of inter-grain corrosion of welded joints. The only problem is minimizing of thermal distortions during welding, especially in a case of welding of thin sheets, as a result of high thermal expansion of austenitic structure steel about $18\text{x}10^{-6}$ 1/K and very low heat conductivity about 15.5 W/mxK [1,6,9]. Previous studies in the field of weldability of wide group of stainless steels indicate that the basic condition for ensuring high quality of welded joints and reducing thermal distortions to minimum is reducing the heat input of welding, moreover the highest quality of welded joints of austenitic stainless steel sheets are ensured only by correct parameters optimization of laser welding [8,10,12-22]. Otherwise, the welded joint will be the weakest part of the whole construction, determining its performance parameters, quality, durability and safety [13-24]. Therefore, the aim of the investigations was to analyze the influence of the basic parameters of laser welding (i.e. laser beam power and welding speed, as well as energy input) of butt joints of the 2.0 mm thick stainless steel AISI 304 sheets on the weld shape and joint quality.

2. Materials and the methodology

To determine the influence of parameters of laser welding without consumables by high power diode laser ROFIN DL 020 on a quality and a shape of butt joints of austenitic stainless steel AISI 304 sheet 2.0 mm thick, tests of bead-on-plate welding and welding of the steel sheets were carried out at different power of the laser beam and different welding speed.

The samples for welding tests were cut by a mechanical guillotine from a 2.0 mm thick sheet of AISI stainless steel at supersaturated conditions into coupons 100 mm long and 40 mm wide. In the supersaturated state the investigated steel display a single-phase austenite structure with a diameter of the average grains in the matrix γ amounting to about 75 μm and a hardness of about 125 HV0.5, containing many annealed twins and single clusters of non-metallic inclusions (Fig. 2). The chemical composition of the applied steel is given in Table 1, while the mechanical properties are given in Table 2.

The welding trials of austenitic stainless steel AISI 304 sheets were conducted by means of an experimental stand equipped with the high power diode laser (HPDL) and the positioning system ISEL Automation. A copper backing plate was used for formation of the weld root, which is recommended for welding of austenitic stainless steels because ensures narrow bead of the weld and low angle distortions of joints, thanks to intensive heat transfer. The experimental stand is shown in Figure 3. The laser was characterized by maximum output power of 2.5 kW. The laser beam spot of size 1.8 x 6.8 mm was set along the welding direction and focused on the top surface of the welded sheets.

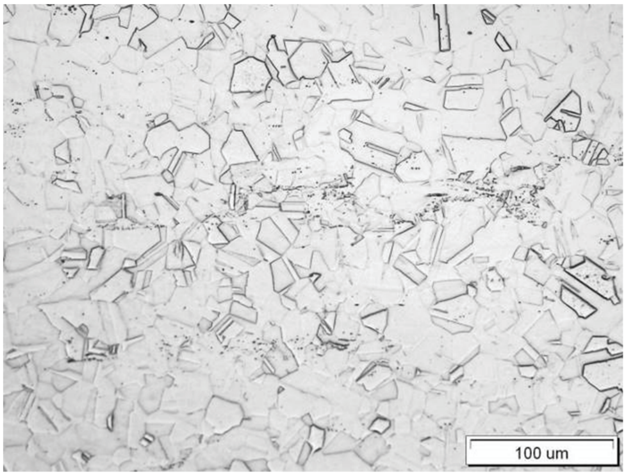

Fig. 2. Microstructure of AISI 304 stainless steel after its austenitizing for 1 hour at a temperature of 1100°C

Table 1.
Chemical composition of 2.0 mm thick sheet of AISI 304 stainless steel, wt.%

C_{max}	Cr	Ni	Mn_{max}	Si_{max}	P_{max}	S_{max}	N_{max}
0.07	17.0-19.0	8.0-10.5	2.0	1.0	0.045	0.0.15	0.11

Table 2.
The mechanical properties of 2.0 mm thick sheet of AISI 304 stainless steel

Tensile strength Rm, MPa	Yield point $R_{p0,2}$, MPa	Elongation A_5, %
540-750	230	45

Shielding gas argon was delivered to the weld region by cylindrical nozzles 10 mm in diameter prior to the welding and the flow rate was kept constant at 12 l/min. At the beginning stage of the study bead-on-plate welding tests were done in a wide range of welding parameters in order to determine the welding conditions that allow to provide a full penetration and a narrow weld at relatively low heat inputs, Table 3. The laser beam power was ranged from 1500 W to 2200 W, while the processing speed was ranged from 200 mm/min to 400 mm/min. After the initial tests of bead-on-plate welding the parameters considered as optimal were chosen for laser welding of real butt joints (Tab. 4).

Fig. 3. A view of the experimental stand for laser welding tests of 2.0 mm thick AISI 304 steel sheets using a high power diode laser ROFIN DL 020

Table 3.
Parameters of bead-on-plate welding of 2.0 mm thick sheets of AISI 304 stainless steel using a high power diode laser ROFIN DL 020

Bead No.	Output power, W	Welding speed, mm/min	Energy input, J/mm	Current intensity, A
1	1500	200	450	15
2	1700	200	150	16.5
3	1600	200	480	15.5
4	2200	400	330	20
5	2200	300	440	20

Other parameters: Shielding gas Ar 5.0; The laser beam spot of size 1.8 x 6.8 mm was set along the welding direction and focused on the top surface of the welded sheets at 82 mm focal length

Table 4.
Parameters of laser welding of 2.0 mm thick butt joints of AISI 304 stainless steel by high power diode laser ROFIN DL 020

Test butt joint	Output power, W	Welding speed, mm/min	Energy input, J/mm	Current intensity, A
A(3)	1600	200	480	15.5
B(5)	2200	300	440	20

Other parameters: Shielding gas Ar 5.0; The laser beam spot of size 1.8 x 6.8 mm was set along the welding direction and focused on the top surface of the welded sheets at 82 mm focal length

The quality of bead-on-plate welds and butt joints was evaluated by visual inspection, macrographs and micrographs observation by light microscopy and also the mechanical properties determined in a static tensile test and microhardness measurement were done. The cross sections were prepared by grinding and subsequent polishing by diamond suspension of 6 µm, 3 µm, and 1 µm respectively. The microstructure was revealed by etching in the Adler II reagent composed of iron chloride $FeCl_3$, hydrochloric acid HCl, and water H_2O, in proportions 1:1:4. Macrostructure and microstructure of samples were analysed by optical microscopy (OM), by means of OLYMPUS SZX9 and NICON Eclipse MA100.

The mechanical properties of the examined butt joints were determined by means of a static tensile test according to PN-EN 4136 standard. The static tensile test were performed on the testing machine ZWICK 100N5A (Fig. 4).

Measurements of microhardness of the across section of butt joints of austenitic stainless steel AISI 304 sheets 2.0 mm welded by high power diode laser HPDL ROFIN DL 020 were carried out by a microhardness tester Micro-Vickers 401 MVD manufactured by Wilson Wolpert, according to to PN-EN ISO 6507-1 standard.

3. Results and discussion

The observations of the laser welding process of butt joints of 2.0 mm thick sheets of AISI 304 chrome-nickel steel have shown that despite a slight spatter the process was stable and reproducible. The results of visual and macrographic tests (Figs. 5-7) have shown that it is possible to make butt joints of high quality and the correct shape of the fusion line, as well as with a smooth surface and uniform width of the face weld.

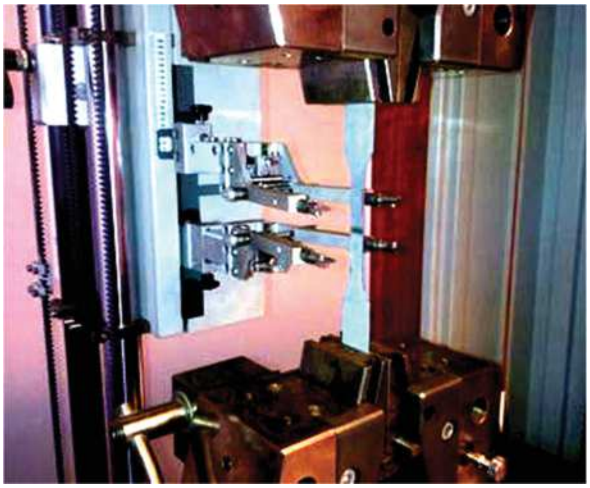

Fig. 4. A view of the tensile sample during static tensile test of a butt joint of 2.0 mm thick steel sheet AISI 304

Preliminary tests of bead-on-plate welding of the austenitic steel AISI 304 sheets 2.0 mm thick by HPDL laser showed that the power of laser beam has a very strong influence on the bead shape and a penetration depth (Fig. 8, Table 3). Increase of the power of laser beam resulted in decreasing of the width of beads and the penetration depth (Figs.7, 9, 10, Table 4). The test joint A (3) welded with 480 J/ mm energy input was characterized by a wide weld width of about 3.5 mm. The fusion line (i.e. the area between fusion zone and base material) was steep and tapered width as the depth increased (Fig. 7a). While, in the test joint B(5) welded with 440 J/mm energy input the average wide weld was about 4.5 mm (Fig. 7b). In this case, the fusion line has an elliptical shape, which means that the stitch width decreased more rapidly as the weld depth increased.

Observations of the micrographs of the welds in the region of fusion line reveal that the width of the heat affected zone (HAZ) is negligible about a few microns. This is due to the high power density of the laser beam as a heat source but also due to relatively low thermal conductivity of the austenitic stainless steel.

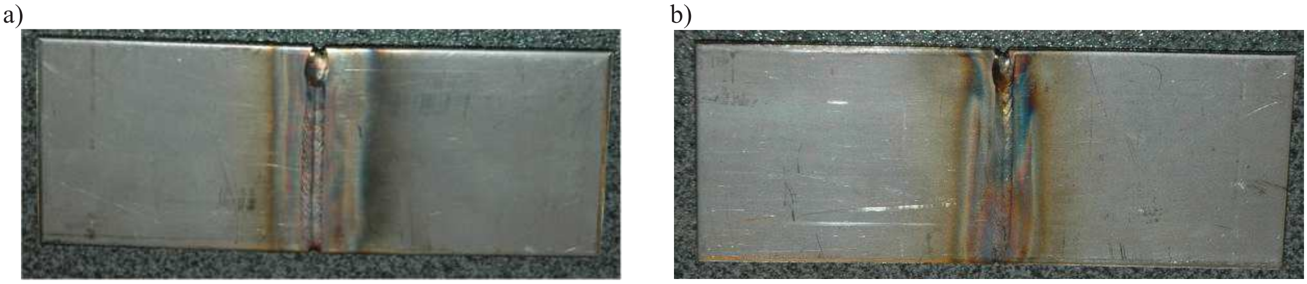

Fig. 5. A view of the test butt joints A(3) of austenitic stainless steel AISI 304 sheets 2.0 mm welded by high power diode laser according to parameters given in Table 4; a) weld face, b) root surface

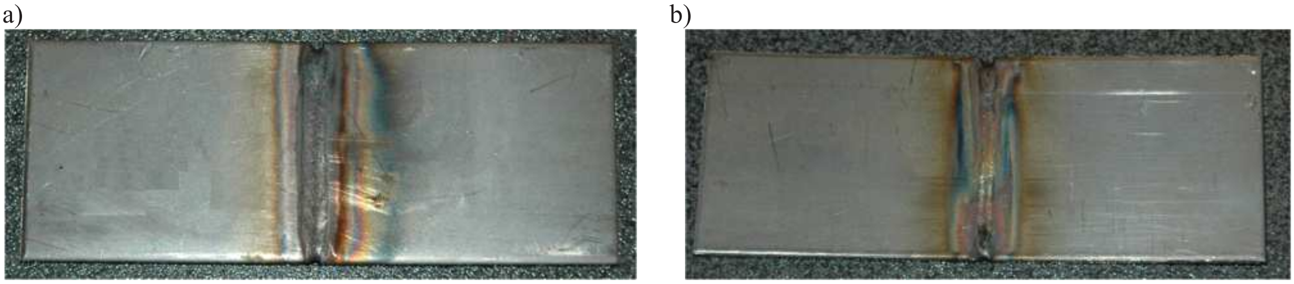

Fig. 6. A view of the test butt joints B(5) of austenitic stainless steel AISI 304 sheets 2.0 mm welded by high power diode laser according to parameters given in Table 4; a) weld face, b) root surface

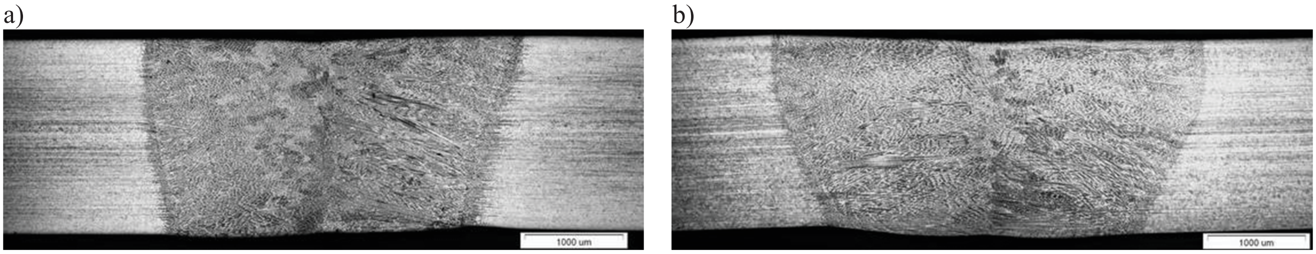

Fig. 7. Macrostructure on cross sections of butt joint of AISI 304 steel sheets 2.0 mm thick welded by high power diode (Tab. 4); a) test butt joints A(3) welded with energy input 480 J/mm, b) test butt joints B(5) welded with energy input 440 J/mm (Tab. 4)

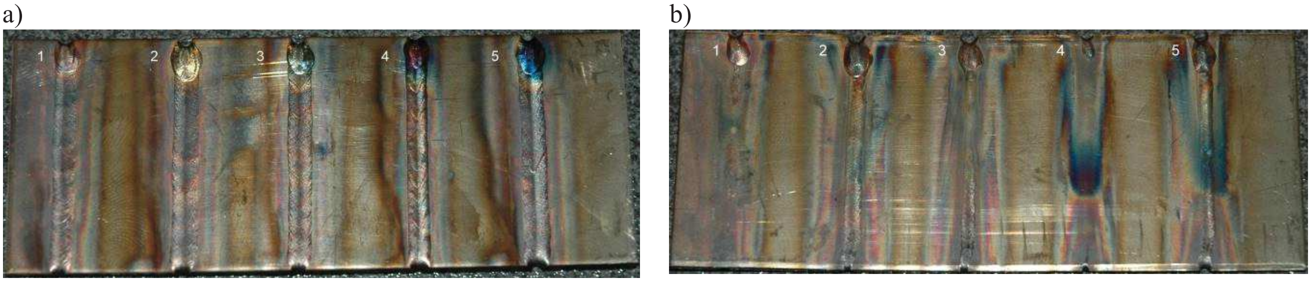

Fig. 8. A view of the bead-on-plate welds produced by high power diode laser melting of 2.0 mm sheet of AISI 304 stainless steel (Tab. 3); a) weld face, b) roof surface

In general, the fusion zone (FZ) of the welds is composed of very fine dendritic grains. As can be seen in the Figure 9 showing the microstructure of the weld produced at the highest energy input of 480 J/mm (laser power 1.6 kW and welding speed 0.2 m/min), along the fusion line partially melted grains from the side of base metal occur. From those partially melted grains, epitaxially grown columnar grains can be observed, which are perpendicular to the fusion line. Within those grains fine dendrites can be identified. The secondary arm spacing depends on the welding parameters, mainly laser output power and welding speed, thus heat input and related cooling rate of the weld metal. The estimated secondary arm spacing for the welds produced in the investigated range of parameters is approximately 5-7 μm, indicating high cooling rates. The frontal surfaces of dendrites meet in the middle of the welds forming the crystallization line, as can be seen on the cross section in Figure 9a. Presence of the crystallization line may lead to deteriorate of mechanical performance of the joints because impurities present in the alloy and eutectics with low-melting point may accumulate in this region.

Detailed observations of micrographs and analysis of the weld metal microstructure indicate that the microstructure is mainly austenitic (Feγ) with a small share of delta (Feδ) ferrite (Figs. 9 and 10). The similar results were also observed by Khalid et al. [3].

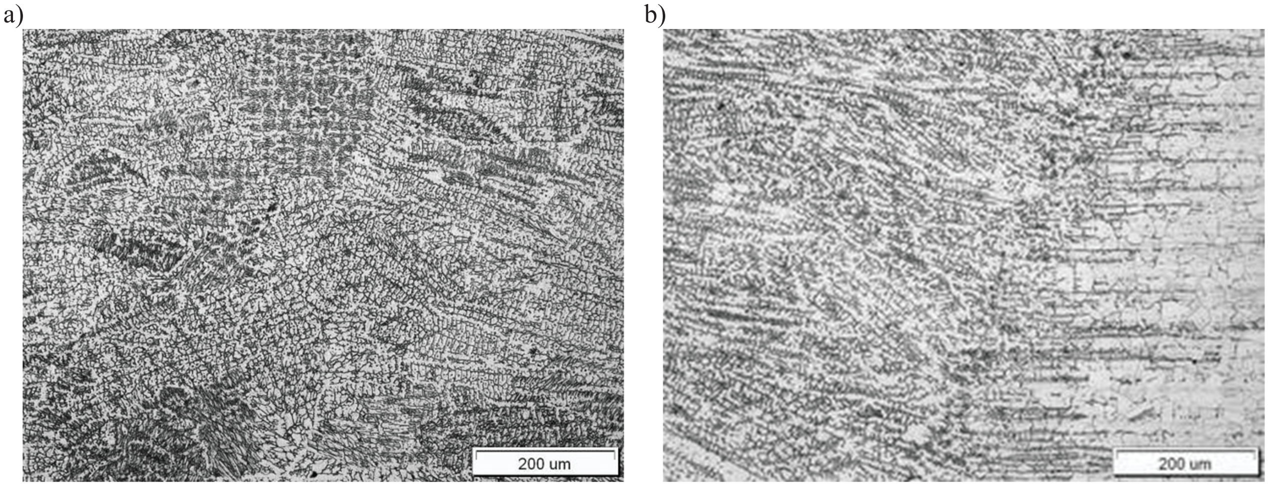

Fig. 9. Microstructure of the butt joints A(3) on 2.0 mm thick sheet of AISI 304 stainless steel produced at the energy input 480 J/mm (Tab. 4); a) middle region of fusion zone, b) fusion line (from right weld metal, fusion line, HAZ)

Microhardness measurements performed on the cross sections of the butt joints in the middle of the sheet thickness showed that the base metal of AISI 304 stainless steel exhibits microhardness in the range from 160-169 HV0.2, Figure 11. While the microhardness in the fusion zone drops down below 140 HV0.2, Figure 11. The lowest drop in microhardness was observed in a case of the test joint welded at energy input of 480 J/mm (power of 1.6 kW, welding speed 0.2 m/min). So it is evident that the welding parameters, especially energy input affect the microhardness in the fusion zone thus mechanical properties of the joints. The obtained results indicate that the drop of microhardness in the fusion zone is clearly related to the energy input of laser welding. The higher energy input of laser welding, the higher drop of microhardness in the weld metal.

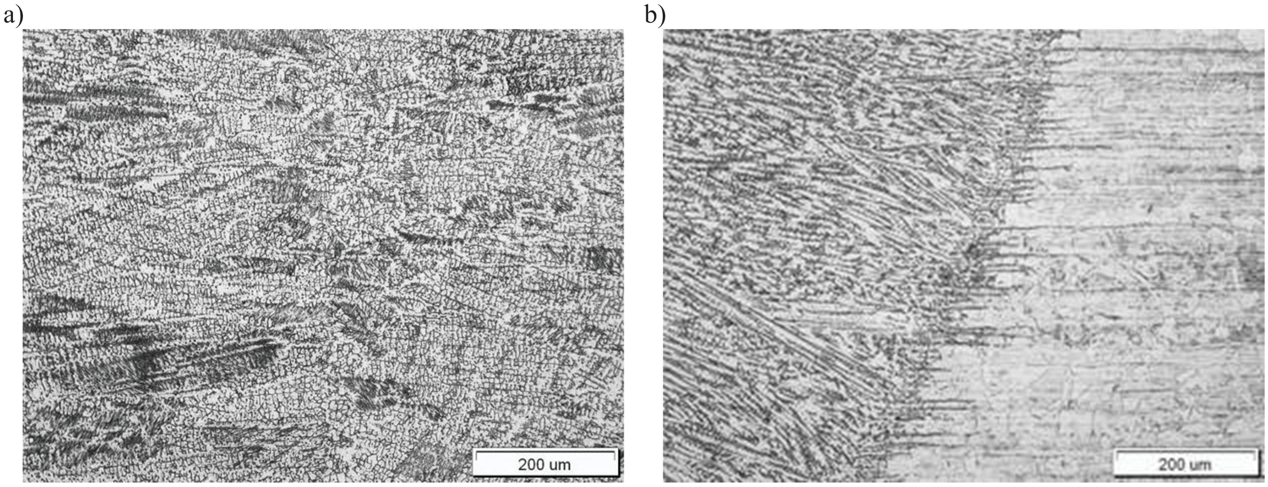

Fig. 10. Microstructure of the butt joints B(5) on 2.0 mm thick sheet of AISI 304 stainless steel produced at the energy input 440 J/mm (Table 4); a) middle region of fusion zone, b) fusion line (from right weld metal, fusion line, HAZ)

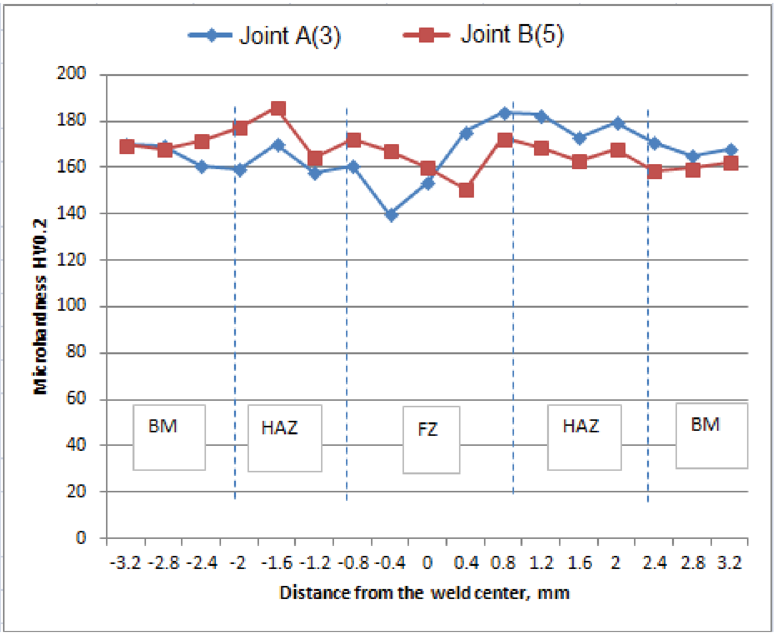

Fig. 11. Microhardness distribution (profile) across the butt joints of 2.0 mm thick austenitic stainless steel sheet AISI 304, welded by high power diode laser (Tab. 4); where: BM – base material, HAZ – heat affected zone, FZ – fusion zone

After the microhardness measurements mechanical tests was performed by means of a static tensile, Fig. 4. The typical engineering stress-strain curve is presented in Figure 12.Tensile testing of cross-weld samples were carried out to measure the tensile properties of the weldment, and also to determine the location of failure. As can be seen, all of the tested samples were broken in the base metal, away from the fusion zone and heat affected zone, Figure 13. All welded sample broke from the joint during the testing at tensile stress between 585 MPa and 605 MPa with corresponding percentage elongation in the range of 45-57%. Thus, the joints strength is not less than the strength of the base metal of 2.0 mm thick AISI 304 austenitic stainless steel sheet.

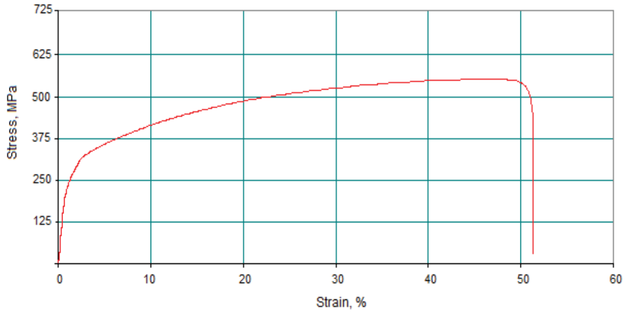

Fig. 12. Typical engineering stress-strain curve of laser welded sample – joint A(3) (Tab. 4)

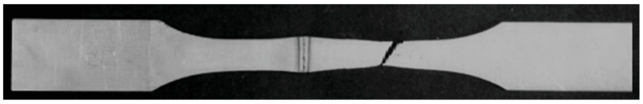

Fig. 13. A view of the broken sample from the tensile tests of the butt joint A(3) welded at 1.6 kW and welding speed of 0.2 m/min (heat input of 480 J/mm, Tab. 4)

4. Conclusions

The study of the welding process of butt joints of austenitic steel AISI 304 sheets 2.0 mm thick by the high power diode laser HPDL showed that it is possible to produce high quality joints in a wide range of laser welding parameters without consumables (Figs. 5 and 6). The surfaces of laser welded joints are flat, smooth and with no undercuts and the height of the weld reinforcement is minimal.

The butt joints of austenitic steel AISI 304 sheets welded by the diode laser at optimal parameters (Tab. 4) are very high quality, mostly without internal imperfections and the structure and grain size of weld metal and HAZ is very small and also the HAZ is very narrow and the fusion zone is very regular (Figs. 7, 9, 10). The welds produced within optimal parameters exhibit very narrow HAZ and fine dendritic microstructure of the weld metal consisting of mainly austenite (Feγ) with a small share of delta (Feδ) ferrite.

The mechanical properties was performed by means of a static tensile, of laser welded butt joints of austenitic steel AISI 304 sheets are not lower than the properties of the base material. As a result of butt joint welding of high power diode laser in the HAZ area, there is a slight increase in microhardness to approx. 185 HV0.2 compared to base material (160-169 HV0.2) and a decrease in microhardness in the fusion zone to approx. 140-150 HV0.2 (Fig. 11). The differences in the microhardness values of individual joint zones result from the specificity of the HPDL laser welding process.

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