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Microstructure of Joints Made of Duplex Steel LDX 2101 Using Concentrated Beams and Various Welding Rates

Abstract: The article presents tests concerned with the welding of duplex steel LDX 2101 using a laser beam, an electron beam and various welding rates. Flat butt joints were made using the laser beam and welding rates of 1 m/min and 2 m/min as well as the electron beam and welding rates of 0.2 m/min and 2 m/min. Microscopic metallographic examinations involved the use of light microscopy. The microstructure of individual areas of the test joints was revealed using colour electrolytic etching. Structural components in individual areas of the joints were identified using NIS Elements-AR software tools (Nikon). The same software was used for measuring the width of the joints and the height of excess weld metal. Test results were used to formulate related conclusions.

Key words: duplex steel, welded joint, laser beam welding, electron beam welding, electrolytic etching, microstructure

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1. Introduction

Duplex stainless steels, constituting an alternative to conventional austenitic steel grades, are characterised by higher strength, higher resistance to stress corrosion and lower price. As a result, duplex stainless steels are becoming more popular in building engineering as well as oil, gas and chemical industries [1, 2].

The primary processes used in the welding of duplex steels involve the use of filler metals aimed at maintaining appropriate phase equilibrium (i.e. where the content of ferrite and austenite does not exceed 70 %) [3, 4].

The use of concentrated energy beam welding processes such as laser beam welding (LBW) or electron beam welding (EBW) is the subject of research all over the world [3, 5].

Research work [6] discussed in the article and performed at Łukasiewicz – Upper-Silesian Institute of Technology, Centre of Welding aimed to identify and compare the morphology of individual areas of laser beam and electron beam welded joints made of duplex steel. The research-related tests were based on colour metallography and optical microscopy. The project included numerous experiments based on the colour etching of welded joints and the use of various reagents aimed at the obtainment of the most favourable images of specimens both on macroscopic and microscopic scales.

The article presents tests and results concerning the laser beam and electron beam welding of flat butt joints in duplex steel LDX 2101, performed using various welding rates.

2. Materials

The tests involved the use of 10 mm thick plates made of duplex steel grade LDX 2101 (EN 1.4162; UNS S32101) and designated with the letter A.

The chemical composition of the steel used was identified using a Q4 TASMAN 170 spark emission spectrometer (Bruker). The chemical composition and mechanical properties of the test steel are presented in Table 1.

Table 1. Chemical composition of duplex steel LDX 2101

In-house chemical analysis							
Chemical element content [wt %]							
C	**Si**	**Mn**	**S**	**P**	**Cr**	**Ni**	**Cu**
0.030	0.75	4.5	0.011	0.025	21.5	1.50	0.30
Chemical composition according to the manufacturer (Sverdrup Steel)							
Chemical element content [wt %]							
C	**Si**	**Mn**	**S**	**P**	**Cr**	**Ni**	**Cu**
max. 0.040	max. 1.00	4.00–6.00	max. 0.015	max. 0.035	21.00–22.00	1.35–1.90	0.10–0.80
Mechanical properties							
Norma		**R_m [MPa]**				**R_e [MPa]**	
PN-EN ISO 10088-1		700–900 MPa				> 480 MPa	

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3. Methodology

3.1. Welded joints

Laser beam welded joints

The joints of the test sheets (having dimensions of 10 mm × 100 mm × 300 mm) were made by welding flat butt joints without bevelling the edges and without using the filler metal. The laser beam welding process was performed using a robotic station equipped with a KR30HA industrial robot (KUKA) and a TruDisk 12002 disk laser (Trumpf) provided with a D70 laser/hybrid welding head (Trumpf).

The welding tests also involved the use of an optical fibre having a diameter of 400 µm. The use of the above-named optical fibre enabled the obtainment of laser beam focus diameter d_{fc} = 0.6 mm at Rayleigh length ZR = 10 mm.

The technological parameters of the laser beam welding process are presented in Table 2.

Table 2. Technological parameters used in the laser beam welding of duplex steel LDX 2101

Plate designation	Joint designation	Beam power, *P* [W]	Welding rate, *v* [m/min]	Gap [mm]
A	AL1	9000	1	0
A	AL2	9000	2	0
One-sided welding of 10 mm thick plate, gap: 0 mm Shielding gas: Ar = 8–10 l/min Nozzle: *d* = 8 mm				

In relation to both duplex steel grades, joints were welded using different welding rates, i.e. 1 m/min and 2 m/min. The main view of the laser beam welded joints is presented in Figures 1 and 2.

Electron beam welded joints

The joints of the test plates (having dimensions of 10 mm × 100 mm × 300 mm) were made by welding flat butt joints

Table 3. Technological parameters used in the electron beam welding of duplex steel LDX 2101

Accelerating voltage	120 kV
Working distance	420 mm
Concentration (focusing) coil current	655 mA
Cathode glow current	22 A
Vacuum in the working chamber	10^{-4} mbar
Vacuum in the electron gun	10^{-5} mbar
Welds made at lower welding rates	
Welding rate	200 mm/min
Welding current	20 mA (beam power: 2400 W)
Welds made at higher welding rates	
Welding rate	2000 mm/min
Welding current	100 mA (beam power: 12000 W)

Fig. 1. Main view of the flat butt joint made of duplex steel LDX 2101 using a welding rate of 1 m/min: a) weld face side and b) weld root side

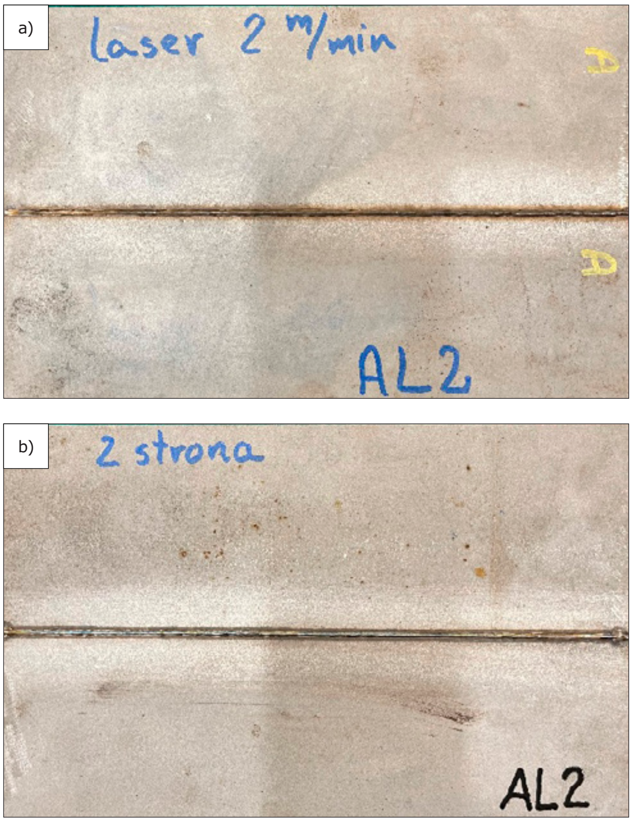

Fig. 2. Main view of the flat butt joint made of duplex steel LDX 2101 using a welding rate of 2 m/min: a) weld face side and b) weld root side

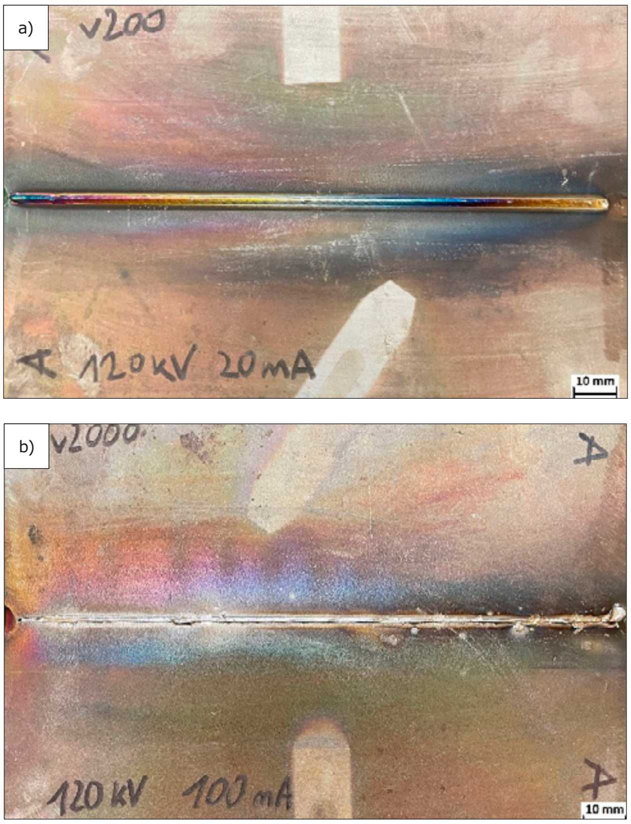

Fig. 3. Main view of the flat butt electron beam welded joint made of duplex steel LDX 2101 using a welding rate of a) 0.2 m/min and b) 2 m/min

without bevelling the edges and without using the filler metal. The electron beam welding process was performed using the welding station located at Łukasiewicz – GIT, Centre of Welding. In order to ensure the penetration of the entire thickness of the test plates, the joints were welded using a backing strip (also made of duplex steel). The joints of both steel grades were welded using different welding rates, i.e. 0.2 m/min and 2 m/min. The technological parameters of the electron beam welding process are presented in Table 3.

Because of the fact that the joints were welded using the backing strip, Figure 3 only presents the main view of the joints on the weld face side.

3.2. Metallographic specimens

The joints made of duplex steel LDX 2101 using laser and electron beam welding processes were sampled for microscopic metallographic specimens. After cutting out, fragments of the test joints were included in resin and sampled for metallographic specimens. The microstructure of the specimens was revealed using colour electrolytic etching. The microscopic metallographic tests of the joints made of duplex steel LDX 2101 using various welding methods were performed using an Eclipse MA200 light microscope (Nikon).

4. Test results

The metallographic test results in the form of the main view of the flat butt laser beam welded joints are presented in Figures 1 and 2.

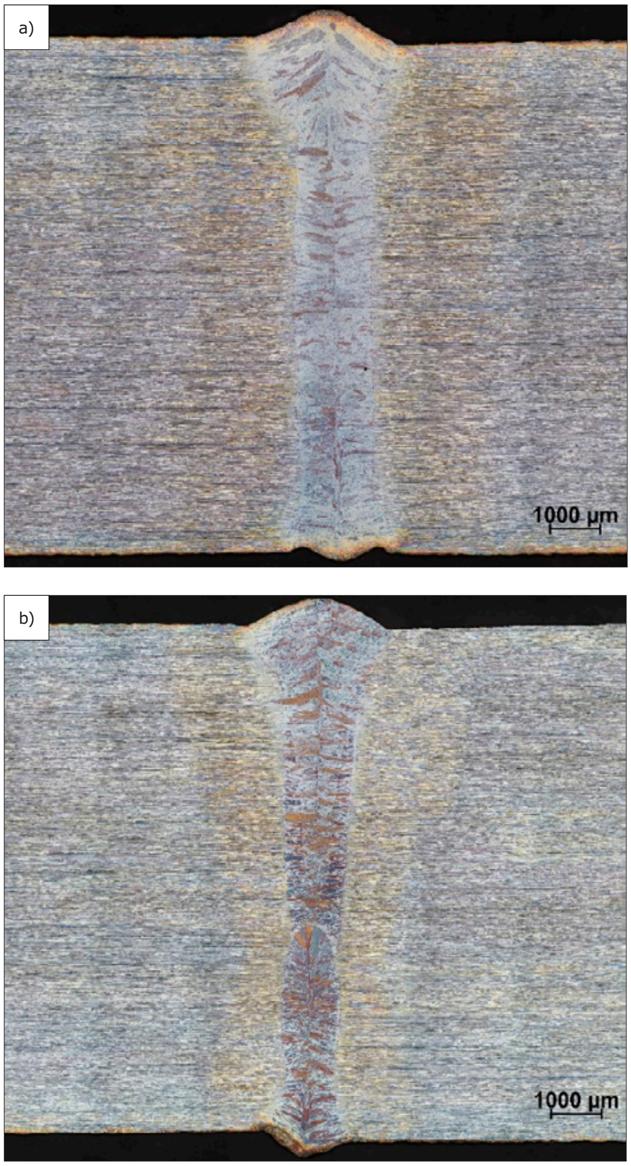

Fig. 4. Flat butt laser beam welded joints made of duplex steel LDX 2101; electrolytic etching, mag. 50×; welding rate a) 1 m/min and b) 2 m/min

Selected results of the microscopic metallographic tests of the flat butt laser beam welded joints made of duplex steel LDX 2101 using welding rates of 1 m/min and 2 m/min are presented in Figures 5 and 6.

The metallographic test results in the form of the main view of the flat butt electron beam welded joints are presented in Figure 7.

Selected results of the microscopic metallographic tests of the flat butt electron beam welded joints made of duplex steel LDX 2101 using welding rates of 0.2 m/min and 2 m/min are presented in Figures 8 and 9.

The metallographic photographs of the joints made of duplex steel LDX 2101 using various methods were used in measurements of various geometric parameters of the joint areas, i.e. excess weld face metal, weld width and undercut depth. The above-named tests and measurements were performed using an Eclipse MA200 light microscope (Nikon) and an NIS Elements-AR image analysis programme (Nikon).

The results of geometric measurements are presented in Figures 10 and 11.

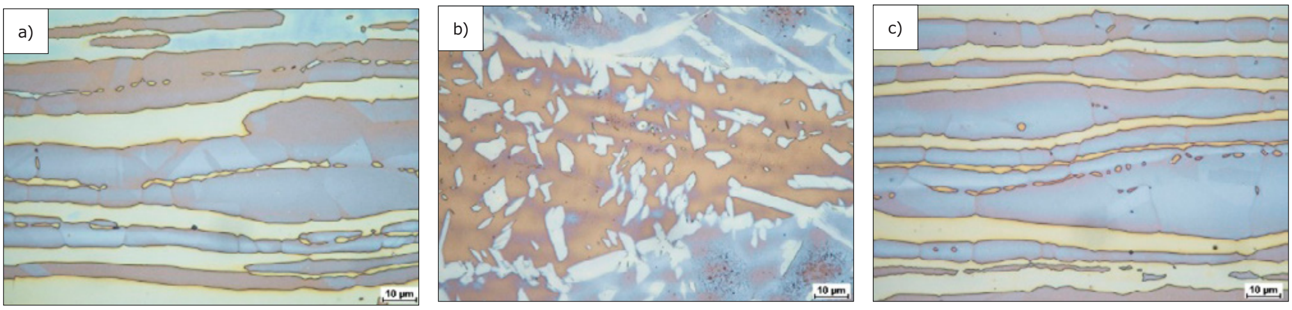

Fig. 5. Flat butt laser beam welded joint made of duplex steel LDX 2101 using a welding rate of 1 m/min; electrolytic etching; mag. 1000×: a) base material: brown and blue austenite, greenish and yellow ferrite, visible strain twins, b) weld and c) heat affected zone (HAZ)

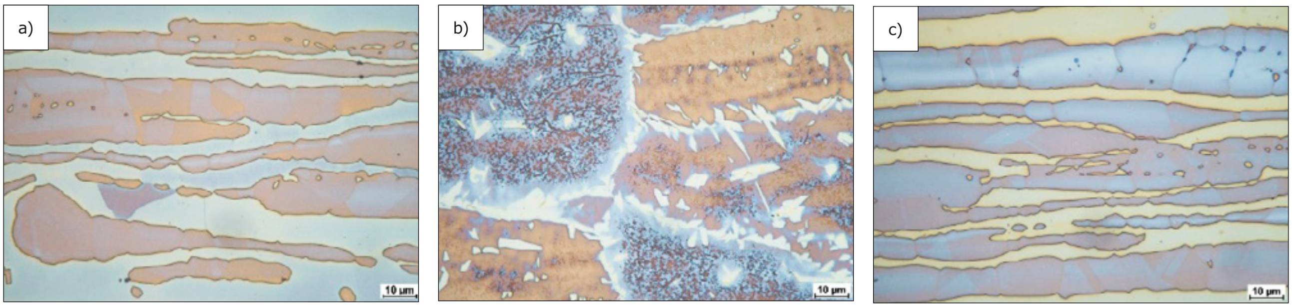

Fig. 6. Flat butt laser beam welded joint made of duplex steel LDX 2101 using a welding rate of 2 m/min; electrolytic etching; | mag. 1000×: a) base material: austenite with visible strain twins, greenish and yellow ferrite, b) weld and c) heat affected zone (HAZ)

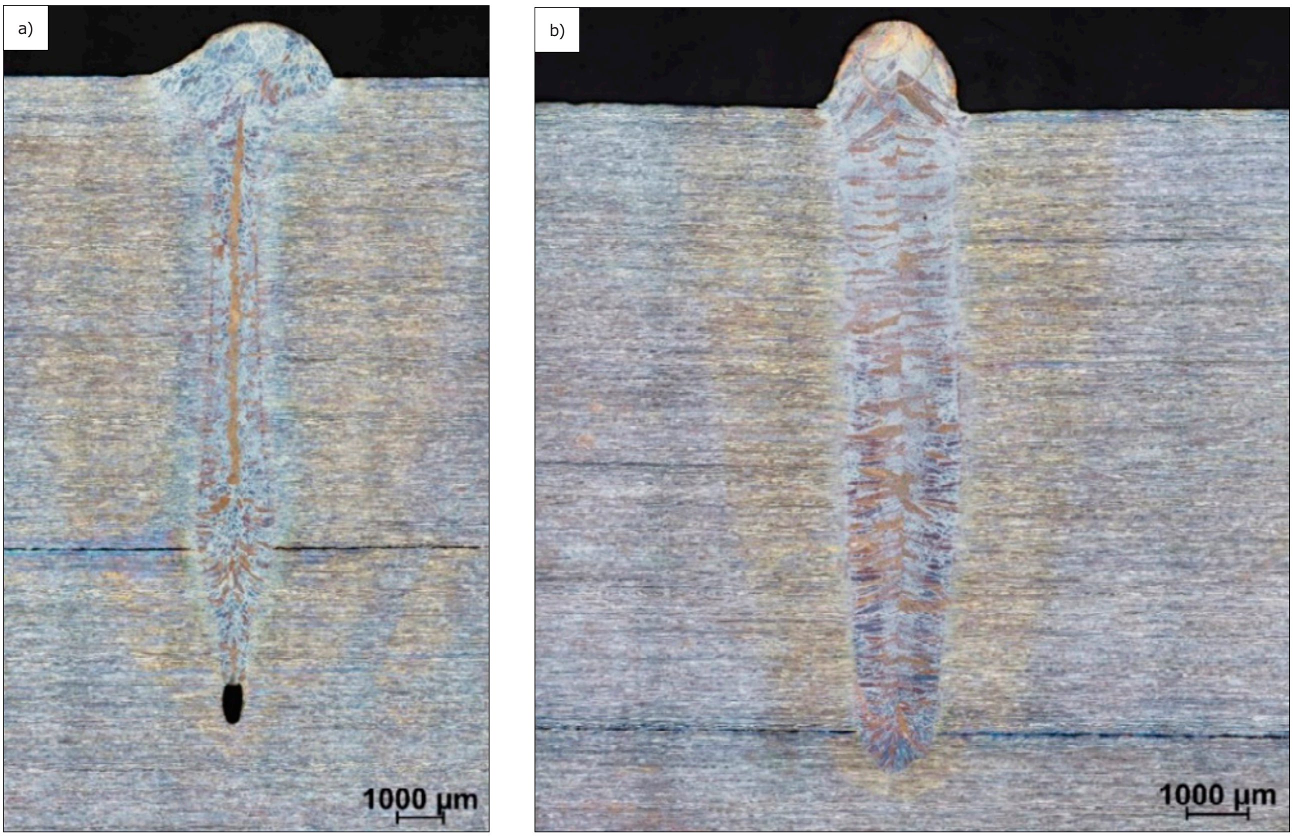

Fig. 7. Flat butt electron beam welded joints made of duplex steel LDX 2101; electrolytic etching, mag. 50×; welding rate a) 0.2 m/min and b) 2 m/min

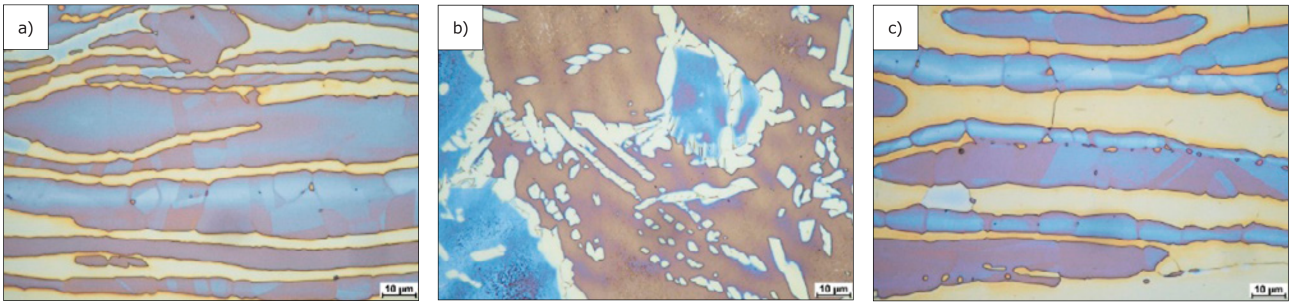

Fig. 8. Flat butt electron beam welded joint made of duplex steel LDX 2101 using a welding rate of 0.2 m/min; electrolytic etching; mag. 1000×: a) base material: austenite with visible strain twins, greenish and yellow ferrite, b) weld and c) heat affected zone (HAZ), strain twins visible in visible

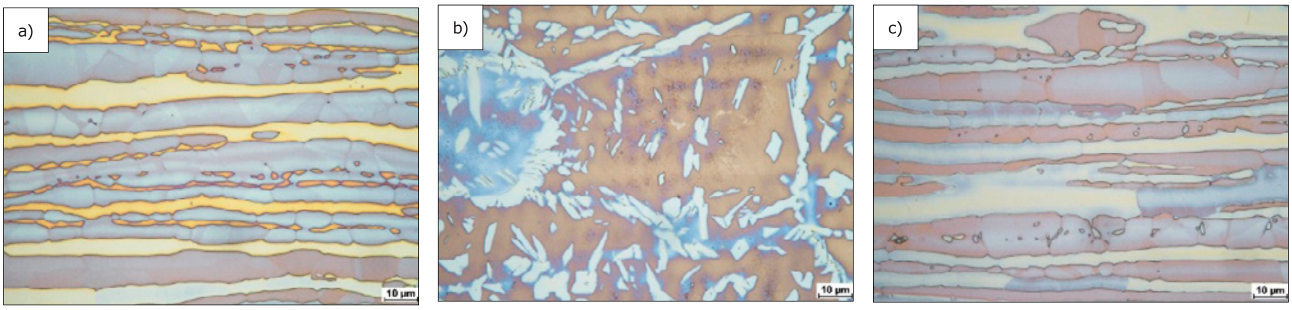

Fig. 9. Flat butt electron beam welded joint made of duplex steel LDX 2101 using a welding rate of 2 m/min; electrolytic etching; mag. 1000×: a) base material: austenite with visible strain twins, greenish and yellow ferrite, b) weld and c) heat affected zone (HAZ)

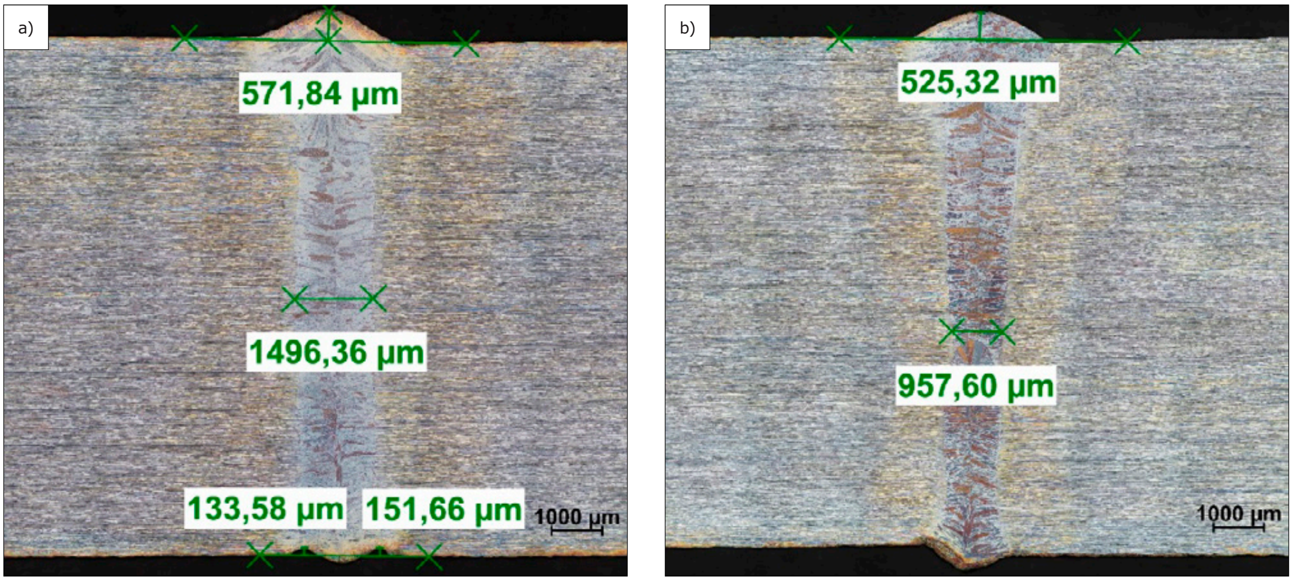

Fig. 10. Flat butt laser beam welded joints made of duplex steel LDX 2101, mag. 50×: a) welding rate: 1 m/min, measurements of the excess weld face metal, undercut depth on the weld root side and weld width, b) welding rate: 2 m/min, measurements of the excess weld face metal and weld width

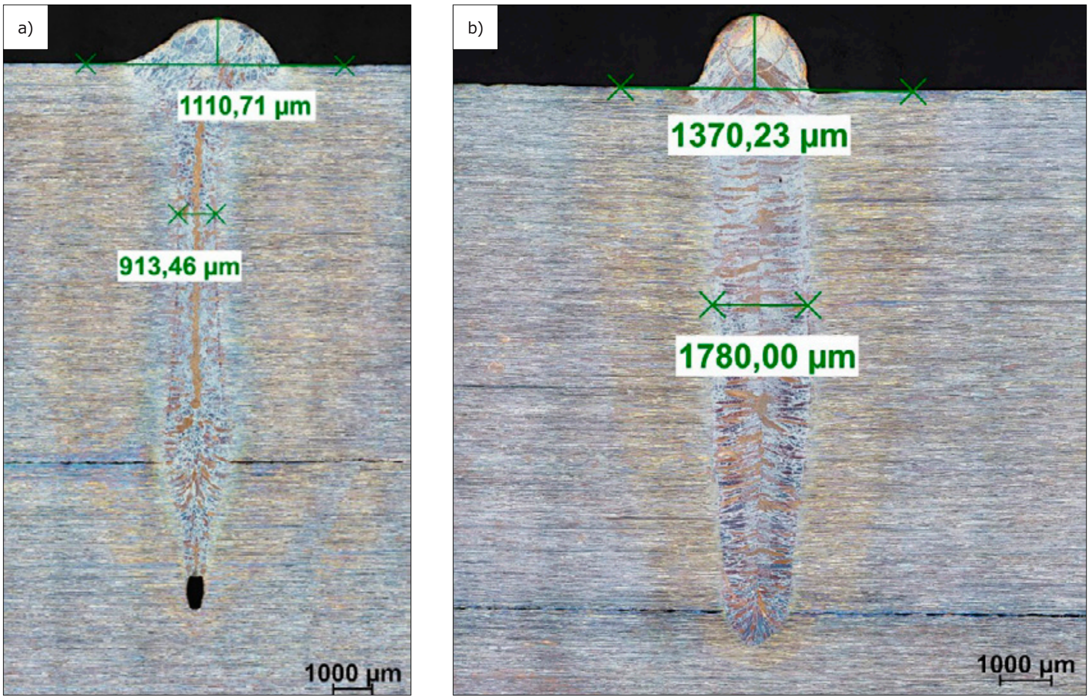

Fig. 11. Flat butt electron beam welded joints made of duplex steel LDX 2101, mag. 50×: a) welding rate: 0.2 m/min, measurements of the excess weld face metal and weld width and b) welding rate: 2 m/min, measurements of the excess weld face metal and weld width

5. Discussion

Figure 4 presents the microstructures of the flat butt laser beam welded joints made of duplex steel LDX 2101 using a welding rate of 1 m/min and that of 2 m/min. The comparison of both joints revealed that the use of the lower welding rate led to the formation of undercuts, more convex weld face and wider weld than those of the joint made using the higher welding rate. The above-presented observation results were confirmed by the measurement results presented in Figure 10. Figure 5 presents the microstructures of the base material, weld and HAZ in the flat butt laser beam welded joints made of duplex steel LDX 2101 using a welding rate of 1 m/min. The weld was composed of a mixture of austenite and ferrite, precipitated primarily along the grain boundaries. The colour of austenite changed from blue to bright-brown, whereas that of ferrite was white. The HAZ area was characterised by greater austenite granularity in comparison with that of the base material (steel). The foregoing resulted from a greater heat input during welding.

Figure 6 presents the microstructures of the base material, weld and HAZ in the flat butt laser beam welded joints made of duplex steel LDX 2101 using a welding rate of 2 m/min. Neither the microstructure of the base material nor that of the weld were characterised by differences compared to the same areas in the joint welded using the lower welding rate. The HAZ area was not characterised by grain growth in comparison with the base material of steel LDX 2101.

Figure 7 presents the main view of the flat butt electron beam welded joints made of duplex steel LDX 2101 using two different welding rates, i.e. 0.2 m/min and 2 m/min. The comparison of both joints revealed that the use of the higher welding rate led to the obtainment of the wider weld characterised by greater uniformity than that of the joint made using the slower welding rate. In addition, the excess weld face metal in the joint welded at a rate of 2 m/min became increasingly large. In turn, the joint welded at a rate of 0.2 m/min was characterised by significantly greater penetration into the joint backing strip than was the case with the joint welded at a rate of 2 m/min. The root of the joint welded at a rate of 0.2 m/min contained a cavity. The above-presented observations were confirmed by the measurement results presented in Figure 11.

Figure 8 presents the microstructures of the base material, weld and HAZ in the flat butt electron beam welded joint made of duplex steel LDX 2101 using a welding rate of 0.2 m/min. The structural composition and microstructural morphology were the same as in the previous case. The weld microstructure was a mixture of austenite and high-temperature ferrite δ. Austenite was multicolour, i.e. blue and brown, whereas ferrite was white. In general, the weld microstructure was coarse-grained. The observations of the weld and HAZ did not reveal any changes in the morphology of microstructural constituents or changes in the grain size.

Figure 9 presents the microstructures of the base material, weld and HAZ in the flat butt electron beam welded joints made of duplex steel LDX 2101 using a welding rate of 2 m/min. The analysis of the weld area did not reveal any differences in morphology, colouring or grain size in comparison with the same areas of the joint welded at a rate of 0.2 m/min. The observations across the thickness of the joint welded at a rate of 2 m/min did not reveal any differences in the microstructural morphology or changes in the grain size in the HAZ. When comparing the joint welded at a rate of 2 m/min with that welded at the slower rate, it was possible to notice that the saturation of colours was more intense in the HAZ of the joint welded at a rate of 0.2 m/min.

6. Conclusions

The above-presented tests and results led to the formulation of the conclusions presented below.

1. The laser beam welding of duplex steel LDX 2101 performed at a welding rate of 1 m/min and that of 2 m/min led to changes in the weld width. An increase in the welding rate was accompanied by a decrease in the weld width. The use of the lower welding rate resulted in the formation of undercuts on the weld face side.
2. The laser beam welding of duplex steel LDX 2101 performed using various welding rates did not trigger changes in the microstructural morphology or grain size in the HAZ.
3. The electron beam welding of duplex steel LDX 2101 LDX 2101 at a welding rate of 2 m/min led to the formation of the wider weld characterised by greater uniformity. In addition, in the aforesaid case, the weld face was characterised by significant excess weld metal. The use of a welding rate of 0.2 m/min resulted in significantly deeper penetration in the joint (backing) strip and the irregular width of the weld across the joint thickness.
4. The electron beam welding of duplex steel LDX 2101 LDX 2101 at various welding rates did not trigger changes in microstructural morphology or grain size.

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