Lechosław Tuz, Krzysztof Sulikowski

Microstructure of Joints Made in High-Strength Steels Using the Robotic Laser Beam Welding Process

Abstract: The paper presents the evaluation of weldability of unalloyed high strength heat-treated steels using of a laser beam welding robotic station. The key factors and properties affecting the usability of the aforesaid welding technology when welding the above-named steels were identified on the basis of the assessment of the microstructure and the measurements of hardness distribution in the related butt welded joints.

Keywords: high-strength heat-treated steels, laser welding, robotics

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Introduction

Technological progress necessitates an innovative approach to classical manufacturing processes and the application of entirely new solutions. In many cases, technological progress enables the miniaturisation of products, the reduction of their weight or the extension of their applicability range. Usually, technological progress is concerned with the use of new materials and manufacturing technologies. The implementation of such technologies faces many challenges (often unidentifiable at the conceptual or design stage), the sources of which lie in the physical properties of materials. The above-named materials also include steels or other metallic materials. In the group of steels there are those characterised by high strength obtained through the Thermo-Mechanical Control Process (MC in accordance with EN 10149) or through toughening (Q in accordance with EN 10025-6). The yield point of the above-named steels is restricted within the range of 500 MPa up to 1300 MPa (or even higher), where their applicability depends primarily on their weldability. By increasing the strength of a product it is possible to decrease its weight and the thickness of its walls, which, in turn, enables the reduction of the amount of welding and welding-related works (e.g. connected with the reduction (elimination) of edge bevelling). In addition, the aforesaid increase in strength translates into the decreased use of filler metals and the reduced necessity of preheating. Figure 1 presents the possible reduction of the wall thickness without decreasing the yield point. In terms of steel S1300 it is possible to change the method of bevelling from double-V, V or square preparation.

When analysing the as-received state, i.e. after toughening, the presence of hard, e.g. martensitic or martensitic-bainitic, structures can be expected. On one hand, the foregoing may result in the reduction of machinability when preparing edges for welding and, on the other,

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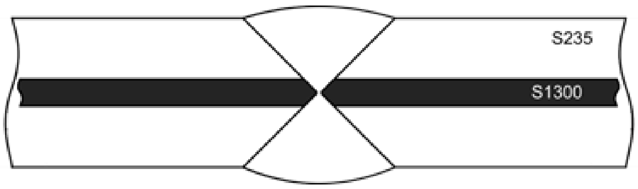


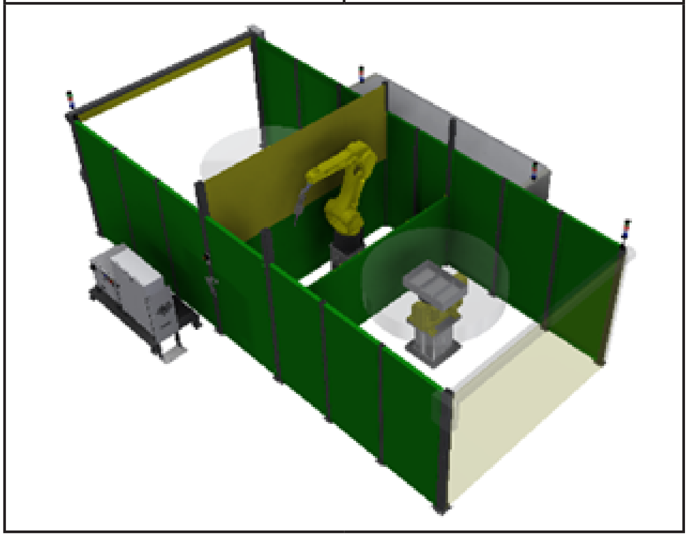
Fig. 1. Schematic diagram presenting the reduction of the wall thickness and the weld volume through the use of high yield point steel (steel S235 into S1300) without compromising the yield point; in relation to distance c = 2 mm, technological threshold b = 2 mm, groove divergence angle α = 60°, reduction of the weld weight from 2.8 kg/m in relation to g = 25 mm to 0.16 kg/m in relation to g = 4.6 mm

can lead to the adverse effect of a heat input during treatment. An excessive heat input to steel may result in its tempering. A heat input can take place during welding or operation (use of excessively high temperature). The above-named situations may lead to the tempering-triggered reduction of mechanical properties and, consequently, operational properties of a product. The foregoing indicates that the key aspect of the welding process is the appropriate control of a heat input to the material. The notion of "appropriate control" implies a heat input which is sufficiently high to melt edges being joined and to provide full penetration (after the crystallisation of the weld), yet sufficiently low to limit the tempering effect to a possibly narrow area or even to eliminate it [1, 2].

The optimisation of welding process parameters is favoured by automation providing the stability of welding process parameters including the constant length of arc and a constant welding rate. The laser beam welding process can be performed in specific positions. The use of the welding robot makes it possible to move the laser head. Therefore, the welding technique/method is adjusted to the geometry of a product and the location of a weld without the reorientation of the product. In spite of relatively low power, the small diameter of the laser beam enables the obtainment of the significant concentration of energy (power density) on a small area, the fast heating of the material combined with a high travel rate of the welding power source and the obtainment of significant penetration depth. Table 1 presents the exemplary configuration of the laser beam welding station. The welding station was used for the making of joints in high-strength steel. The related results of microscopic tests are discussed in the remainder of the article.

Table 1. Welding station hardware configuration

Source	IPG YLS 6000
Head	LaserWeld
Laser type	fibre
Wavelength	1070+/-10 nm
Focal length	150 mm
Focus diameter	0.3 mm
Robot	Fanuc Robot M-710ic70



Test materials

Materials used in the tests were 4 mm thick sheets made of steels having a guaranteed yield point of 1300 MPa. Table 2 presents the primary mechanical properties of the steels according to the producer's data contained in the technical specification. The analysis of the chemical composition was performed using spark spectroscopy. The results of the analysis were compared with data provided by the producers (Table 3). The comparison of the chemical composition-related data provided by TyssenKrupp (Xabo) and SSAB (Strenx) revealed that the steels satisfied the requirements of the EN ISO 10025-6 standard. However, the steels differed in terms of alloying agents; Xabo contained a vanadium addition, whereas Strenx contained copper and boron additions. The content of Cu and B affects hot cracking susceptibility, therefore the tests involved the use of steel having the commercial name of Strenx 1300.

Table 2. Selected mechanical properties of steel S1300QL in the as-received state in accordance with 3.1 according to EN 10204

Yield point $R_{p0,2}$, MPa	**Tensile strength R_m, MPa**	**Elongation A_5, %**	**Impact energy KV, J at a temperature of -40°C**
1300	1400–1700	8	Min. 27

Because the content of such elements like oxygen, nitrogen, carbon or sulphur is rather an inaccurate result in spark spectroscopy, the analysis (performed using a LECO machine) was extended and also included carbon and sulphur. The tests performed using a spark emission spectrometer involved specimens subjected to mechanical grinding performed with abrasive paper, the granularity of which was restricted within the range of 100 to 600. After grinding, specimens were washed. The analysis performed using the LECO machine involved drillings obtained using a laboratory drill.

Visual inspection and macroscopic tests

To verify the repeatability of the welding process, all of the welded joints were subjected to tests. Depending on process parameters, the joints differed slightly from one another. Exemplary results of initial tests are presented in Table 4. The visual inspection and the assessment of the welded joints were based on the PN-EN ISO 17637 standard and the requirements of quality level B in accordance with PN-EN ISO 13919-1. Figure 2 presents the exemplary weld face (a) and the cross-section of the welded joint (b), subjected to detailed microscopic tests. The joint was characterised by a regular symmetric shape. Macroscopic tests revealed the slight incompletely filled groove, which could act as a notch in the case of fatigue. The weld was characterised by a uniform width of approximately 0.65 mm in relation to a joint shape factor (b/h) of approximately 0.16. The width of the heat affected zone heated above Ac1 did not exceed 0.3 mm and was clearly visible. At a distance of approximately 1 mm it was possible to observe the different behaviour of the steel during etching. The foregoing led to the conclusion that outside the "classical HAZ", i.e. in the area heated below AC1, heat triggered changes in properties.

Table 3. Chemical composition of steel S1300QL according to producers' data (maximum % by weight in accordance with heat analysis) [1,2], in accordance with PN-EN ISO 10025-6 in relation to the product and individual tests

Name of steel	C	Si	Mn	P	S	Cr	Mo	Ni	V[a]	Cu	B	N	Nb[a]	Ti[a]	Zr[a]
XABO 1300	0.25	0.5	1.4	0.015	0.005	0.8	0.7	2.0	0.08	-	-	-	-	-	-
Strenx 1300	0.25	0.5	1.4	0.020	0.005	0.8	0.7	3.0	-	0.3	0.005	-	-	-	-
Acc. to standard*	0.22	0.86	1.8	0.025	0.012	1.6	0.74	2.1	0.14	0.55	0.006	0.016	0.07	0.07	0.17
Spark spect.	0.23	0.23	0.83	0.009	0.004	0.46	0.39	1.23	0.017	0.009	0.0016	-	0.011	<0.002	<0.002
LECO	0.23	-	-	-	0.0012	-	-	-	-	-	-	-	-	-	-

* – indicated values refer to products designated as QL, i.e. having guaranteed toughness at a temperature of -40°C
a – chemical elements (at least 0.01%) added for grain refinement; it is also possible to add aluminium, where the minimum amount of dissolved aluminium should amount to 0.01%, which corresponds to at least 0.013% of total aluminium

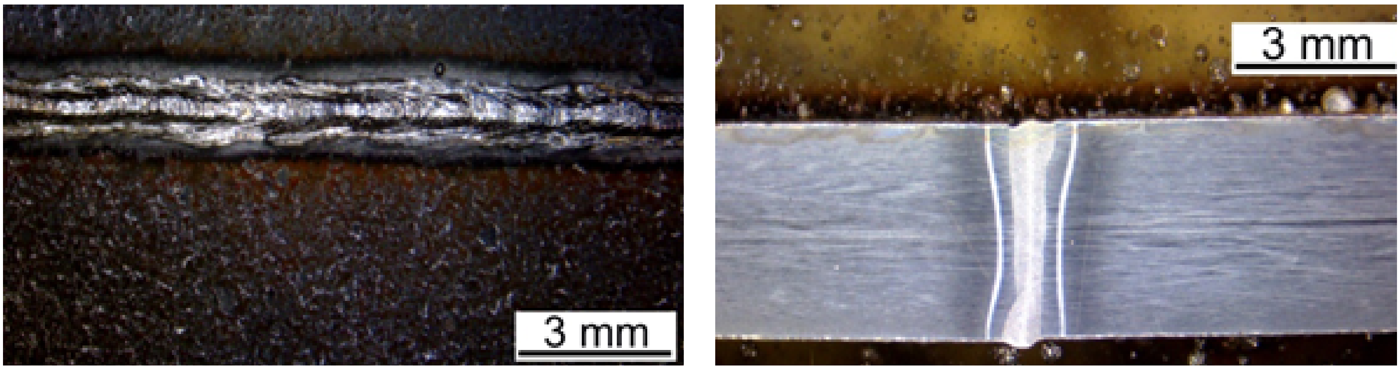


Fig. 2. Weld face (a) and the macrostructure in the cross-section of the joint (b)

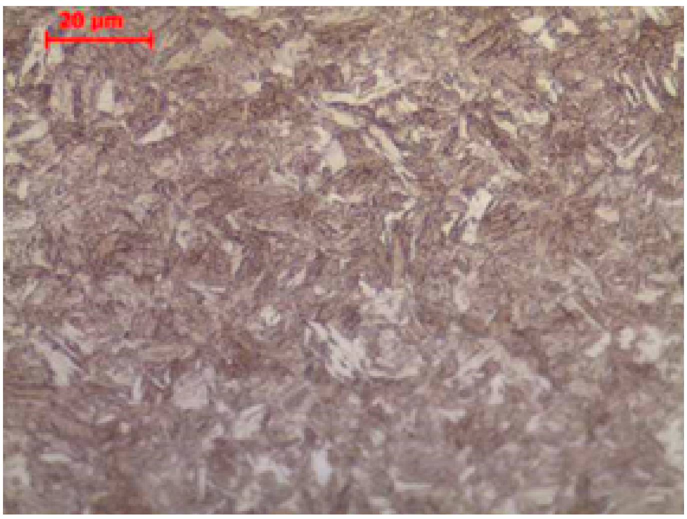
Microscopic tests

The microstructure of steel S1300QL in the as-received state is presented in Figure 3. The steel contained the fine-grained microstructure of tempered martensite and bainite with numerous dispersive carbide precipitates located both within martensite laths as well as within grain boundaries and martensite laths. The presence of the above-named precipitates resulted from the chemical composition of the steel, i.e. V and Nb additions.

The welded joint in the HAZ area was characterised by three visible areas, i.e. a superheated area, a normalised area and a very narrow partly recrystallised area. All of the above-named areas contained the martensitic structure. The area superheated within the rage of A_{c1} to A_{c3} (partly recrystallised area) contained bright fields of fresh martensite against the background of the etched structure of high-tempered martensite. In the superheated area, directly next to the fusion line, the slight grain growth was observed.

In the area heated below A_{c1}, having a width of up to 1 mm, it was possible to notice the presence of carbides and carbonitrides, intensifying the boundaries of former austenite. In addition, behind the partly recrystallised zone it was possible to observe bright areas resulting from the tempering of the steel and the formation of subgrains. In the superheated area it was possible to observe slight grain growth.

The weld contained the martensitic structure, where columnar crystals were arranged from the fusion line to the weld axis. The foregoing resulted from the narrow width of the weld and the fast discharge of heat to the base material.



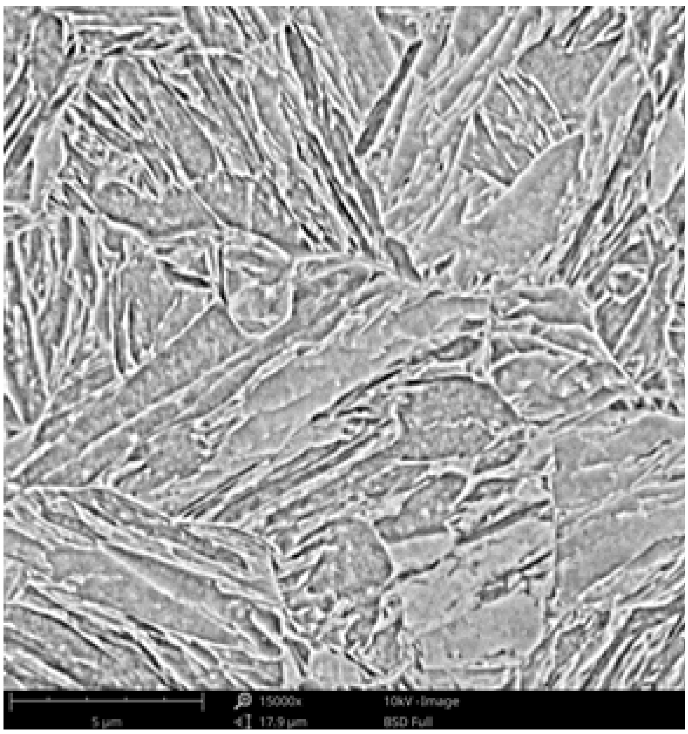
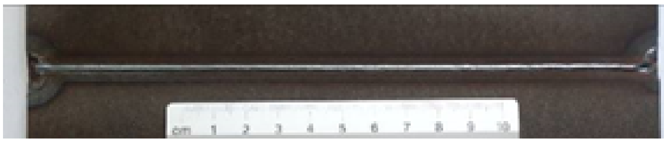


Fig. 3. Microstructure of the steel in the as-received state observed using:
a) light microscopy; magnification: 1,000x,
b) scanning electron microscopy; magnification: 10,000x

Table 4. Results of tests of the joints made of the 4 mm thick sheet (test lot no. 432)

<table>
<tr><td>Joint number</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td></tr>
<tr><td>PJ in accordance with EN ISO 13919-1</td><td>B</td><td>B</td><td>B</td><td>C</td><td>B</td><td>B</td><td>C</td><td>B</td><td>C</td><td>B</td></tr>
<tr><td colspan="11">Visual tests (VT) – specimen 3</td></tr>
<tr><td colspan="6">Face</td><td colspan="5">Root</td></tr>
<tr><td colspan="6"></td><td colspan="5"></td></tr>
<tr><td colspan="11">Ultrasonic tests (UT)</td></tr>
<tr><td>Joint no.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td></tr>
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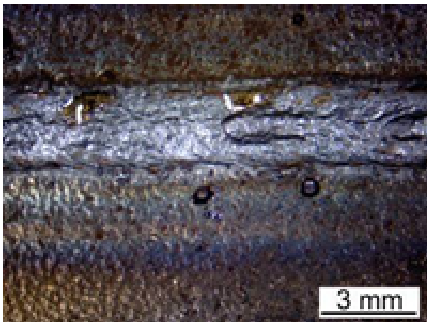
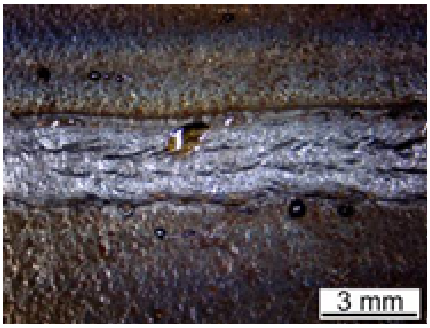
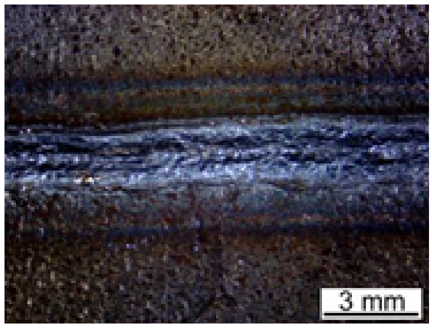
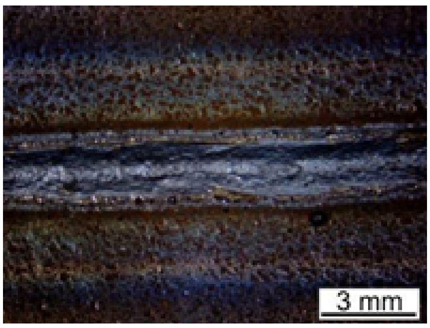
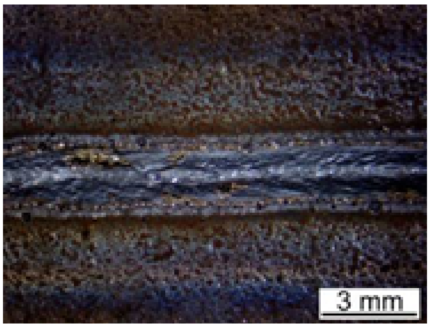
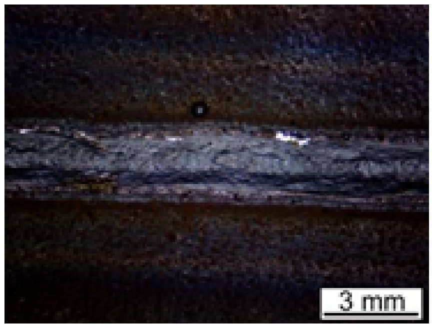
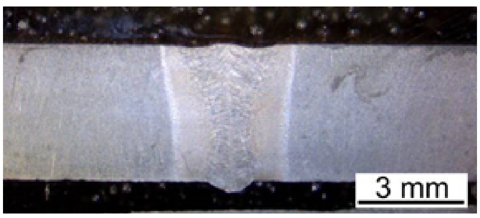
<tr><td colspan="11">Macroscopic tests – outside</td></tr>
<tr><td colspan="3">Specimen 1</td><td colspan="4">Specimen 3</td><td colspan="4">Specimen 7</td></tr>
<tr><td colspan="11">Face</td></tr>
<tr><td colspan="3"></td><td colspan="4"></td><td colspan="4"></td></tr>
<tr><td colspan="11">Root</td></tr>
<tr><td colspan="3"></td><td colspan="4"></td><td colspan="4"></td></tr>
<tr><td colspan="11">Macroscopic tests – transverse metallographic specimen</td></tr>
<tr><td colspan="11"></td></tr>
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In the weld axis it was possible to observe the phenomenon of transcrystallisation, i.e. maintaining the direction of the growth of columnar crystals towards the weld axis along the entire length of the weld. Because of the high purity of the steel (low contents of S and P), the crystal contact area was free from bands of impurities.

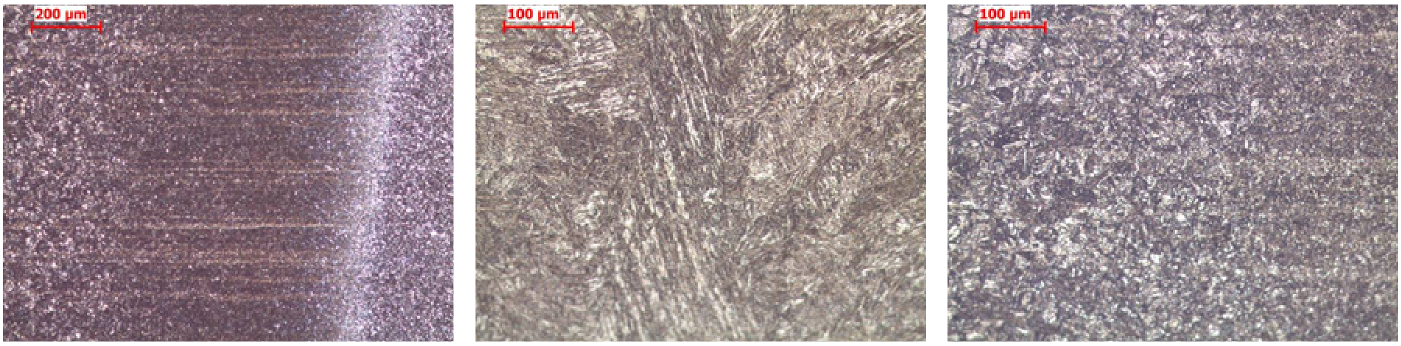
Exemplary microstructures along with their characteristics are presented in Figure 4.

Summary

The above-presented tests revealed the possibility of obtaining the high quality of laser beam welded joints in high-strength steel having a guaranteed yield point of 1300 MPa without the use of the filler metal. The performance of the welding process without the use of the filler metal required the additional preparation of edges to be welded, i.e. to ensure the parallelism of the edges and a possibly narrow gap (below 0.1 mm), enabling the obtainment of the slightly convex weld face and weld root.

However, the welding process itself constituted a certain limitation because the manner in which desirable mechanical and plastic properties (in terms of metallurgy) were obtained could create significant technological challenges. An increase in the yield point of the steel was accompanied by an increase in the number of significant problems potentially leading to the operational disqualification of products. It is therefore important to use the appropriate welding technology and adjust welding parameters accordingly where the restriction of a heat input to the material reduces the negative effect of the former on steel, including the width of the soft zone (area of tempered steel being the result of heat discharge during welding).

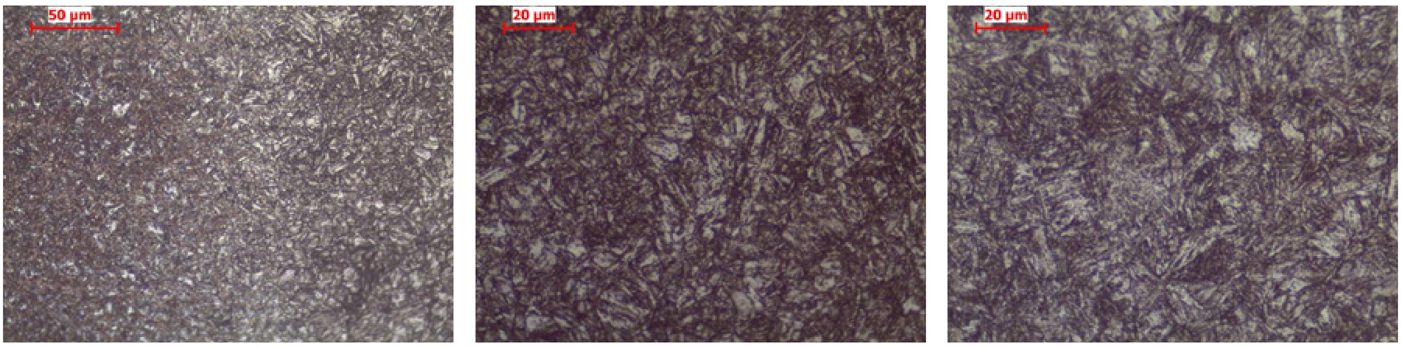
The effect of a fast thermal cycle of the local effect of high temperature is responsible for the



HAZ – microscopic view; visible banding the structure, characteristic HAZ areas (from the left): weld, fusion line, superheated area, normalised area and partially recrystallized area

Weld – zone of transcrystallisation in the weld axis; coarse crystalline structure
Martensitic structure – lath martensite

Area next to the fusion line with the superheated area



Normalised area (1) and partially re-crystallised area (2)

Area of high-tempered martensite heated up to temperature below A_{c1} (visible boundaries of former austenite)

Base material – structure of tempered martensite

Fig. 4. Microstructure of the welded joint; etchant: 4% Nital (description under the photographs)

fact that obtained welds and heat affected zones are very narrow and the fact discharge of heat enables the occurrence of transcrystallisation. The low content of admixtures prevents the formation of an area of accumulated impurities in the weld axis. The above-named impurities increase cracking susceptibility during welding. In addition, a decrease in hardness in the HAZ (softened zone) is not accompanied by the loss of the mechanical of the welded joint (immediate strength). However, it can be supposed that the foregoing may affect fatigue strength. The welded joint area contained the martensitic structure composed of lath martensite.

Acknowledgements

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References

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[2] Tasak E., Ziewiec A.: Spawalność materiałów konstrukcyjnych. Vol. 1, Spawalność stali. Wydawnictwo JAK, Kraków, 2009.

Related standards

- PN-EN ISO 17637 Badania nieniszczące złączy spawanych – Badania wizualne złączy spawanych.
- PN-EN ISO 13919-1 Spawanie – Złącza spawane wiązką elektronów i wiązką promieniowania laserowego – Wytyczne do określania poziomów jakości według niezgodności spawalniczych – Część 1: Stal.
- PN-EN 10025-6 Wyroby walcowane na gorąco ze stali konstrukcyjnych – Część 6: Warunki techniczne dostawy wyrobów płaskich o podwyższonej granicy plastyczności w stanie ulepszonym cieplnie