DOI: 10.24425/123785

J. GÓRKA*#

STRUCTURE AND PROPERTIES OF HYBRID LASER ARC WELDED T-JOINTS (LASER BEAM – MAG) IN THERMO-MECHANICAL CONTROL PROCESSED STEEL S700MC OF 10 mm THICKNESS

In this article examinations of hybrid welding technology (laser beam + MAG) of T-joints from thermomechanically worked high strength steel S700MC 10 mm thick were presented. Joints welded from one side and both sides were made. Carried examinations enabled to classify joints in quality level B according to ISO 12932 (Welding. Laser-arc hybrid welding of steels, nickel and nickel alloys. Quality levels for imperfections). In case of one sided welding with partial penetration with beam power of 8.5 kW 8 mm of penetration was achieved without noticeable distortion of web. Double sided joints were characterized with correct geometry. Joint metal is bainitic-ferritic in structure and its hardness rises about 40 HV1 in comparison to base metal hardness (280 HV1). In HAZ a slight softening of material in comparison to base metal is present.

Keywords: HLAW hybrid welding, T-joints, S700MC steel, quality of welded joints

1. Introduction

Technical and economic aspects resulting from the possibility of manufacturing metallurgical products made of TMCP steels characterised by high yield points and suitable when making various structures, including those exposed to extreme weather conditions, are responsible for the significant interest in this group of materials, their development and joining, also by means of HLAW techniques [1-15].The hybrid laser arc welding (HLAW) technology combines two conventional welding methods. This process involves the simultaneous use of a heat source in the form of a laser radiation beam and electric arc. According to the ISO 15614-14 standard, a welding process can be referred to as hybrid where two coupled heat sources are used to form one common weld pool. The combination of two independent welding methods into one hybrid process results in the synergic effect of two heat sources. Consequently, the hybrid welding process is characterised by advantages typical of both methods. In addition, the above-presented combination reduces or eliminates limitations and disadvantages related to the use of only one heat source. Arc methods usually used in the HLAW method are those where the electrode is the filler metal fed to the welding area in a continuous manner (MIG, MAG) [16-22]. The filler metal makes it possible to adjust the chemical composition of the weld through supplying appropriate alloying elements to the weld pool and ensures the proper course of the welding process when joining sheets with a gap (in terms of laser welding, there should be no gap between elements to be joined). The laser beam enables the obtainment of deep penetration using low linear energy, stabilises arc and improves the thermal efficiency of the process. The electrode wire ensures the complete filling of the weld groove gap and the formation of excess weld metal. The process of hybrid welding can be particularly useful in large-size industrial-scale production, primarily because of higher tolerance when preparing elements to be welded, the possibility of joining sheets in one run and lower accuracy when positioning sheets to be joined [23-29].

2. The range of studies

The research-related tests aimed to identify the properties of the hybrid welded (laser beam – MAG) T-joints made of 10 mm thick steel S700MC using a solid wire GMn4Ni1.5CrMo having a diameter of 1.2 mm. The chemical composition and the properties of the steel and weld deposit are presented in Tables 1 and 2, whereas the steel structure is presented in Fig. 1.

2.1. Welding process

The welded joints were made at using a robotic station (Fig. 2). The tests were performed using a TruLaser Robot 5120 chamber equipped with a TruDisk 12002 disc laser (TRUMPF) having a power of 12000 W (wavelength *l* = 1030 nm) and an EWM Phoenix 452 RC PULS synergic power source. The hybrid

* SILESIAN UNIVERSITY OF TECHNOLOGY DEPARTMENT OF WELDING ENGINEERING, 18 A KONARSKIEGO STR., 44-100 GLIWICE, POLAND

Corresponding author: jacek.gorka@polsl.pl

TABLE 1

Chemical composition according to PN EN 10149-2 and the mechanical properties of steel S700 MC subjected to thermomechanical treatment used for cold moulding

Chemical composition, % by weight											
C max.	Si max.	Mn max.	P max.	S max.	$Al_{tot.}$ min.	Nb max*.	V max.	Ti max.	B max.	Mo max.	C_e** max.
0.12	0.60	2.10	0.008	0.015	0.015	0.09	0.20	0.22	0.005	0.50	0.61
Mechanical properties											
Tensile strength, *Rm*, MPa			Yield point, *Re*, MPa			Elongation, A_5, %			Impact strength, J/cm^2 (–20°C)		
822			768			19			135		
N = 72 ppm, the nitrogen content was measured using the high-temperature extraction method * – total amount of Nb, V and Ti should amount to a maximum of 0.22% ** C_e – carbon equivalent											

TABLE 2

Chemical composition and mechanical properties of filler metal GMn4Ni1.5CrMo

Chemical composition, % by weight							
C	Mn	Si	Cr	Ni	Mo	Ti	
0.1	1.8	0.7	0.3	2.0	0.55	0.07	
Mechanical properties							
Tensile strength, *Rm*, MPa		Yield point, *Re*, MPa		Elongation, A_5, %		Impact strength, J/cm^2 (–40°C)	
900		810		18		55	

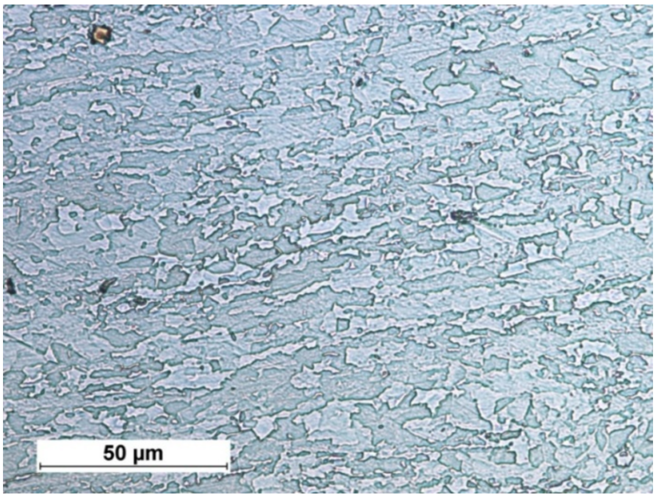


Fig. 1. Structure of bainitic-ferritic steel S700MC with visible effects of plastic deformation

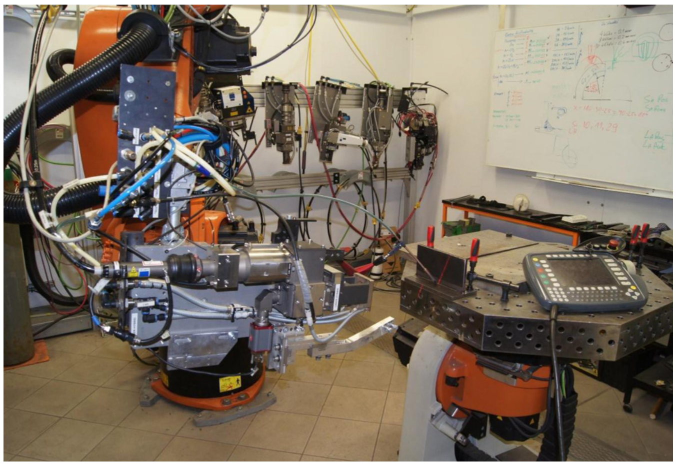


Fig. 2. Hybrid welding station (laser beam – MAG)

welding head (laser beam – MAG) was fixed on the robot wrist. The focal length of the laser optics collimator was f_c = 200 mm, whereas the focal length of the focusing lens amounted to f_{foc} = 400 mm. The diameter of the optical fibre supplying energy from the laser to the robot was d_{fiber} = 0.4 mm. The above-presented arrangement of the optics made it possible to obtain the diameter of laser beam focus d_{foc} = 0.8 mm. The electrode extension was l = 18 mm. The shielding gas used in the tests was mixture M21 (18% CO_2 + 82% Ar), whereas the gas flow rate amounted to 18 dcm^3/min. Welding joints are prepared at "I", with no gap. The filler metal was solid wire GMn4Ni1.5CrMo having a diameter of 1.2 mm. The electrode was inclined in relation to the welded surface at angle α = 65°, whereas the distance between the electrode tip and the laser beam was a = 2 mm.

A series of welding tests involving T-joints was performed changing the primary process parameters (Table 3) and obtaining one-sided welded joints with complete and incomplete penetration as well as two-sided welded joints. The position of a MAG torch was similar to that used when making a fillet weld in the horizontal position. The laser beam was inclined at an angle of 10^o in relation to a vertically positioned web of a T-joint (Fig. 3). All of the welding tests except for the last one involved the use of a welding direction where the leading heat source was a laser beam, i.e. LA (Laser Leading) welding direction. The LA technique allows to obtain a significant penetration depth, which is very important in such joints. The parameters used when making the joint (adjusted on the basis of preliminary tests) are presented in Table 3.

Exemplary one-sided and two-sided welded joints are presented in Figs. 4 and 5.

TABLE 3

Parameters HLAW hybrid welding (laser beam – MAG) T-joints

Joint no.	Beam power, *P*, [kW]	Welding current, *I*, [A]	Configuration	Joint assessment
1	8.5	280	LA	High quality; slight angular displacement of plates
2	7	295	LA, two-sided	High quality
3	7	295	LA, two-sided	High quality
4	7	290	LA	High quality
5	8.5	290	LA	Low quality; excessive melt-through with excess penetration bead along the entire length of the joint
6	7.6	290	LA	Low quality; excessive melt-through with excess penetration bead in the initial and final part of the joint; significant amount of spatters
7	7.6	290	AL	Low quality; excessive melt-through with excess penetration bead in the middle and final part of the joint; significant amount of spatters
Welding speed v = 1.1 m/min				

Fig. 3. View of the welding process

Fig. 4. T-joint one-sided welding technique LA

Fig. 5. T-joint welded double-sided welding technique LA

2.2. Tests of Welded Joints

The test welded T-joint was subjected to the following non-destructive tests**:**

- visual tests performed on the basis of the requirements specified in the ISO 17637:2011 standard;
- magnetic particle tests performed following the guidelines referred to in the ISO 3059:2005, ISO 9934-2:2003 and ISO 9934-3:2003 standards. The necessary contrast was

obtained using white contrast paint MR 72. The tests were performed using magnetic powder suspension MR 76S and a yoke electromagnet.

Following the non-destructive tests, the welded joint was subjected to the following destructive tests:

- macroscopic metallographic tests performed using an Olympus SZX9 light stereoscopic microscope; the test specimens were etched using Adler's reagent;macroscopic metallographic tests performed using a NIKON ECLIPSE MA100 light microscope; the test specimen were etched using Nital; hardness measurements performed using a Vickers 401MVD hardness testing machine (Wilson Wolpert) and a load of 1 kg. Three measurements were taken in each joint area in accordance with the requirements of ISO 9015: 2011E.

3. Results and discussion

Related visual tests enabled the elimination of the joints characterised by the lack of penetration or excessive penetration on the root side and failed to satisfy quality-related requirements (joints nos. 5-7, Table 3). Related macroscopic tests revealed that joints nos. 1-4 were free from welding imperfections and were characterised by proper geometry (Fig. 6).

Microscopic tests of the joints revealed changes in the microstructure of the weld and HAZ areas in comparison with that of the base material. Both in the weld and HAZ of each test joint the plastic strain effect in the form of grains elongated in the direction of rolling, obtained during the production of the plates, was eliminated. The weld area structure was dendritic and composed of bainite and ferrite lamellas formed out of retained austenite grains. The HAZ in each of the test joints contained a fine-grained microstructure visibly dominated by ferrite (Figs. 7 and 8). Both the weld and HAZ areas of each test joint revealed the presence of hard nitride precipitates (Fig. 9).

Hardness tests revealed that an HLAW (hybrid welding) thermal cycle translated into higher hardness in the weld area and lower hardness in the HAZ area in comparison with that of the base material. The base material hardness amounted to approximately 280 HV1, the hardness in the weld area was restricted within the range of 295 HV1 to 315 HV1, whereas the hardness in the HAZ area was restricted within the range of 235 HV1 to 260 HV1. The increased hardness in the weld area resulted from the effect of filler metal alloying agents, increasing hardenability. In turn, the decrease in the HAZ hardness resulted from the loss of properties obtained during the thermomechanical control process, (Fig. 10 and 11) and lost through the effect of a welding thermal cycle.

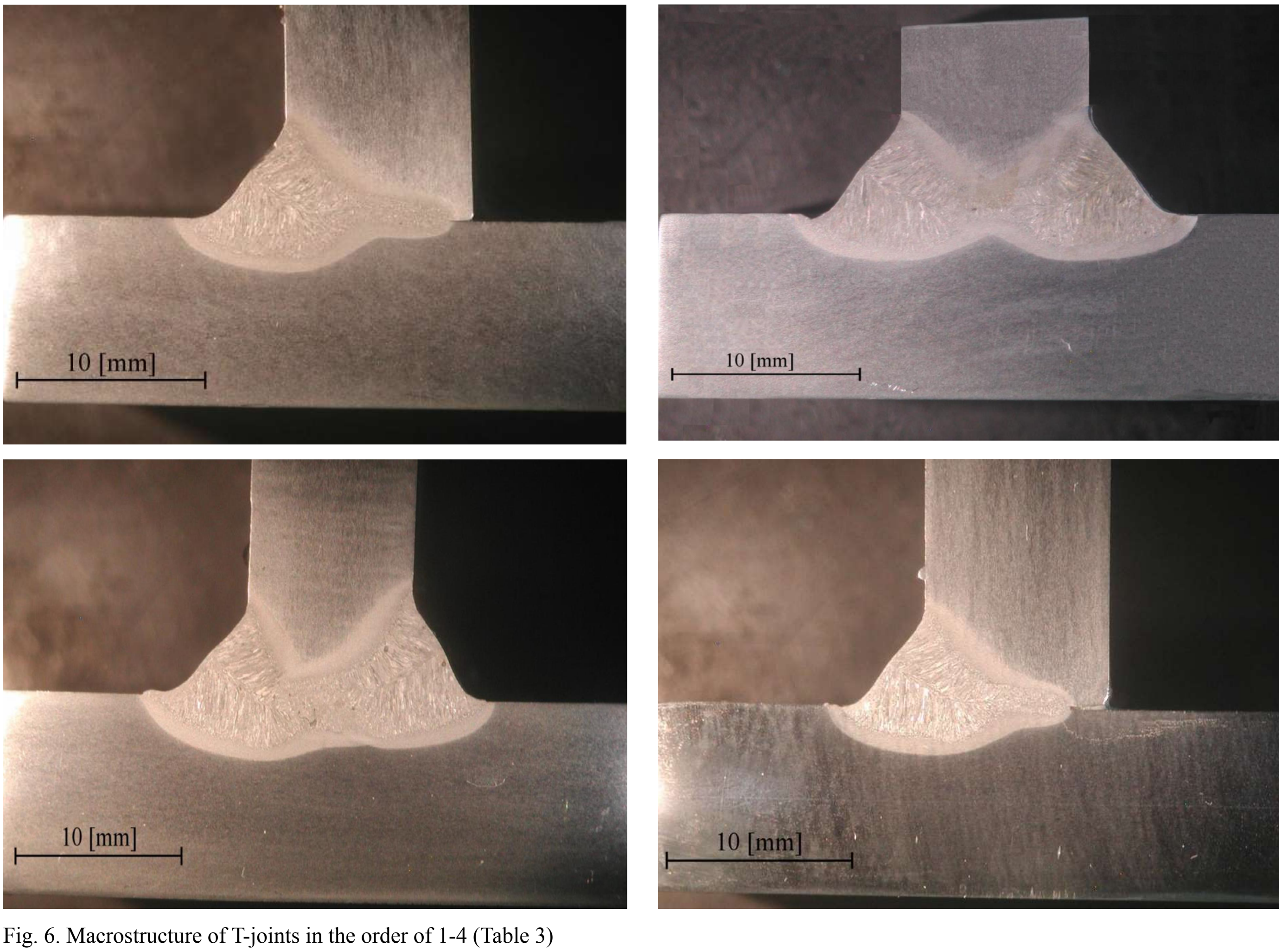


Fig. 6. Macrostructure of T-joints in the order of 1-4 (Table 3)

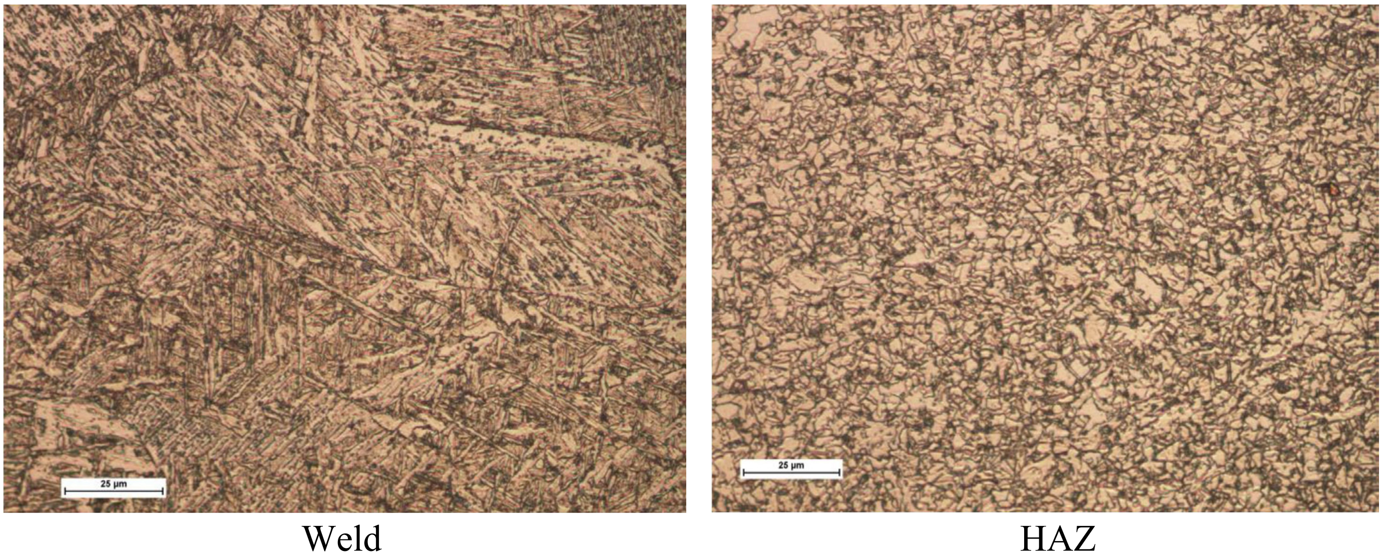


Fig. 7. Microstructure T-joint welded one sided

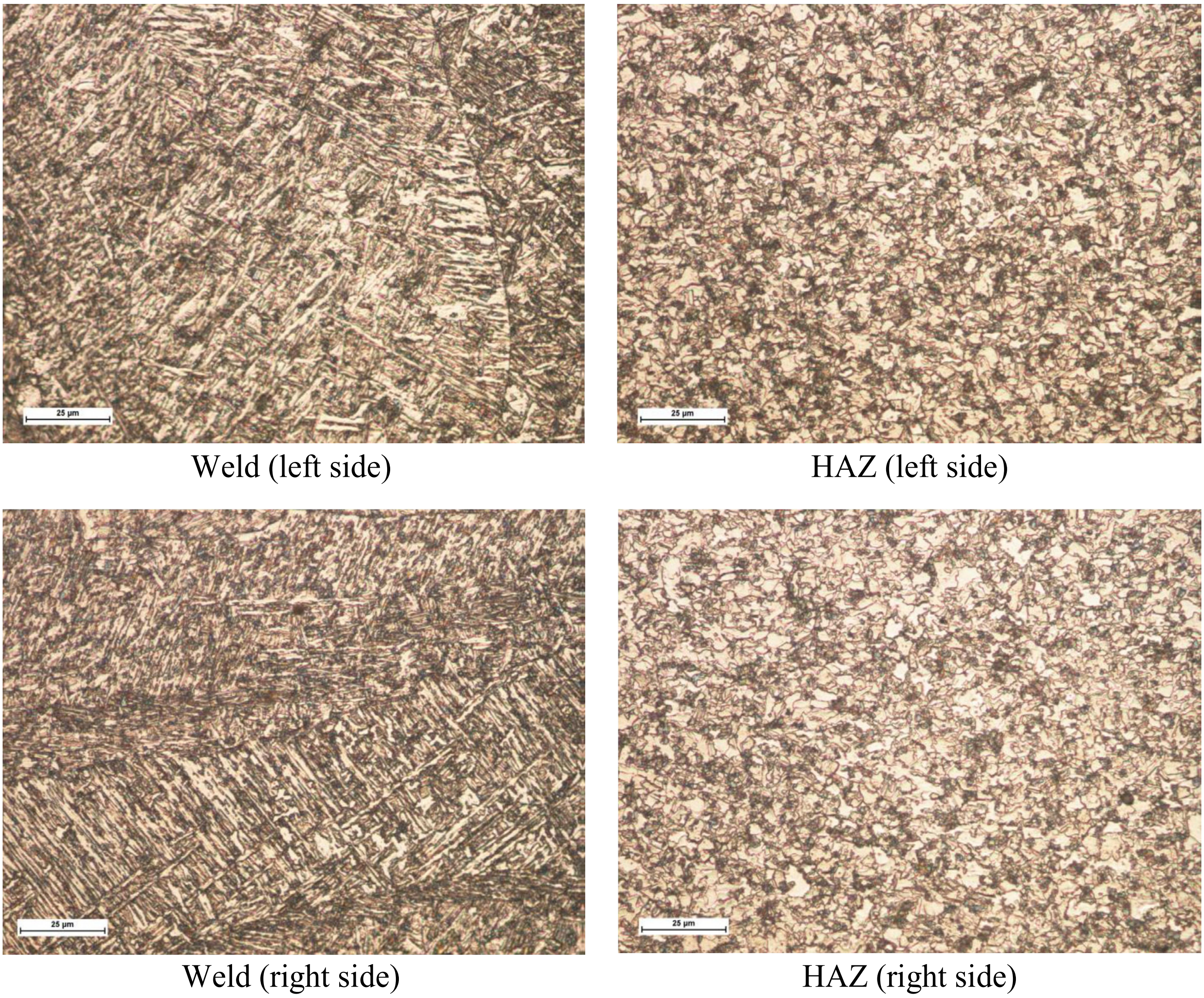
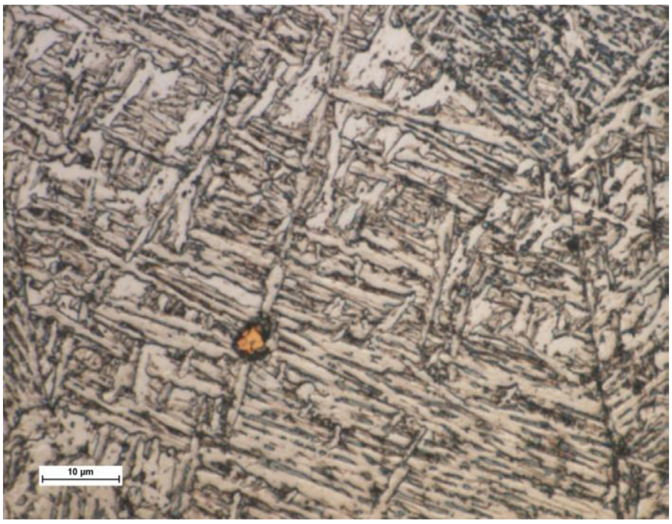
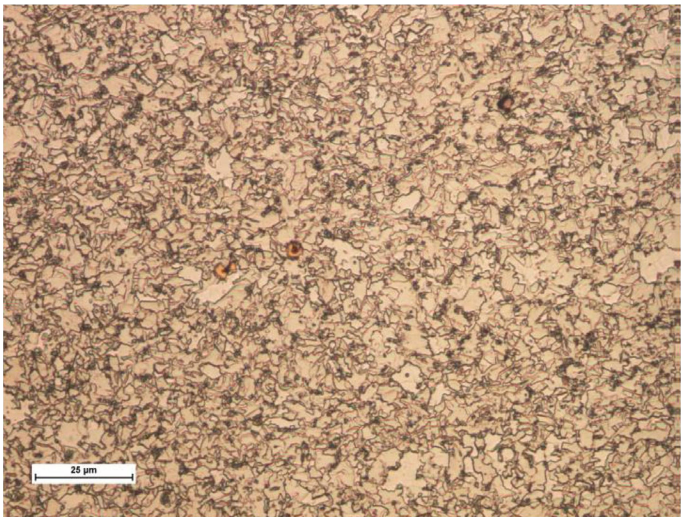


Fig. 8. Microstructure T-joint welded double-sided



Weld



HAZ

Fig. 9. The separation of nitrides in a welded joint hybrid (laser – MAG)

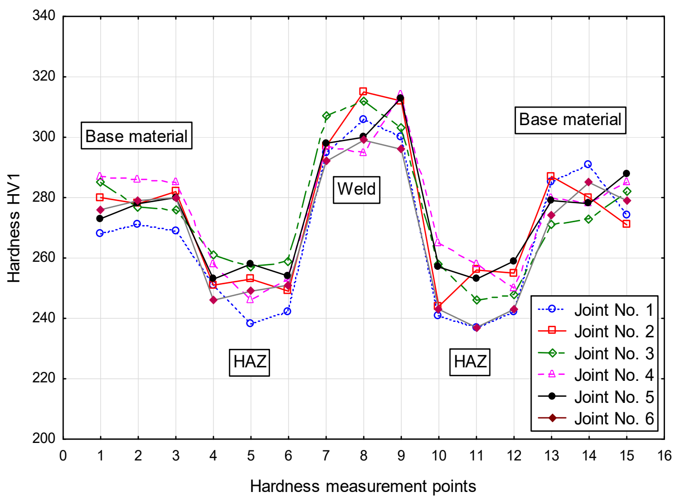


Fig. 10. HV1 hardness distribution in the examined joints (measurement line across the joint)

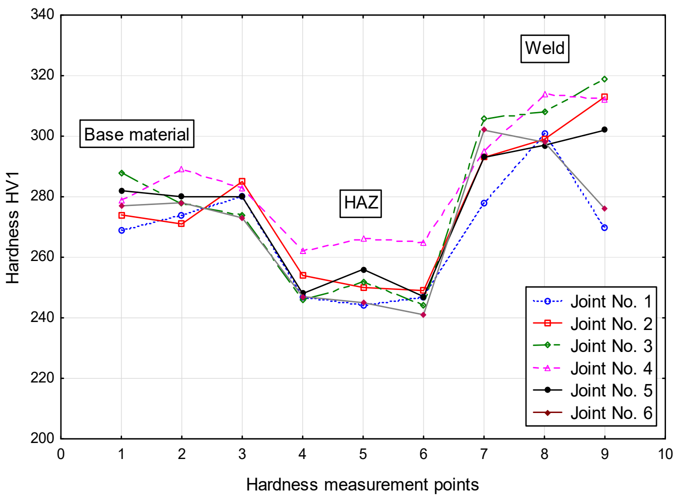


Fig. 11. HV1 hardness distribution in the examined joints (measurement line across the weld)

4. Summary

The tests justified the formulation of the following conclusions:

- The obtainment of a butt weld with full penetration in a T-joint made of 10 mm thick plates in one run during welding performed using the HLAW method is difficult because of the high volume of the liquid metal pool formed during welding and excessive penetration tending to occur on the weld root side.
- One-sided hybrid welding (with incomplete penetration) of T-joints made of 10 mm thick plates in steel S700MC enables the obtainment of high quality welds characterised by a penetration depth of 8mm. Parameters decisive for the penetration depth of welds in hybrid-welded T-joints include the power of the laser beam and the angle at which the laser beam is inclined in relation to the horizontal plane of the plate subjected to welding.
- The two-sided hybrid-welded (HLAW) T-joint was characterised by the highest quality in comparison with that of the remaining test joints. Two-sided welding enables the obtainment of full penetration using lower laser beam power, which, in turn, facilitates the stabilisation of the welding process. In addition, the above-named welding method eliminates slight angular deformations which might occur during one-sided welding.
- The LA (Laser Leading) technique allows to obtain a significant penetration depth, which is very important in such joints.
- The base material structure was bainitic-ferritic and contained irregular-sized gains elongated in the direction of thermomechanical rolling. The weld area structure was dendritic and contained ferrite and bainite lamellas. The HAZ area contained the homogenous structure as regards the size of grains.

- The weld area hardness was higher (up to 320 HV1) than that of the base material (280 HV1). As a result of the welding thermal cycle effect, the HAZ area lost its properties obtained during the thermomechanical rolling process. Consequently, the hardness of the HAZ area dropped to 250 HV1.

REFERENCES

[1] V. Flaxa, J. Shaw, Steel Grips **1** (4), 255-261 (2003).

[2] M. Opiela, Mater. Technol. **49** (3), 395-401 (2015).

[3] M. Opiela, Arch. Metall. Mater. **59** (3), 1181-1188 (2014).

[4] A. Grajcar, J. Therm. Anal. Calorim. **118** (2),1011-1020 (2014).

[5] C. Mikia, K. Homma, T. Tominaga, J. Constr. Steel. Res. **58**, 3-20 (2002).

[6] C. Lee, H. Shin, K. Park, J. Constr. Steel. Res. **74**, 134-139 (2012).

[7] V. Ollilainen, H. Hurmola, H. Pontinen, J. Mater. Eng. Sys. **5** (4), 222-232 (1984).

[8] S. Shipitsyn, Y. Babaskin, I. Kirchu, L. Smolyakova, N. Zolotar, Steel in Translation **38** (9), 782-785 (2008).

[9] I. Rak, V. Gliha, M. Kocak, Metall. Mater. Trans. **28** (1), 199-206 (1997).

[10] K. Chang, C. Lee, K. Park, T. Um, Int. J. Steel Struct. **11** (3), 315-324 (2011).

[11] K. Nishioka, K. Ichikawa, Sci. Technol. Adv. Mat. **13** (2), 1-20 (2012).

[12] A. Grajcar, M. Różański, M. Kamińska, B. Grzegorczyk, Mater. Technol. **50** (6), 945-950 (2016).

[13] M. Żuk, J. Górka, A. Czupryński, M. Adamiak, Metalurgija **55** (4), 613-616 (2016).

[14] J. Górka, Mater. Technol. **50** (4), 617-621 (2016).

[15] J. Górka, Metals **8**, 169 (2018). DOI:10.3390/met8030169.

[16] R. Burdzik, T. Węgrzyn, Ł. Konieczny, A. Lisiecki, Arch. Metall. Mater. **59** (4), 1275-1281 (2014).

[17] A. Kurc-Lisiecka, A. Lisiecki, Mater. Technol. **51**, 199-204 (2017). DOI:10.17222/mit.2015.158.

[18] J. Górka, D. Janicki, M. Fidali, W. Jamrozik, Int. J. Thermophys. **38** (12), 1-21 (2017).

[19] J. Górka, Materials **11**, 1192 (2018). DOI:10.3390/ma11071192.

[20] A. Grajcar, P. Matter, S. Stano, Z. Wilk, M. Różański, J. Mater. Eng. Perform. **26** (4), 1920-1928 (2017).

[21] A. Grajcar, M. Morawiec, M. Różański, S. Stano, Opt. Laser Technol. **92**, 52-61 (2017).

[22] M. Kubiak, W. Piekarska, S. Stano, Z. Saternus, T. Domański, Arch. Metall. Mater. **60** (3), 1965-1972 (2015).

[23] Y. Naito, S. Katayama, A. Matsunawa, LAMP 2002 Proceedings **4831**, 357 (2002).

[24] C. Bagger, F. Olsen, Proceedings of ICALEO 2003, Jacksonville, FL, 11-20 (2003).

[25] N.J. Orozco, Proceedings of ICALEO 2003, Jacksonville, FL, 31-40 (2003).

[26] T. Murakami, M.H. Shin, K. Nakata, Transactions of JWRI. **39** (2), (2010).

[27] M. Banasik, M. Urbańczyk, Biuletyn Instytutu Spawalnictwa **1** (60), 6-13 (2017).

[28] M. Banasik, M. Urbańczyk, Biuletyn Instytutu Spawalnictwa **2** (61), 17-24 (2017).

[29] M. Banasik, E. Turyk, M. Urbańczyk, Przegląd Spawalnictwa **5** (89), 21-28 (2017).