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Effect of Hybrid Laser Arc Welding on the Structure and Properties of High Yield Point Steel S960QL

Abstract: The article discusses the advantages of the hybrid laser + MAG welding method as well as the advantages and exemplary applications of high yield point steel S960QL. The study involved the performance of the hybrid welding of butt joints having various thicknesses and made of high yield point steel (960 MPa) in the flat and in the horizontal position. In addition, the study included macro and microscopic metallographic tests of the test joints.

Keywords: Hybrid Laser Arc Welding, HLAW, steel S960QL

DOI: 10.17729/ebis.2018.5/21

Introduction

Welding technologies are the most popular methods used when joining steels. Increasingly high requirements related to the quality of welded joints and the efficiency of welding processes impose the necessity of developing new innovative joining methods. Research centres and producers of welding equipment and materials incessantly improve welding technologies, processes and the quality of welded joints.

Laser welding is a technologically advanced method increasingly popular in many industries (Fig. 1) [1, 2].

Presently, the implementation of laser technologies in industry is regarded as one of the most important trends in the improvement of technological processes. Laser welding is a process characterised by the high proportion of the penetration depth to the weld width as well as by the relatively low effect of heat on the material being welded, even in cases of thick elements. The application range of laser welding is permanently expanding as the high power of laser radiation, necessary for effective welding, no longer poses a technical restriction where the market offers lasers having power between 10 and 20 kW [3, 4].

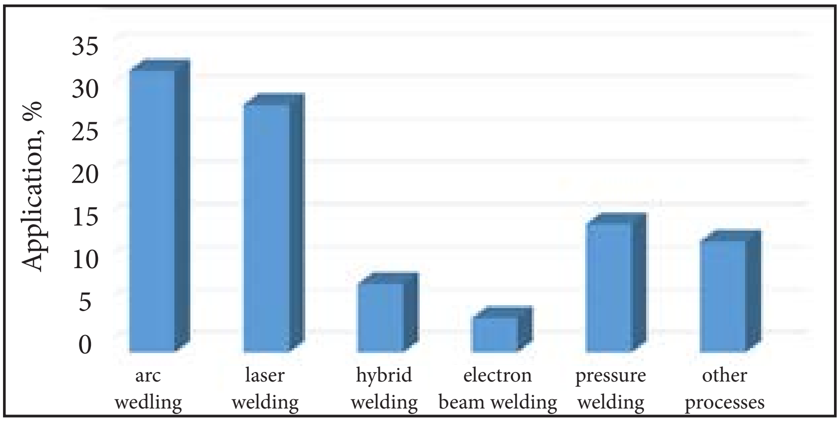

Fig. 1. Various welding methods [1]

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In spite of many advantages, the laser welding of butt joints is characterised by certain technological disadvantages connected with the preparation of elements before welding. Elements to be welded should be matched without a gap, which in relation to elements cut using various presses, guillotine shears or classical thermal cutting methods (oxygen cutting) can be difficult to achieve.

One of the most technologically attractive methods is hybrid welding. In turn, one of the most popular hybrid welding methods is the one combining two processes, i.e. laser welding and arc welding, also known as Hybrid Laser Arc Welding (HLAW) [4-6]. The hybrid laser + MAG electric arc welding involves the simultaneous use of two heat sources, i.e. the laser radiation beam and electric arc. During the process of welding the above-named heat sources are responsible for the formation of one common weld pool (Fig. 2a). The hybrid laser welding involving the use of a combined heat source (laser radiation and electric arc is characterised by a number of advantages surpassing those typical of each of the processes used separately (Fig. 2b).

Advanced industry is characterised by increased demand for weldable structural steels having high mechanical and technological properties. Recent years have seen a rapid development of steel production and the increased popularity of steels characterised by high and very high yield point values resulting from the development of increasingly complex steel structures without compromising high operational properties [8, 9].

Mechanical properties of fine-grained steels depend on their chemical composition and manufacturing regime. Steels subjected to the thermomechanical control process are usually characterised by more favourable properties than those characteristic of normalised steels. The highest yield point values are typical of toughened steels [10]. The production of toughened steels has been developed over the past decades and resulted in the manufacturing of steel grades characterised by increasingly high yield point values. For the past few years the market offer has included steels characterised by yield points exceeding 1000 MPa [11].

The use of fine-grained toughened structural steels is characterised by numerous advantages both for the users and manufacturers of steel structures:

- reduced material thickness translating into lowers structural weights (Fig. 3),
- reduced manufacturing costs, shorter welding time, lower consumption of welding consumables, cheaper transport of structures,
- improved technical parameters of elements obtained through increased service loads [9, 12, 13].

High yield point (960 MPa) toughened steels belong to the most popular materials when

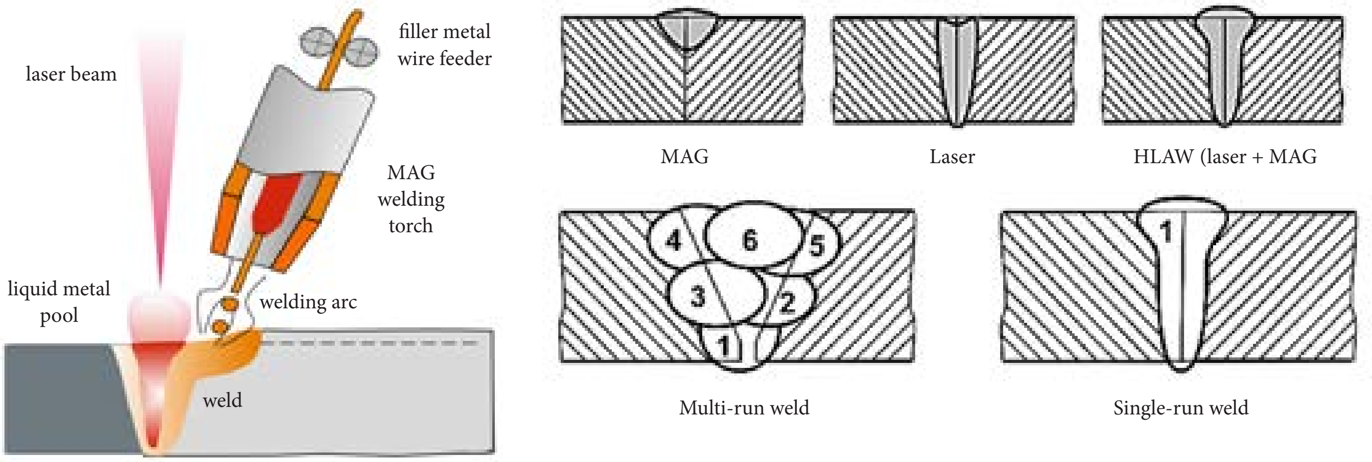


Fig. 2. HLAW method: a) hybrid laser + MAG welding principle, b) differences between the shape and geometry of welds obtained in MAG, laser and hybrid laser + MAG welding [7]

making elements exposed to high loads and composing critically important structures. Steel S960QL is used in the making of stationary and self-propelled cranes, car bodies, lifts, gantry cranes, poles and supports of oil rigs, railway cars, agricultural and forestry machinery as well as XXL type structures [10, 15, 16]. Selected exemplary applications of toughened steels characterised by a yield point of 960 MPa used in elements exposed to high loads and composing critically important structures, e.g. in hoisting engineering, are presented in Figure 4.

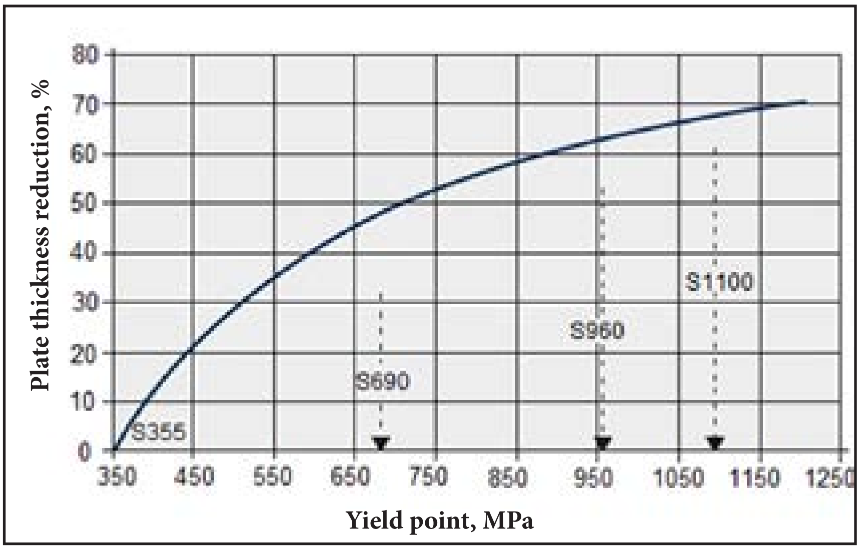


Fig. 3. Decreased in required plate thickness when using high yield point steels compared to thicknesses of structures made of steel S355 [14]


Fig. 4. Exemplary applications of high yield point steel S960QL [15, 16]

Hybrid Laser Arc Welding of plates made in steel S960QL

The welding tests aimed to determine the effect of the hybrid laser + MAG welding on the structure and properties of butt joints made steel S960QL characterised by various thicknesses, i.e. 5 mm + 7 mm. The joints of the above-named thicknesses are often used in crane structure elements.

The hybrid welding tests (laser + MAG) were performed using a robotic station provided with the latest generation TruDisk 12002 disc laser and a KUKA KRC30HA welding robot equipped with a hybrid welding head and a filler metal wire feeder (Fig. 5). Welding systems as the one presented above are presently used in advanced robotic industrial lines. Once configured, such systems can be used for laser welding, hybrid laser + MIG/MAG welding or just MIG/MAG welding. The station used in the tests was provided with an inverter synergic MIG/MAG welding power source. After developing an appropriate software programme, welding power source parameters and laser parameters are adjusted using the robot control panel.

Fig. 5. Universal HLAW station at Instytut Spawalnictwa: a) station with a TruDisk 12002 disc laser and the protective cabin, b) inside the cabin – hybrid welding head and marked heat sources

The tests involved the use of 5 mm and 7 mm thick plates made of steel S960QL (150x350 mm). The chemical composition of the plates made of steel S960QL according to data provided by the manufacturer and according to the check chemical analysis performed using a Q4 TASMAN 170 spark emission spectrometer (Bruker) is presented in Table 1. The composition was consistent with the catalogue data of the producer of the steel and satisfied the requirements of the PN-EN 10025-6+A1:2009 standard [17].

The welding of steel S960QL was performed using filler metal wire Union SG700 (NiMoCr/ LWE:SG700/ID-No. 822000508, EN ISO 16834-A) having a diameter of 1.2 mm (Böhler Schweisstechnik). The shielding gas used in the MAG welding was gas mixture M21 (Ar – 82%, CO_2 – 18%) according to standard PN-EN ISO 14175. The single-sided test butt joints were made in the flat and in the horizontal position. The edges of the plates were subjected to square butt weld preparation and matched without a gap (b=0) in the interface (between elements being joined). The parameters of the hybrid laser + MAG welding process are presented in Table 2. The joints viewed from the face and the root side as well as the macrostructure of the butt joints (5 mm +7 mm thick) made in the flat and in the horizontal position are presented in Figure 6.

The joints were characterised by the uniform and smooth spatter-free face and the properly shaped root (Fig. 6a, b). Visual tests revealed that the joints represented quality level B according to PN-EN ISO 12932 [18]. The microscopic tests of the hybrid welded joints made of steel S960QL revealed the presence of the three primary areas (Fig. 7a), including the base material containing the fine-grained structure of tempered martensite (Fig. 7b), the approximately 1 mm wide heat affected zone (Fig. 7c) and the weld area (Fig. 7d).

The heat affected zone contained the coarse-grained martensitic structure formed as a result of the effect of the complex welding thermal cycle (Fig. 7c). In turn, the weld contained the homogenous acicular martensitic structure (Fig. 7d). The foregoing was confirmed by observation results obtained using a scanning electron microscope (SEM) (Fig. 8a-c) and a transmission electron microscope (TEM) (Fig. 8d-f). In the base material structure, the martensite laths revealed significant dislocation density related to the process of making and hardening of high yield point steel S960QL. During welding, the heat affected zone subjected to the effect of a thermal cycle underwent austenitisation

Table 1. Chemical composition and mechanical properties of the test plates made of steel S960QL

Steel grade	**Standard**	**Chemical composition, [%]**										
	Analysis	C	Si	Mn	P	S	Cr	Cu	Ni	Mo	V	CEV
S960QL	PN-EN 10025-6	max 0.20	max 0.80	max 1.70	max 0.02	max 0.01	max 1.5	max 0.50	max 2.0	max 0.70	-	max 0.82
	Check analysis	0.13	0.39	1.40	0.009	0.001	0.01	0.01	0.19	0.44	0.03	0.47
Mechanical properties												
Steel grade	**Standard**	Rm [MPa]				Re [MPa]				A5 [%]		
S960QL	PN-EN 10025-6	980 ÷ 1150				960				10		

Table 2. Parameters applied during the hybrid welding of 5 mm +7 mm thick joints made in the flat and horizontal position

P [kW]	Vs [m/min]	Vd [m/min]	I [A]	V [V]	Cor. V [V]	b [mm]	Q [kJ/mm]
3.75	1.3	8.5	275	27	+3	0	0.56
P- laser power, Vs – welding rate, Vd – filler metal wire feeding rate, I – welding current, V – arc voltage, Cor. V – arc voltage correction, b – interface gap, Q – heat input							

and the growth of austenite grains. During cooling the zone underwent the martensitic transformation resulting in the formation of coarse-grained martensite (Fig. 8b). The zone also revealed the presence of fine carbides (Fig. 8e). In turn, the weld contained fine-grained martensite with numerous fine carbides (Fig. 8c). The martensite laths were characterised by significant dislocation density, confirmed by the hardening of the joint in this area.

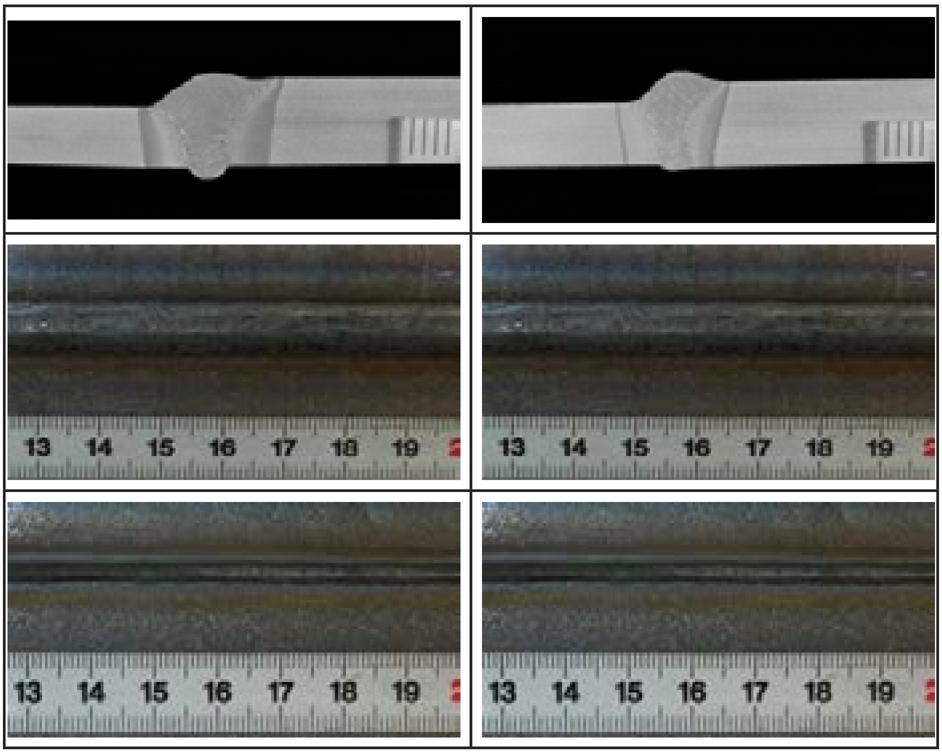


Fig. 6. Macrostructure and the hybrid welded joint (5 mm + 7 mm) viewed from the face and root side in: a) flat position, b) horizontal position

The mechanical properties of the joints were determined in tensile, bend, impact strength and hardness tests performed in accordance with the requirements of PN-EN ISO 15614-14 [19].

The tensile strength of the joint should not be lower than the minimum strength of the base material. The test joint satisfied condition Rm ≥ 980 MPa, obtaining mean value Rm ≥ 1053 MPa. The rupture took place outside the weld, in the HAZ area.

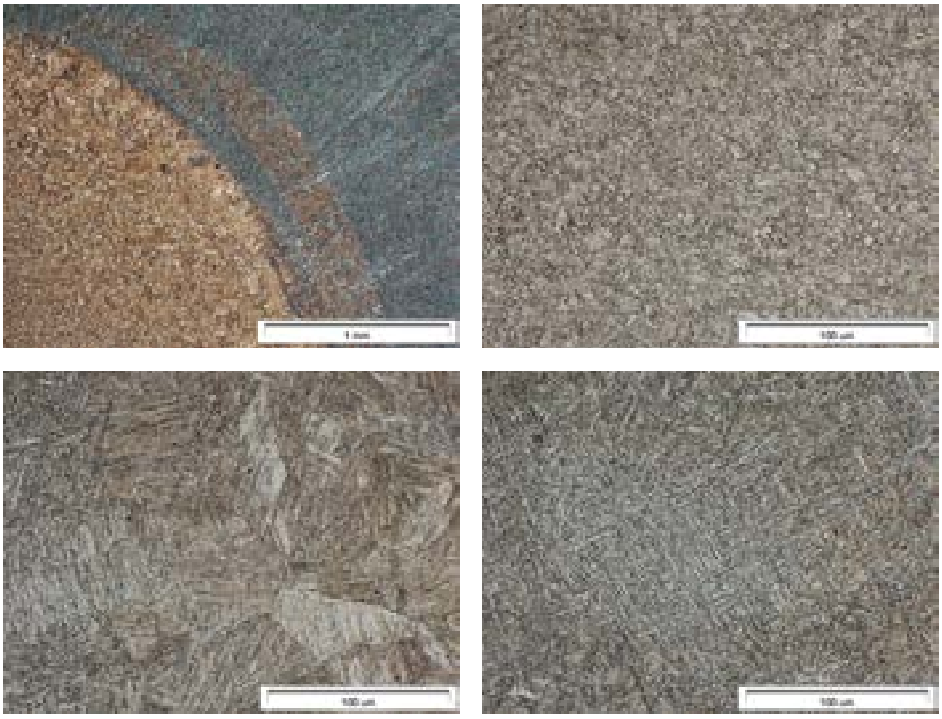


Fig. 7. Structure of the hybrid welded joint (laser + MAG) made of steel S960QL, LM: a) macrostructure, visible heat affected zone and the weld area, b) fine-grained martensite in the base material, c) heat affected zone containing coarse-grained martensite, d) weld containing the martensitic structure

A bend test led to the obtainment of a bend angle of 1800, both during bending on the face and on the root side. The bend test revealed that the joint was characterised by high plastic properties.

An impact strength tests performed at a temperature of -40°C resulted in the obtainment of the required value of impact energy both in the weld area and in the HAZ. In the weld area, the mean impact energy (of three tests) amounted to 30 J. In the HAZ, the mean impact energy (of three tests) amounted to 46 J. The requirements specified in the PN-EN 10025-6 were satisfied.

Hardness measurements related to the welded joint were performed following the requirements of the PN-EN ISO 9015-1:2011 standard

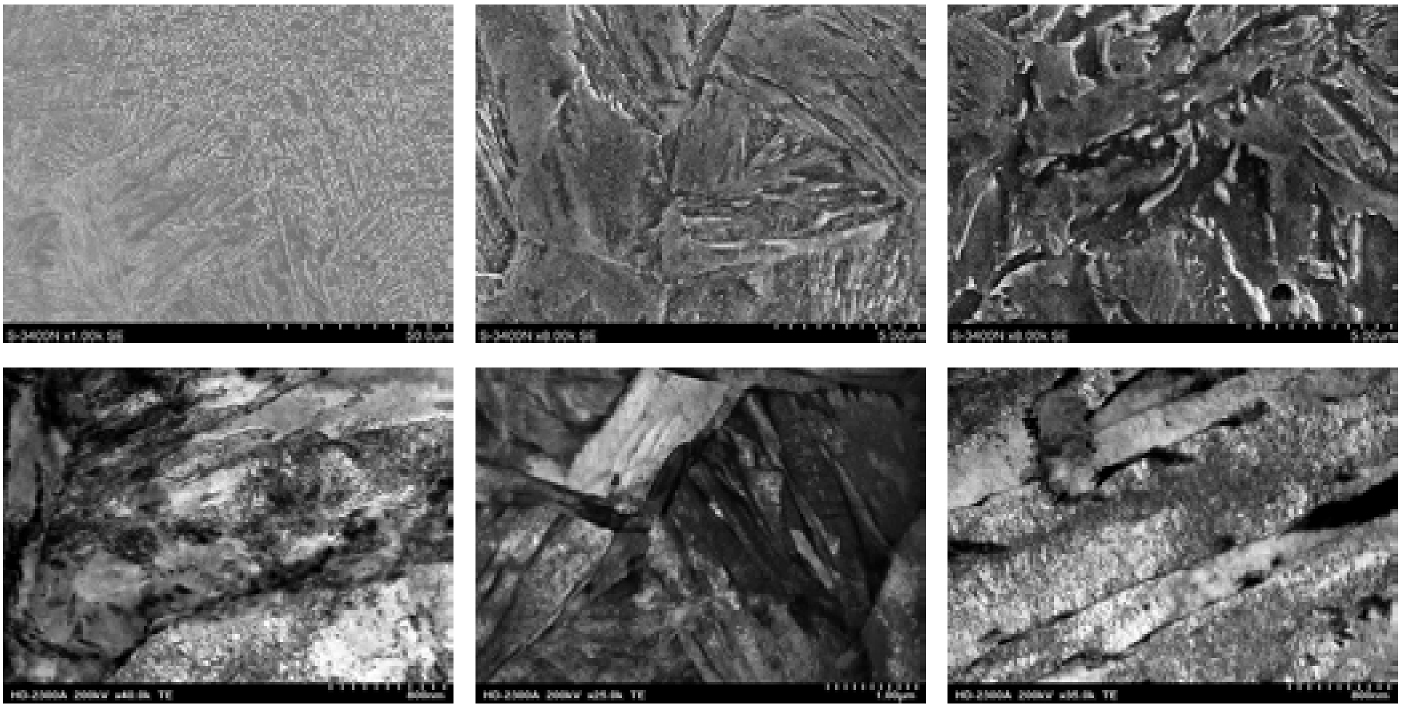
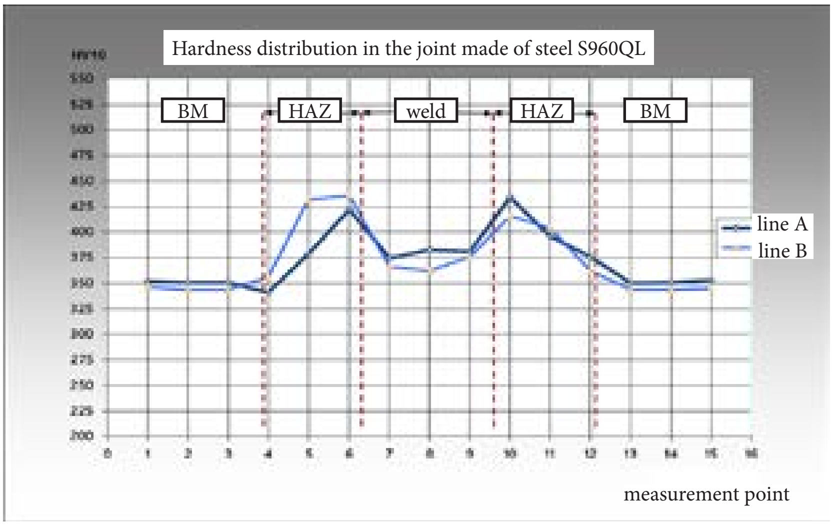


Fig. 8. Microstructure of the welded joint made of streel S960QL: a) fusion line (SEM), b) heat affected zone (SEM), c) weld (SEM), d) base material – martensite with visible dislocations (TEM), e) martensite revealed in the HAZ (TEM), f) martensite laths in the weld; visibly increased dislocation density

[20], in two measurement lines – 2 mm below the surface of the plates (line A in Figure 7) on the face side and 2 mm above the surface of the plates (line B in Figure 7). The measurement results and the distribution of hardness in the joint are presented in Figure 7.

The highest hardness, amounting to 436 HV10 and 434 HV10, was identified in the HAZ near the fusion line, at point 6 of measurement line B and at point 10 of measurement line A. The maximum hardness in the weld axis amounted to 383 HV10 (point 8 of measurement line A). In accordance with PN-EN ISO 15614-14, the maximum permissible hardness in the joint in relation to material group 3 according to ISO/TR 5608 amounted to 450 HV10. In relation to steel characterised by ReH > 890 MPa the above-named standard allows the application of special valued agreed on between the parties (contractor/ordering party). The test joint satisfied the hardness-related requirements (≤ 450 HV) according to standard PN-EN ISO 15614-14.



	BM			HAZ			WELD			HAZ			BM		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	352	351	351	341	379	422	375	383	381	434	396	376	350	351	353
B	346	344	344	356	432	436	366	362	376	416	404	362	344	344	345

Fig. 9. Measurement results and the distribution of hardness in cross-section of the joint made using the HLAW method: MB – base material, HAZ – heat affected zone

Summary

Hybrid laser + MAG welding is an innovative technology which can be used for the welding of toughened steel S960QL. The tests revealed that the application of the HLAW method when joining plates (5mm +7 mm thick) made of steel S960QL in the flat position and in the horizontal position enabled the obtainment of butt joints characterised by the smooth face and the properly formed root of the weld, representing quality level B of the PN-EN ISO 12932 standard.

The microscopic metallographic tests revealed that the base material contained the structure of tempered martensite, typical of high yield point steels hardened through toughening. The martensitic structure was also present in the weld and in the HAZ.

The mechanical tests revealed that the joints satisfied the requirements of the PN-EN ISO 15614-14 standard specifying the conditions of hybrid welding procedure qualification.

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