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PTA-GMA hybrid welding of UHSS steel in structures of large-scale

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ABSTRACT

Purpose: An analysis of application possibilities for PTA-GMA hybrid welding in large-sized high-strength steel structures that require using particularly effective and high-performance technologies as related to quality and costs.

Design/methodology/approach: Welded joints were made of S960QL steel by employing plasma and GMA hybrid welding by using various welding parameters. The tests were designed so that interrelations between particular welding technologies can be demonstrated. Macroscopic and microscopic examinations as well as hardness and tensile strength tests for welded joints were carried out.

Findings: It has been shown that traditional welding methods SAW and GTA can be replaced by PTA-GMA hybrid welding. The obtained welded joints show different geometric features and hardness depending on welding technology used.

Research limitations/implications: The description of welded joint structure and mechanical properties was based on welding toughened steels by using an innovative welding method and a filler that has been proposed.

Practical implications: The parameters of plasma and GMA hybrid welding for industrial uses were established at the company Teleskop Sp. z o.o. The selected best welding technologies will be subject to welding procedure approval according to PN-EN 15614-1 and implemented into mass production. The information gained from toughened steel welding is an important basis for future research on metallurgical walkability by using high-performance methods of hybrid welding of large-sized structures.

Originality/value: The problems associated with welding S960Q steels by using various welding technologies, including the use of an innovative GMA plasma hybrid welding method that is still at the initial stage of research work and there are no original references regarding the suitability of the a/m welding method for large-sized structures made of high-strength toughened steels were established. It has been shown that PTA-GMA hybrid welding has a significant effect on base metal structural changes resulting from a unique nature of combined heat sources of plasma and electric arc.

Keywords: S960Q steel; Testing procedures; PTA-GMA hybrid welding; Welded large-sized structures; Toughened steels

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MATERIALS

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1. Introduction

Steel large-sized structures are welded industrial, building and marine structures of weight exceeding 25 tones and length from 15 to 16 m, width from 3.5 to 4.0 m or height between 3.0 and 3.5 m.

Large-sized steel structures comprise among other things: bridges, construction machinery bodies, offshore facilities, quayside and ship cranes, silos, hoppers, pressure vessels, pallets, steel containers, floating anchors, bearers and pipelines, ship deck sections, ship ramps, watercraft superstructures, hull sections, sports hall and stadium framing, offshore drilling platforms, offshore wind tower foundations on which masts and wind turbines will be installed.

A very specific example of large-sized weld structures are new solutions for chemical tankers where complex and innovative welding techniques are used and presented, for example in papers [1-4].

Another example of highly advanced design and technology employed for large-sized structures are large self-propelled crane telescopic booms composed of welded U-shaped sections bent from sheet metal by using cornice brakes.

The subject of this paper are self-propelled crane telescopic booms that are more and more often made of high-strength toughened steels belonging to UHSS (Ultra High Strength Steels): S690Q, S980Q, S1100Q and S1300Q, thus enabling their load capacity and outreach to be increased, while decreasing the crane deadweight at a good quality-to-price ratio.

Self-propelled cranes are large-sized structures that are allowed to drive on roads and are subject to road user regulations. The largest structure of this type in the world is Liebherr LTM 11200-9.1 of 108 tonnes in deadweight and 1200 tons load capacity is shown in Figs 1-3. The maximum travelling speed of the Liebherr LTM 11200-9.1 crane is 75 km/h (Fig. 1).

The essential welded structure components of a self-propelled crane are: vehicle frame, turntable and telescopic boom. The use of toughened steels for self-propelled crane construction caused that appropriate welding procedures are being looked for to ensure the highest welding quality and cost effectiveness.

The self-propelled crane telescopic boom consists of two U-shaped sections bent from sheet metal by using cornice brakes. These sections are of different thickness and it has been assumed that the thinner one is 4 mm thick, while the thicker one is 6 mm thick (Figs 1-3) [4,5].

Individual sections are welded by using semi-automatic MAG (135) method - root run and SAW (121) - filling runs in a butt joint. The welding is carried out in the downhand position (PA), thus requiring that the structure is rotated by 180° four times when welding (Fig. 4).

To avoid imperfections on the side of weld root made by MAG (135), the root run is practically cut out at its entire length before SAW (121) run is made. Such welding technology is labour consuming, thus affecting productivity. Another technological problem during welding is a large size of SAW weld cross sectional area leading to large welding deformations.

Fig. 1. Liebherr LTM 11200 9.1 - the largest self-propelled crane in the world [5]

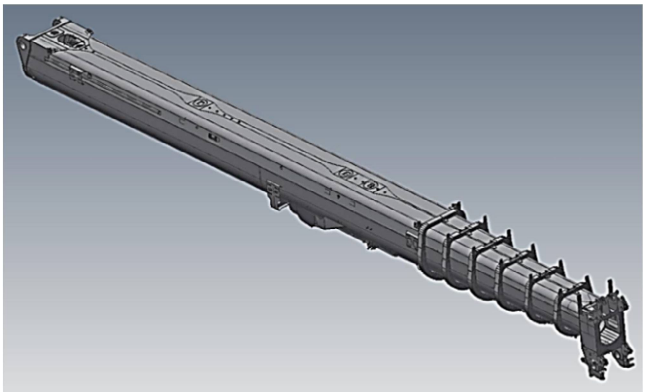

Fig. 2. General view of a complete crane boom assembly [7]

After welding the booms are straightened mechanically to the required shape specified in design documentation. In recent years R&D works are focused on developing new highly effective welding methods ensuring high quality welded joints and reduced manufacturing costs [6].

So far, the GAM and SAW multi-run welding techniques used in manufacture of these structures were found to be low effective, as they do not ensure competitive productivity. Therefore, hybrid welding is considered to be used as a new technique for welding large-sized telescopic boom components [6].

Fig. 3. View of a finished telescopic boom of a self-propelled crane [7]

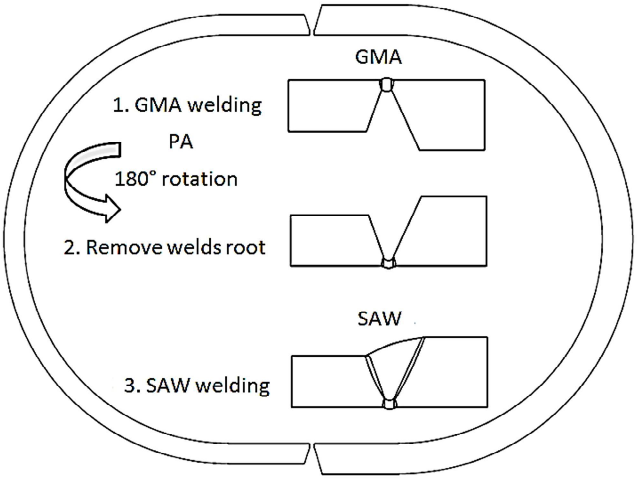

Fig. 4. Crane telescopic boom cross section

2. The essence of PTA-GMA hybrid welding

In ISO 4063 "Welding and allied processes-Nomenclature of processes and reference numbers", method 151 is called Plasma MIG welding. This process is considered as a hybrid welding method. In this study plasma welding (Ar 99.999%) + MAG (135) in mixed shielding gas M21(Ar + 18% CO_2) was used. Hereinafter this process is referred to as GMA plasma welding.

The hybrid welding methods simultaneously use various heat sources in the same weld pool, thus combining advantages of both combined methods [8-9]. As the heat sources of GMA plasma welding are based on an electric arc, it is necessary to pay attention to differences in ways of base metal heating (Fig. 5).

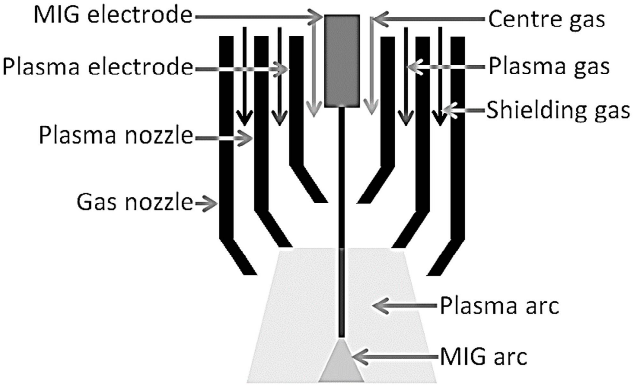

Fig. 5. Configuration of a plasma-GMA (MIG) torch

A plasma arc transfer heat due to bombardment of the anode with electrons concentrated in so-called vapour channel, while GMA methods are conductive in nature. Plasma-GMA hybrid welding due to combination of a concentrated heat source (plasma) and distributed heat source (GMA/MAG) enables deep penetration, high fusion efficiency and low costs of edge preparation at moderate expense. An additional advantage of this method is a high welding speed that decreases linear energy of welding.

Additional advantages of hybrids are: a high accuracy tolerance of joint preparation, large penetration depth, thus enabling single-run welding.

Additional benefits are also reduced welding deformations due to narrower heat affected zone (HAZ). Disadvantages include the cost of buying equipment, necessary automatic torch manipulations and technological complexity of a new method.

A filler in the form of a wire that is fed continuously into the molten weld pool produced by a thermally ionized gas. An electric arc melts the wire in the plasma beam that glows from a high frequency current. A plasma arc glows between the workpiece and the water-cooled nozzle, i.e. non-transferred arc.

Also another hybrid welding method involving laser and MIG/MAG that allows a synergistic effect of various heat sources to be obtained was considered.

However, it is difficult to use laser hybrid welding in industrial conditions for manufacturing large-sized structures due to the risk of laser beam reflection, limited size of the work area and technological constrains.

3. Modern steels used in production of self-propelled crane telescopic booms

Low-alloy weldable fine-grained toughened steels used for manufacturing telescopic booms are the subject of PN-EN 10025-6. These steel grades designed for welded structures have yield strengths increased from 500 MPa to 1300 MPa, high KVL 27 J impact strength at -60°C and good walkability. S960Q steel was used for further analysis. This grade, like other similar ones, is used for construction of heavy machinery and lifting equipment that carry high loads, for example self-propelled cranes and lifts, mining and road building machinery.

These steels are produced in the toughening process carried out due to high performance systems and started with heating up to a temperature above A_{c3}. Then metal sheets are cooled with pressurized water stream, thus allowing martensitic and/or bainitic structure to be formed. Next to chemical composition that is adjusted for elements increasing steel hardening capacity, the second most important factor deciding on mechanical properties is high tempering. These steels have a martensitic structure especially susceptible to cold cracking, thus low-hydrogen welding processes should be used [10]. When welding with restrained linear energy no problems with brittle fractures should occur. The structures made of toughened steel shall be used at positive temperatures [11].

In PN-EN 10025-6+A1:2009 "Hot rolled products of structural steels - Part 6: Technical delivery conditions for flat products of high yield strength structural steels in the quenched and tempered condition" the requirements for flat products of high yield special alloy steels delivered in the quenched and tempered state are specified.

The application of hot rolled steel for flat products of minimum nominal thickness of 3 mm and maximum nominal thickness <= 150 mm for steel grades S460, S500, S550, S620 and S690, and maximum nominal thickness <= 100 mm for S890 steel and maximum nominal thickness <= 50 mm for S960 steel grade was specified. These steels after quenching and tempering have the minimum yield strength from 460 MPa to 960 MPa.

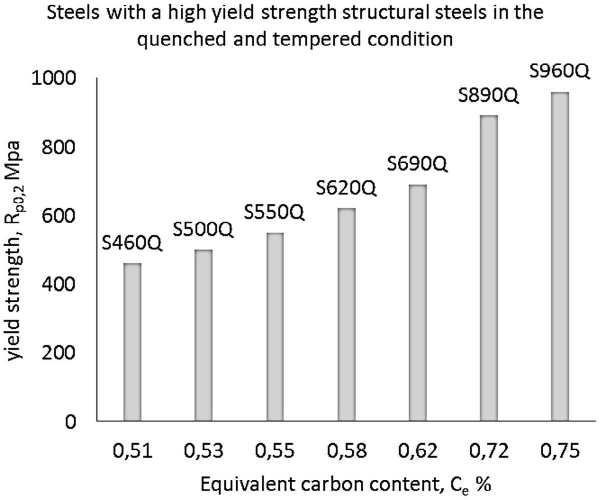

Fig. 6. Comparison of carbon equivalent C_e versus offset yield strength $R_{p0.2}$ for high yield strength steels in the quenched and tempered state [12]

PN-EN 10025-6+A1:2009 does not standardize such steel grades as: S1100QL (1.8942), S1300QL (1.89XX), however they are generally available, for example from SSAB AB characterized by the value of carbon equivalent presented in Fig. 6.

4. Fillers used in welding crane telescopic booms of UHSS steel

The latest grades of structural steels pose a big challenge to the welding industry. To meet the requirements for mechanical parameters of welded joints, it is required to use specialized fillers and appropriate linear welding energy so that the time t8/5 is kept in the range of 6-12 s. Fillers available in the market have lower offset yield strength around 960 MPa, thus being suitable for S960QL steel grade.

High strength fillers for GMA welding should provide the same strength parameters as those of base materials, and then such materials are called 'matching materials', i.e. having strength parameters equal to 90% of those of the base material. Otherwise, when matching is below 90% such materials are referred to as under matching and this applies to S1100QL and S1300QL steels.

Table 1.
GMA electrode wires according to ISO 16834-A arranged by increasing tensile strength R_m [MPa] (comparison developed internally)

Wire grade	Designation according to ISO 16834-A	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
LNM MoNi	G 62 4 M Mn3NiCrMo	635	770	19
Union NiMoCr	G 69 6 M21 Mn4Ni1,5CrMo	720	780	18
Bohler NiCrMo 2,5-IG	G 69 6 M21 Mn3Ni2,5CrMo	810	910	18
ED-FK 1000	G 89 6 M21 Mn4Ni2CrMo	890	940	15
Union X 90	G 89 6 M21 Mn4Ni2CrMo	890	950	15
Bohler X 90-IG	G 89 6 M21 Mn4Ni2CrMo	915	960	20
Union X 96	G 89 5 M21 Mn4Ni2,5CrMo	930	980	14
OK AristoRod 89	GMn4Ni2CrMo	920	1000	18

Table 2.
GMA electrode wires according to ISO 18276 arranged by increasing tensile strength R_m [MPa] (comparison developed internally)

Wire grade	Designation according to ISO 18276	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
Filtech VR 15	T 69 6 Z P M 1 H5	690	770	17
Outershield 690-HSR	T 69 4 Z P M 2 H5 T	720	770	20
Filtech VB 15	T 69 5 Mn2NiCrMo B M 4 H5	690	840	17
Outershield 690-HSR	T 69 4 Z P M 2 H5	800	930	17
Megafil 1100M	T 89 4 Mn2NiCrMo M M 1 H5	890	980	15
Filtech VM 20	T 89 4 Mn2NiCrMo M M 2 H5	960	980	15
AMC 20	T 89 4 Mn2NiCrMo M M 2 H5	960	980	15
Filtech VB 20	T 89 4 Mn2Ni1CrMo B M 4 H5	890	990	15

There are many types of welding wires according to PN-EN ISO 16834 and PN-EN ISO 18276 available in the market, but they are designed for steel grades of lowest yield strengths and considered to be alternative materials (under matched, i.e. matched as well as possible to the chemical composition on the base material). This requires changes in the design to be made, mainly setting out the structure joints in the base material and moving the welds beyond the main load axis.

An additional problem for achieving the minimum $R_{p0.2}$ of 960 MPa is proper fitting of welding parameters by using special treatments, initial heating and obeying a technological regime. Argon, helium or its mixtures are used as the plasma gas. When welding carbon and high-alloy steels, Ar + CO_2 active mixtures are also used [13].

In Table 1 electrode wires for GMA welding in M21 (Ar + 18% CO_2) shielding gas mixture according to ISO 16834-A arranged according to increasing tensile strength R_m. In Table 2 welding wires for GMA welding in M21 (Ar + 18% CO_2) shielding gas mixture according to ISO 16834-A arranged according to increasing tensile strength R_m. For test GMA plasma welding the product Union X90 was used.

5. Criteria for welding crane booms of UHSS steel

When designing a steel structure it is important to optimize costs of joint cutting, bevelling and cleaning before welding. For large-lot production of crane booms the factory shall use a cutting technology enabling cutting the thickness as large as possible, while keeping the required cut quality. When considering the optimization of cutting costs, the risk of occurrence of oxides and other contaminants on the surface of the weld pool must be minimized [14,15].

For plates up to 15 mm in thickness, plasma welding can be used (assuming large-lot production), because it is more effective and provides better quality than oxygen cutting. Due to the specifics of manufacturing, prefabricated elements are long and telescopic, thus involving a high labour consumption and time during welding preparation. In addition, the weld volume will determine deformations after welding.

The smaller weld cross-section volume, the lower costs of deformation repairs, lower costs of welding and fillers.

Criteria for welded joint bevelling are as follows:

- lowest possible cost of mechanical treatment,
- lowest possible cost of weld groove cleaning,
- shortest possible time of prefabricate preparation,
- smallest possible weld volume to reduce deformations.

For GMA plasma welding by using pool technique a welding robot connected to Supra-Elco Super-MIG® was employed. The parameters are presented in Table 3.

Table 3.
GMA plasma welding parameters

MAG plasma welding parameters				
Sample	5	6	7	8
Plasma DC (-) current intensity [A]	155	160	165	170
Arc voltage [V]	29	29	29	29
Welding speed [mm/s]	5	4.1	3.3	3.3
Plasma gas flow rate [l/min]	1.2	1.2	1.2	1.2
Shielding gas flow rate [l/min]	4-6	4-6	4-6	4-6
Tungsten electrode diameter +Th φ [mm]	1	1	1	1
Plasma nozzle shape and size φ [mm]	11	11	11	11
MAG wire diameter φ [mm]	1.2	1.2	1.2	1.2
Wire feed [m/min]	1.6	1.7	1.8	1.8

6. Characteristics of welded joints of telescopic booms of UHSS steel

Macroscopic examinations of welded joint were carried out according to PN-EN 1321:2000 "Welding technology. Non-destructive tests of metal welded joints. Macroscopic and microscopic tests of welded joints". The specimen surface was machined; ground, polished and etched in Adler Acid with the chemical constitution:
3 g $CuCl_2 \cdot 2NH_4Cl \cdot 2H_2O$; 15 g $FeCl_3$, 50 ml HCl (ρ=1.19 g/cm^3); 25 ml H_2O.

To examine the structure of welded joints the reflected light optical microscope Nikon Epiphot 200 was used. The observations were made at magnification 500X on non-etched metallographic specimens to find fractures and microsections etched with 5% Nital.

Hardnesss tests were performed on macroscopic specimens. Vickers hardness tests were performed according to the provisions contained in the PN-EN ISO 15614-1:2008/A1:2010 and PN-EN ISO 9015-1:2011 standards. A diagram of measuring points distribution is presented in Fig. 7.

The following equipment was used for testing:

- automatic hardness tester LECO LV700AT,
- measurement standard 0.01 mm Olympus AX0011 OB-MM 1/100;
- hardness standard LECO No. 078281 574.19@10000 GF.

Load applied was F = 98.07 N.

Tensile tests of the specimens cut off the joint according to the PN-EN ISO 15614-1:2008/A2:2012 standard were performed in accordance with the provisions contained in the PN-EN ISO 4136:2013-05 standard.

Testing conditions were the following: measuring device: ZD100; range 0-1000 kN, test temperature 20ºC; accuracy of readout: 500 N. Fracture out of the weld, max. 20% fracture in HAZ/weld R_{p02} min.: 960 MPa; R_m min.: 980 MPa.

Non-standard design of self-propelled crane boom cross section consists of metal sheets of various wall thickness. The thinner part is 4 mm thick, the thicker one is of 6 mm in thickness. To perform MIG plasma hybrid welding it is sufficient to make: a one-sided joint to avoid workpiece rotation, one-sided bevelling, asymmetric to make savings during bevelling.

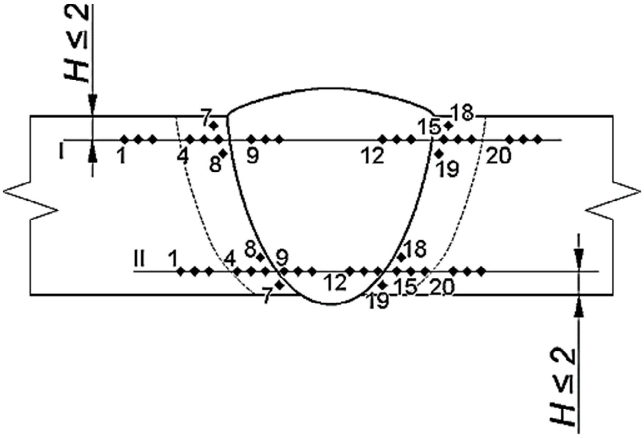

Fig. 7. Hardness measurement points distribution scheme

If plate thickness difference does not exceed 30% and 5 mm, it is possible to use butt joints without thinning out the thicker component. The face of weld shall go smoothly from the thicker to the thinner metal sheet. When making butt joint of plates of different thickness a smooth cross section transition shall be ensured. Different inclinations for various structure types are recommended. The Polish building code, PN-90/B-03200 allows 1:1 inclination for static loads and 1:4 inclination for dynamic loads.

7. Joint structure and properties

As a result of the macroscopic investigation (Figs 8-11) it was found that tested joints have no cracks; no lack of penetration; no porosity; regular profile with smooth transition to the base material.

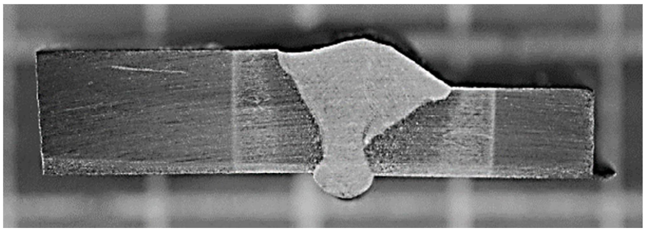

Fig. 8. Macroscopic image of sample 5

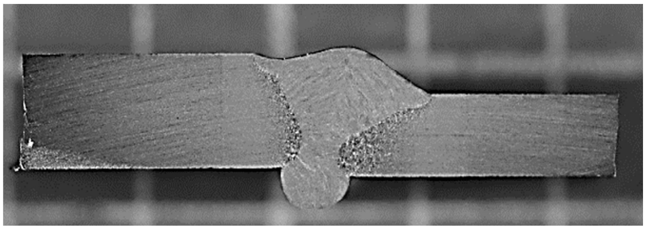

Fig. 9. Macroscopic image of sample 6

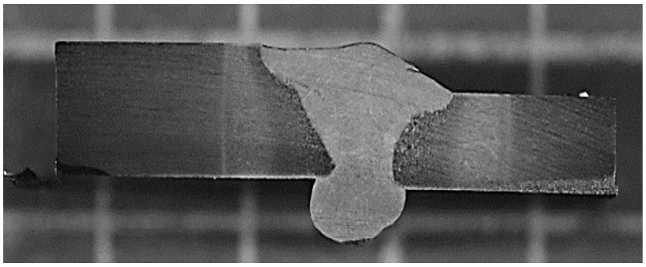

Fig. 10. Macroscopic image of sample 7

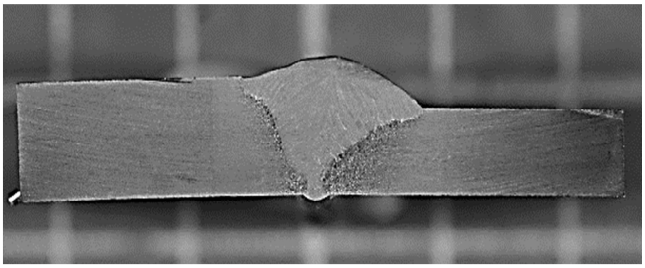

Fig. 11. Macroscopic image of sample 8

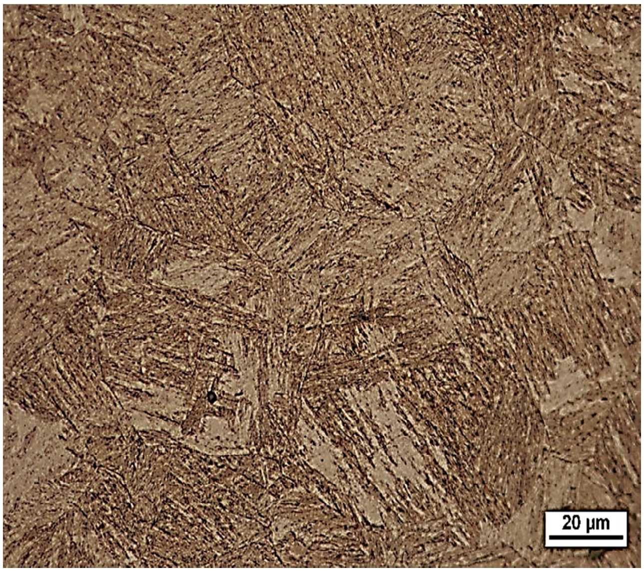

Fig. 12. Microscopic image of the heat affected zone within the S960Q welded with the Union X90 filler in the overheated zone of sample 8

As a result of hybrid welding with parameters specified in Table 3 a deep penetration and excess penetration bead were obtained (504 according to ISO 5817). By changing parameters the number of welding imperfections was decreased.

The welding parameters for sample #3 in Table 3 appear to be promising ones. The width of the heat affected zone varies with weld thickness, thus indicating better heat abstraction from the side of thicker plate. In samples 5 and 6 the welding head was set at angle of 5°, as shown in metallurgical specimen (Figs 8, 9).

The structure overheated within the heat affected zone is shown in Fig. 12, while within the weld in Fig. 13. This is a typical structure for S960Q steel within overheated zone welded with the Union X90 wire. Just next to the line of fusion the zone of grown martensite and bainite grains is visible. With increasing distance from the line of fusion an increasing refinement of structure is observed.

To reveal the steel structure components, 5% Nital etch was used. S960Q is a fine grained steel. The weld microstructure consists of carbon oversaturated ferrite. Weld morphology depends on the amount of introduced heat. For a welded joint of lower parameters used the microstructure is more homogeneous.

Fig. 13. Microscopic image of the S960Q steel welded with the Union X90 filler of sample 8

The hardness distributions for individual samples are presented in Figs 14-17. According to PN-EN 15614-1 toughened steels have hardness 450 HV10 (material group 3 acc. to CR ISO 15608). The highest hardness recorded was 444 HV10 in sample # 5.

The lowest hardness recorded was 278 HV10 in sample # 8. There are similar hardness values for welded joints, depending mainly on filler used and its chemical composition. For each sample the lowest hardness in the weld with respect to the heat affected zone and base material was recorded.

The highest hardness was noted within the heat affected zone. The undermatched filler of different chemical composition that that of the base material causes a significant hardness increase directly beyond the line of fusion.

Fillers contain elements increasing steel hardening capacity to ensure appropriate strength of welded joint compared to that of the base material. All welded joint samples subjected to tensile strength tests were broken in weld that is the weakest point when welding with so called undermatched fillers.

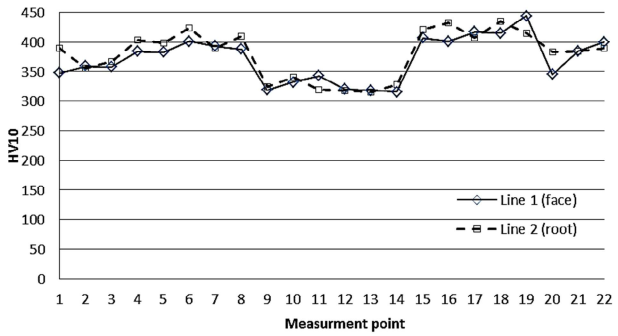

Fig. 14. Hardness measurements made on sample 5. Max 444, min. 316

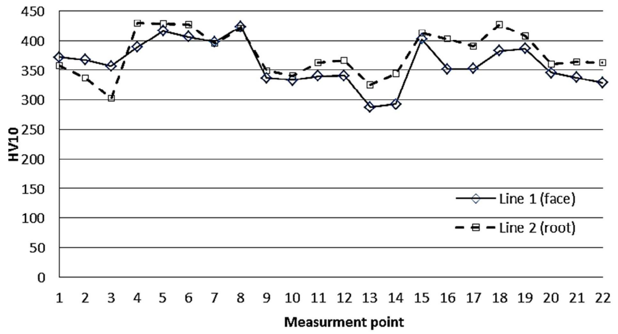

Fig. 15. Hardness measurements results on sample 6. Max 430, min. 288

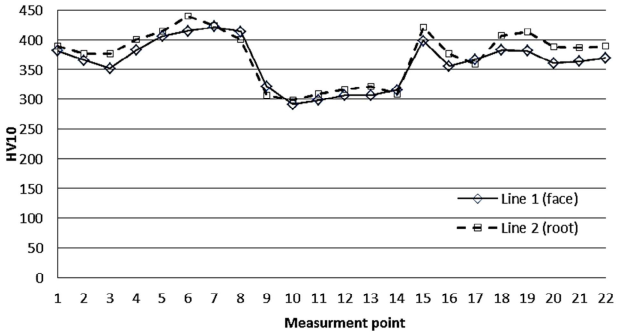

Fig. 16. Hardness measurements results on sample 7. Max 440, min. 292

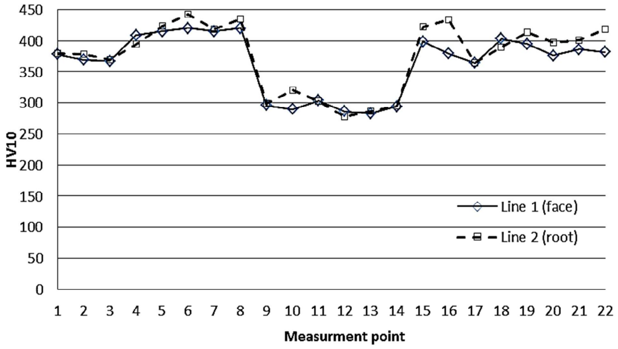

Fig. 17. Hardness measurements results on sample 8. Max 443, min. 278

The filler X90 that meets relevant requirements was used, but the results obtained show no large discrepancies, as presented in Table 4. Telescopic booms are designed so that the main load axis was beyond the welding centres and therefore a filler of lower mechanical properties is allowed. Below there is also a graph of the static tensile strength test not showing a clear yield point for S960Q steel test joint welded with the X90 filler of lower linear welding energy than that of samples 5, 6, 7 and 8, causing that $R_{p0.2}$ and R_m are slightly lower (Fig. 18).

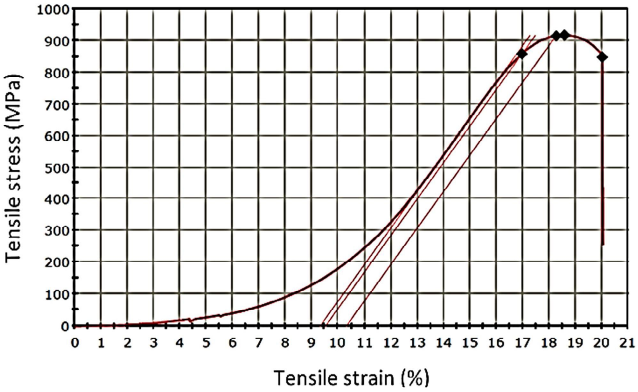

Fig. 18. An example of graph for a tensile strength test of SQ960Q steel welded joint filled with X90 without a clear yield point

Table 4.
Tensile tests results-crack location: weld

Sample	Yeld point 0.2%, MPa	Tensile strength, MPa
5	962.5	985.4
6	979.7	994.1
7	982.8	996.3
8	969.2	980.9

8. Conclusions

In this paper the welding processes for self-propelled crane telescopic booms were discussed. In their construction, high strength steel grades of distinguishing mechanical and technological properties are used, while welding them poses some problems in the context of metallurgical weldabilty.

More effective GMA plasma welding method was proposed. Its partial results open up prospects for further tests and research. The selection of undermatched fillers should take into account the degree of mixing with the base material, depending on welding method. Welding large-sized boom construction made of S960Q steel should be performed with fillers of the highest mechanical properties that provide high quality welds and carrying large loads.

Joints made with GMA plasma welding featured of acceptable hardness. The maximum hardness for this steel grade is 450 HV10.

MAG plasma welding can be used for welding sections of different thickness in manufacture of self-propelled crane booms. The focused energy beam and large welding speeds enable the weld to be made properly. Due to application of this new method the welding time is twice as short.

The use of MIG/MAG plasma hybrid welding is significantly cheaper compared to MIG/MAG laser hybrid welding at almost the same possibilities. Due to the method employed, larger welding speeds were obtained compared to those of double-sided MAG and then SAW welding. This method also allows post weld deformations to be reduced due to the lower linear welding energy. The weld groove must not be bevelled and the joint of materials of different thickness can be welded without a gap with filler I. This reduces the costs and treatments necessary for edge preparation for welding. The welded joints show promising mechanical properties and the joints made in the last test meet the requirements of recognized standards related to welding technologies being currently applicable.

The MIG/MAG plasma hybrid welding method is clearly suitable for large-scale industrial applications also due to energy savings and environmentally friendly nature.

The higher technological regime of welding involves the necessity of automation that should be considered when planning the manufacture of high strength toughened steel components. From the welded joint usage point of view, the key item is the amount of introduced heat and process stability that can be easily achieved in automatic welding and freely shaped, thus affecting the HAZ properties-the most important zone in any welded joint.

The limitation of welding high strength steels is the selection of fillers. Although new welding wire types are placed in the market, the problem is their poor weld ability that entails high manufacturing costs. The tests we performed have indicated that the knowledge of properties of joints welded with materials of better walkability but lower and potentially higher nominal mechanical properties is the key to a properly made welded joint.

Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the

Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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