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Welding of MART steel with the use of matching fillers

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ABSTRACT

Purpose: This paper attempts to determine the influence of using fillers of various kinds on strength of a welded joint of MART steel depending on the amount of heat supplied.

Design/methodology/approach: Test welded joints were made of S1100QL steel with GMAW method, and using different fillers as well as different values of supplied heat. The tests were designed in such a way so as to demonstrate the prospected interdependencies as clearly as possible. Macroscopic examination was carried out, Vickers hardness, impact strength and tensile strength were measured, and technological bend test was conducted on the joint.

Findings: Significant differences between the joints obtained resulting from the fillers used and welding parameters applied were noticed. The strength of a joint is lower than that of welded steel, it concentrates in the weld and is similar to the strength of parent material.

Research limitations/implications: Conducting research concentrating on welding using particular filler in a wider range of heat supplied would make it possible to obtain more precise results. By delineating the interdependencies between strength parameters, it would be possible to optimise the mechanical properties of welded joints made of MART steels. It would require the employment of automated welding that allows for unrestricted and stable control of parameters.

Practical implications: The conditions for making a proper joint of S1100QL steel were determined. Reasons were given for the choice of joint testing methodology and the purposefulness of comprehensive tests of joint parameters. The need for changing test procedures in order to eliminate the causes of inappropriate evaluation was manifested. The influence of automation as an important factor that determines the fulfilment of strict parameter regime of joint formation was emphasised. Determination of the interrelations between mechanical properties of a joint and welding parameters applied would allow to conduct a welding process in such a way so as to obtain a joint of desired usefulness in given technological conditions.

Originality/value: Problems associated with welding of S1100QL steel with the use of filler metals of matching materials were defined and possible solutions for these problems were presented. The mechanism of welding thermal cycle influencing structural changes in the joint that result from the complex cycle of hardening and tempering was demonstrated.

Keywords: GMAW, High strength steel, MART steel, S1100QL, Testing procedures, Heat treatment

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Among the achievements of modern materials science that allow to pick up the challenges of contemporary industry, advanced grades of high strength structural steels, classified as one of the branches of a large group of Advanced/Ultra High Strength Steels, deserve special attention.

Making heavily loaded joints, whose mechanical parameters need to be equal or at least approximate to the values of the basic material, requires the use of high strength filler metals of tensile strength equal to that of parent alloy, the so-called matching filler metals.

In comparison to welding wires of lower strength, matching filler metals are considerably more expensive, less flexible and require more accurate preparation of bevelled surfaces of joined elements.

The use of matching filler metals entails certain risks that arise from departures from very strict technological regime. In consequence, welding of high strength steels in some conditions proves highly expensive and difficult to conduct.

It is possible to use low strength fillers of considerably lower strength value in the following cases:

- forming joints located in the construction areas that are subject to lower stresses;
- making joints that will be subject predominantly to fatigue loads;
- producing welds of reduced hardness in order to facilitate subsequent machining thereof;
- joining high strength steels with materials of markedly lower strength (e.g. conventional structural alloys).

Such materials are referred to as undermatching filler metals.

1.1. MART steels

Due to their diffusionless microstructure type, they are commonly referred to as MART (martensite) steels. When compared to modern multiphase alloys, they are distinguished by the highest available tensile strength values, currently reaching around 1700 MPa (Fig. 1). Thorough developmental research on the techniques of manufacturing such steels suggests that in the near future the Rm of state-of-the-art steel grades will reach the value of around 2000 MPa. MART steels are fine-grained, low- or micro-alloyed structural steels that are treated thermomechanically as well as tempered. They are characterised by their high yield point and low ductile/brittle fracture transition temperature [1-5].

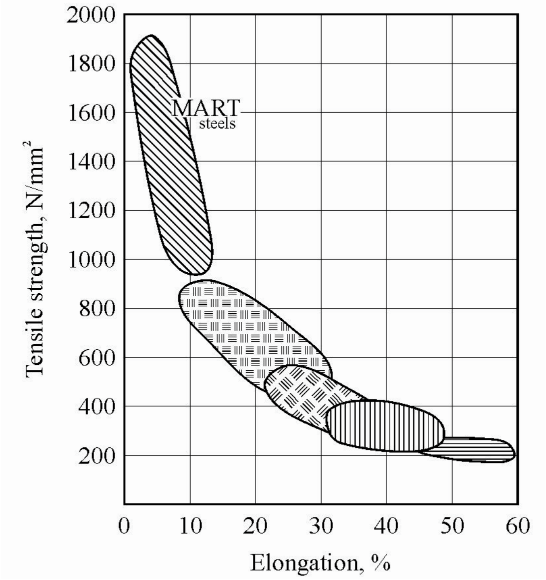

Fig. 1. Pictorial diagram of the occurrence range of advanced tempered structural steels in relation to other A/UHSS structural materials showing elongation to tensile strength ratio

Reduced content of carbide formers (Mo, V, Nb, Ti) along with increased ratio of strong austenite-forming elements (Mn, Ni) causes the steels in delivery condition (i.e. state of equilibrium) to exhibit practically homogenous structure of low-carbon, tempered lath martensite with possible high-melting phase separations of MX type, i.e. carbides (e.g. Mo_2C, V_4C_3, NbC) and/or carbonitrides (e.g. V-CN), inside individual planes. The presence of Nb and V elements also contributes to the formation of fine grains of austenite during thermo-mechanical treatment which later transform into small martensitesheets in the course of hardening procedures. It is possible to increase the impact strength of such steels, for example by adding higher amounts of Ni [6].

Increase in the strength of MART structural steel (Fig. 2), obtained by means of metallurgical procedures, is caused mainly by alloy micro-additions (e.g. Ni, V, Ti) of maximum total content not exceeding 0.22%. Their presence conditions the occurrence of mechanisms of solution hardening with interstitial atoms as well as precipitation hardening with dispersive secondary phases [7].

High values of strength parameters of modern structural steels can be obtained also by means of phase transitions generated by rapid cooling of alloy in final forming temperatures in the lower end of austenite occurrence. Cr and Mo alloy additions that reduce the value of critical cooling rate of steel and thus increase its hardenability, facilitate the occurrence of martensite transformation which is linked to the increase in the volume of individual grains of microstructure, occurrence of compressive stresses around them and intensive generation of dislocation. In order to increase hardenability, micro-addition of boron in amount around 0.005% is supplied into the volume of liquid alloys (solid solutions). As a result of the segregation of elements on austenite grain boundaries, critical cooling rate gets reduced. Because of strong chemical affinity of boron for oxygen and nitrogen, desired results can be obtained only in case of boriding structural materials of proper metallurgical purity. The excess of gas inclusions triggers the formation of boron trioxides (B_2O_3) in metallic liquid that later pass into the slag. Stable boron nitrides (BR) form in alloy that remains in a solid state. There is, in fact, a possibility to dissolve such compounds in solid solution during austenization of steel, though it requires annealing in very high temperatures in which aluminium nitrides (AlN) and intermetallic phases of MX type that strengthen the material and condition its fine-grain structure undergo decomposition. In order to prevent the formation of BN particles, elements of higher chemical affinity for nitrogen, such as aluminium or titatnium, are added to the melt. Proper amounts thereof (i.e. ten times the ratio of Al, or three or five times the addition of Ti in relation to N_2 content) guarantee fixing whole nitrogen into high strength AlN/TiN phases.

The extent of the influence of alloy additions on the properties of steel is highly dependent on the state of thermo-mechanical treatment. Dispersive nitride and carbonitride particles separating on dislocations and grain boundaries block the growth of austenite boundaries, slowing down the processes of recrystallization and recovery during high-temperature plastic deformation, and once the processes end, inhibiting the intensity of recrystallization phenomena. Thus, due to strong precipitation hardening, a fine-grained structure is obtained which guarantees the formation of sufficiently small nuclei in the process of secondary crystallization (e.g. caused by welding).

During solidification of liquid metal, heat dissipates from the material into several specific directions, thus the temperature gradient of the melt in the cross-section of the material is heterogeneous. Microstructure crystals nucleate in cooler areas and grow towards warmer ones. The phenomenon of crystals growing in the directions of heat dissipation (so-called privileged directions) is characteristic for casting microstructures. Additional mechanical procedures (e.g. thermomechanical rolling) applied at the stage of steel manufacturing result in the final microstructure of the material consisting of refined, homogenously-oriented columnar grains strengthening the material. Such global grain orientation is conducive to the occurrence of nitrides and carbonitrides (e.g. AlN, VN, VCN) that enhance the strength of the alloy [8].

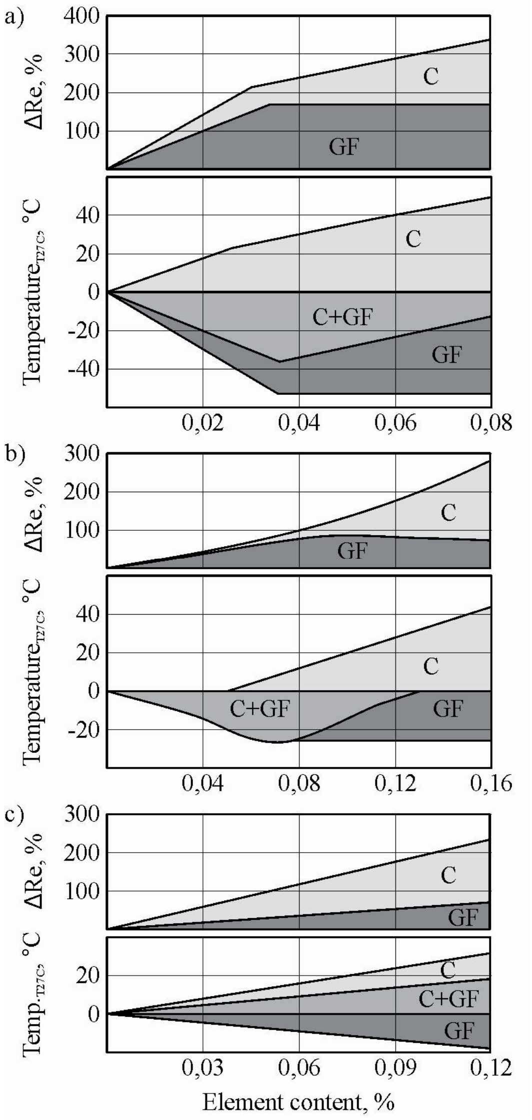

Fig. 2. Schematic representation of the influence of Nb, Ti and V on the increase in Re and brittle temperature of MART steel. Symbols: C – precipitation hardening, GF – grain refinement [7]

1.2. Thermal processes

Bonding advanced structural alloys whose yield point exceed the value of 500 MPa results in changes in microstructure of joints, which leads to the emergence of coarse-grained softened areas directly adjacent to the fusion line (Fig. 3). Both width and hardness of these areas are linked to the thickness of the joined sheetsteel and the amount of heat supplied to them in the course of welding procedures. Reducing cross-sections of joint constituents as well as intensive heating thereof coupled with accelerated cooling, and thus with shorter t8/5 times, conditions the formation of more widespread zones of low strength parameters. Reducing the values of welding linear energies and increasing the number of passes welded, usually results in improved ductility and impact strength of both the welds themselves and heat-affected zones, as well as in the increase in global strength of the whole joint. It is also believed that if the amount of heat supplied is kept at optimum level, the influence of softened SWC areas on the decrease in strength of the whole joint proves negligible. Tensile strength tests of specimens of butt joints with butt welds of MART steel prove that growing load almost instantly brings about triaxial state of stress that results in inhibition of further strain development. This phenomenon also explains why the specimens fracture directly in the welds or the parent material, and not within heat affected zones. In order to achieve such a favourable result, the value of the t8/5 parameter should fall into the range of 5-15 seconds [9-11].

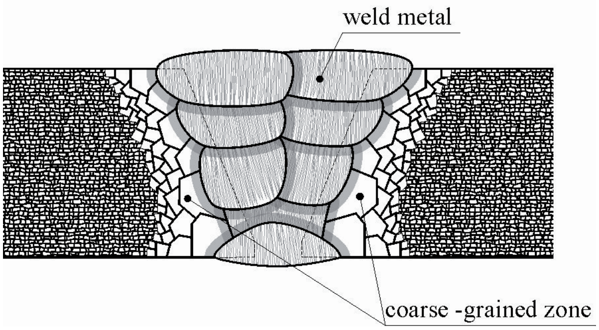

Fig. 3. Pictorial diagram of microstructure grains shapes and orientation in the cross-section of butt joint with high strength structural sheet steel butt weld. A zone of randomly oriented, coarse grains of irregular profiles (coarse-grained zone) directly adjacent to the fusion line is visible

Multi-pass processes resulting in accumulation of thermal energy in welded elements require corrected values of the amounts of heat supplied during welding subsequent layers.

In one-pass processes as well as in multi-pass welding of long butt joints with butt welds, it is acceptable to increase the maximum recommended amount of heat supplied into joined materials by around 10-15%. Still, in case of making joints with fillet welds, the value of linear energy can be increased even by around 40-50%. In case of joining sheet steel of different thickness, the value of linear welding energy should be conditioned by the recommendations concerning the thinnest of the joined sheets [12-14].

1.3. Fillers

The choice of filler plays an important part in the effectiveness of welding procedures on tempered structural steels. The strength of welds depends mainly on the value of mechanical parameters and quality of filler metals used (Tab. 1) [15].

Table 1.
A comparison of the results of destructive tests on specimens of butt joints with butt welds made with high strength welding wires on sheets of 1.2-2 mm thickness made of Docol 1200-1500 steel

Steel type	R_m– steel, MPa	R_m– filler, MPa	Crack location
S960QL	ca. 800	850-900	weld
S1100QL	ca. 900		
S1300QL	ca. 950		

The procedures of joining the most modern tempered structural steel grades with arc welding methods constitute a serious challenge for the welding industry. More often than not, fulfilling the demands regarding mechanical parameters of such alloys is becoming possible only by means of using specialist filler metals. Unfortunately, none of the leading manufacturers of welding materials have developed a technology for manufacturing wires of strength corresponding to that of steels of S1100QL and S1300QL type. Filler metals distinguished by the highest strength of those available in the European market are characterised by minimum yield points oscillating around 960 MPa, which means that they match the strength of alloys of S960QL grade at best [16-25].

Filler metal used skilfully should guarantee the strength of the formed weld metal at least at the level of 90% of the value of yield point of parent material. Otherwise, the filler metal is considered undermatching [26].

There are many different varieties of welding wires available in the course of trade, both solid and flux-cored, but none of them can be labelled matching material with regard to MART-type steel of Re > 960 MPa. Welding of S1100QL and S1300QL alloys is possible only with the use of undermatching filler metals, and the efficiency of joining processes remains dependant on the proper project of structure nodes made, the values of the welding parameters used, application of special procedures and following technological regime.

The use of undermatching filler metals usually brings a number of benefits, such as increased plasticity of the weld, increased cold crack resistance and reduced welding stresses. In case of multi-pass processes, using several grades of non-alloy or low-alloyed fillers differing in the values of tensile strength proves especially efficient. For example, in case of butt joining of S960QL and S1100QL plate steel:

- for tack welds and penetration layers, plastic (so-called undermatching), low-hydrogen filler metals of G4Si1 grade are required, for they provide high impact strength and lower rigidity of welds, which leads to the reduction of internal stresses in the joint and minimisation of the risk of cold crack occurrence therein. The use of ductile materials while welding root passes makes it possible to lower the preheating temperature, too. The procedure is not devoid of negative influence on the joint strength which gets slightly reduced, i.e. by about 3%;
- for subsequent layers, high strength (so-called matching) filler metals containing Ti, V, Nb and/or B micro-additions in amounts that will not deteriorate their welding properties are recommended;
- for fill passes, only undermatching fillers (i.e. those whose strength is lower than that of parent material) are recommended [27].

Due to such advantages as the possibility to fashion chemical constitution of weld metal without restraint, so-called flux-cored materials are becoming more and more popular. In comparison with basic and flux welding wires, not only do flux-cored welding wires with rutile core provide greater stability of arc burning, but they also make the appearance of the face of weld more aesthetically pleasing. Powdered filler metals are conducive to increasing the shock-resistance of the joints produced [28].

2. Research

An attempt was made to weld joints made of S1100QL steel (ThyssenKrupp XABO®1100 1.8942) with the use of fillers used for welding S690QL and S960QL steels. Such a solution resulted from the lack of fillers for welding of tempered steels of high strength. Filler of nominally lower strength results in the formation of weld of higher strength – comparable to that of parent material – when appropriate technological regime is followed under dynamic solidification conditions.

2.1. Samples

Four test joints of S1100QL steel were made. The joints were welded on both sides, and the root of weld removed as shown in Figure 4.

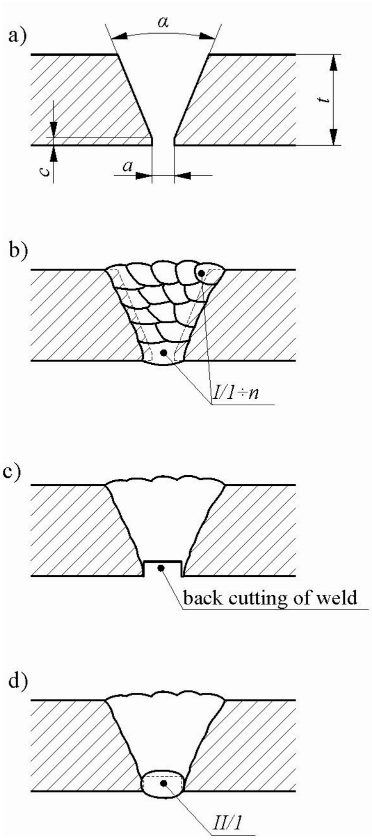

Fig. 4. Welding technology od sample joints: a) main dimensions: a = 2-3 mm, c = 0-1 mm, t = 10 and 20 mm, α = 50°; b) welding part 1: joint filling with SG700 or X90 (I/1-n); c) back cutting of weld; d) welding part 2 with SG700 or X90 (II/1)

The groove was filled with target filler of high strength. The next step of joint formation was the complete removal of the root layer and replacement thereof with root pass. Such a technological process allowed for the production of a proper welded joint with method 135.

The requirements employed for test joint resulted from the strength of the wire whose properties are show in Table 2.

The following wires were used for filling the joint:

- X90 (PN-EN ISO 16834:2012 G Mn4Ni2CrMo; Thyssen Union X90);
- SG700 (PN-EN ISO 16834:2012 G Mn4Ni1.5CrMo Thyssen Union NiMoCr – SG700).

Table 2.
Mechanical properties of the materials used

Feature	Parent material	Filler materials	
	S1100QL	SG700	X90
Yeld point 0.2%: Rp$_{0.2}$, N/mm^2	min. 1100	min. 680 max. 720	min. 880 max. 920
Tensile strength: R$_m$, N/mm^2	min. 1200 max. 1500	min. 740 max. 780	min. 940 max. 980
Elongation: A, %	min. 8	16-18	16-20
Impact energy KV, J (-40°C)	min. 30	47-95	65-95

Butt joints were welded with the GMAW method in PA position with butt welds of 10 and 20mm thickness. Welding was performed with shielding gas made up of M21 mixture. The joints were preheated to the temperature of 150°C, while interpass temperature was 100-200°C. Self-cooling of the joint after welding took place outdoors. Weldedjoints characteristic is shown in Table 3.

The thickness of each plate was hand-made in the first place.

Table 3.
Welded joints characteristic

Joint	Welding process	Thickness, mm	Filler	Heat input, kJ/cm
10A	GMAW	10	X90	5.3-6.3
10B	GMAW/robot	10	SG700	9.4-13.1
20A	GMAW	20	X90	5.9-9.0
20B	GMAW/robot	20	X90	6.5-11.2

2.2. Methodology

Macroscopic examination of one specimen was done for each joint. The samples were cut off the tests joints according to PN-EN ISO 15614-1:2008/A1:2010. The specimen surface was machined; ground, polished and etched in Nital with the chemical constitution: 10% Nitric acid (HNO_3), 90% Ethanol (C_2H_5OH).

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 Figure 5.

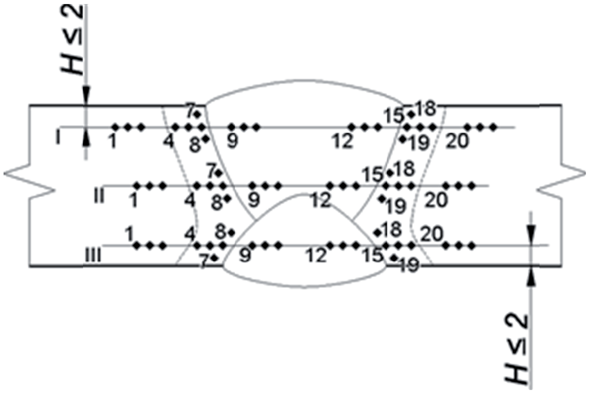

Fig. 5. Hardness measurement points distribution scheme

The following equipment was used for testing:

- automatic hardness tester LECO LV700AT;
- measurement standard 0.01mm Olympus AX0011 OB-MM 1/100;
- hardness standard LECO nr 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, temperature test: 20°C; accuracy of read: 500 N.

Technological transverse bend test was performed in accordance with the provisions contained in the PN-EN ISO 5173:2010 standard. Due to the properties of the joint, bending was performed with the use of a bending roller, as shown in Figure 6. In case of MA and MB joint of 20 mm thickness, side bending was conducted. For RA and RB joints of 10 mm thickness, face and root bending was conducted. In each case, bending mandrel diameter was calculated according to the following dependence: d=[(100•t)/A]-t; where t – material thickness (10 mm); A – elongation (8%).

Due to varying plasticity of the joint, the bend test differs from standard three-point bending test. Since the parent material is elastic and characterised by lower elongation, the strain of plastic joint is too high. Excessive stresses in a specimen undergoing three-point bending causes the specimen to fracture and test result to be negative. Bend test with the use of bending roller entails bending by gradual shift of strain zone (Fig. 6). Only such course of the test will ensure that it is conducted in a proper and competent way.

Impact strength tests were conducted on specimens cut off the joint according to the PN-EN ISO 15614-1:2008/A2:2012 standard, in accordance with the provisions contained in the PN-EN ISO 9016:2013-05 standard. Two types of specimens were tested:

- VWT0/2 – notch in centre of weld, 2 mm below parent material surface;
- VHT2/2 – notch in heat affected zone, 2 mm from fusion line, 2 mm below parent material surface.

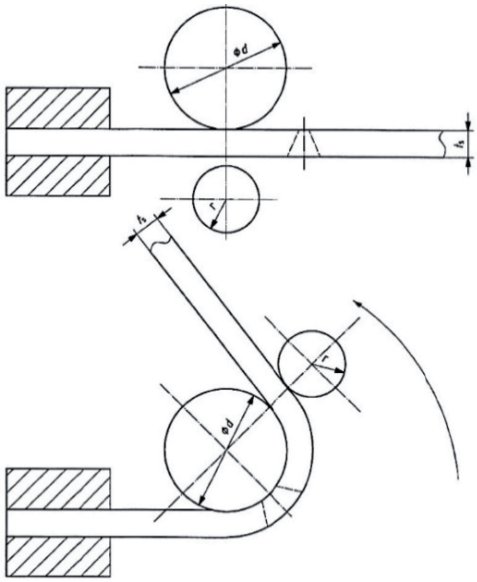

Fig. 6. A diagram of proper bend test with the use of a bending roller [29]

The tests were conducted in the temperature of -40°C. For joints of 10 mm thickness, specimens of 7.5 x 8 mm were used, and for joints of 20 mm thickness, standard 10 x 8 mm specimens were used.

2.3. Test results

As a result of the macroscopic investigation (Figs. 7-10) it was found that tested joints have no cracks; no lack of penetration; no porosity; regular profile with smooth transition to the base material.

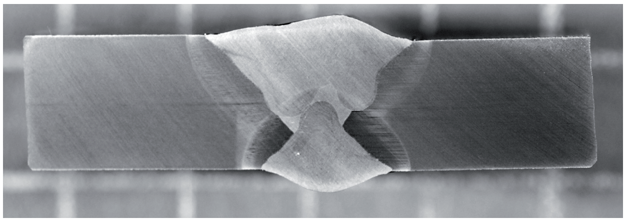

Fig. 7. Macroscopic image of sample 10A

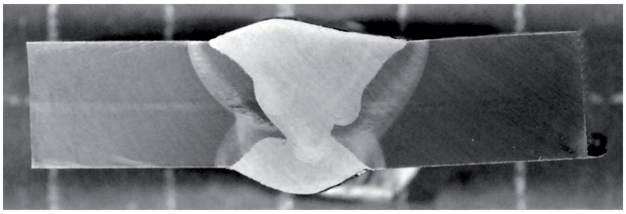

Fig. 8. Macroscopic image of sample 10B

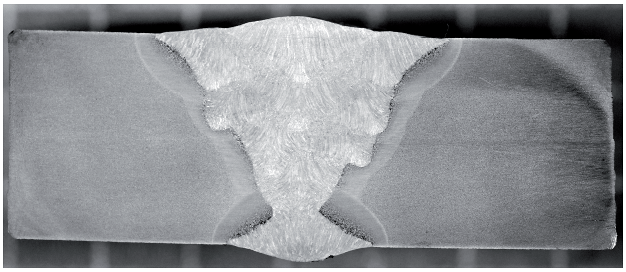

Fig. 9. Macroscopic image of sample 20A

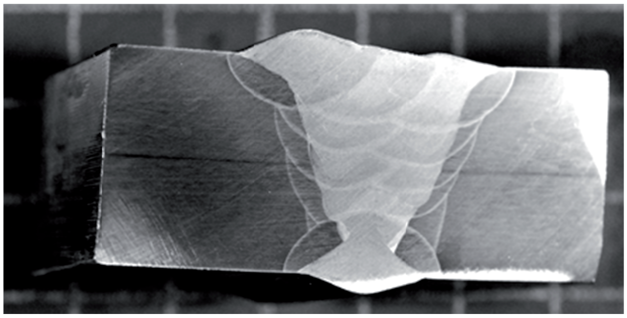

Fig. 10. Macroscopic image of sample 20B

The specimens produced are characterised by deep penetration and distinctive root pass being the result of back welding of the joint. Such joint structure ensures minimum amount of imperfections in the root of weld. The width of the heat-affected zone changes along with the thickness of the joint, which indicates better heat abstraction from thicker sheets. In specimens 20A and 20B, one can see subsequent passes overlain on one another, which causes mutual penetration of heat affected zone and tempering zone.

Decrease in hardness in 10B sample in comparison to 10A sample is caused by two factors, depending on joint zone (Fig. 11):

- weld – the replacement of filler with wire of lower strength and hardness;
- HAZ – the increase in welding parameters and thus the amount of heat supplied to the joint and longer t8/5 time.

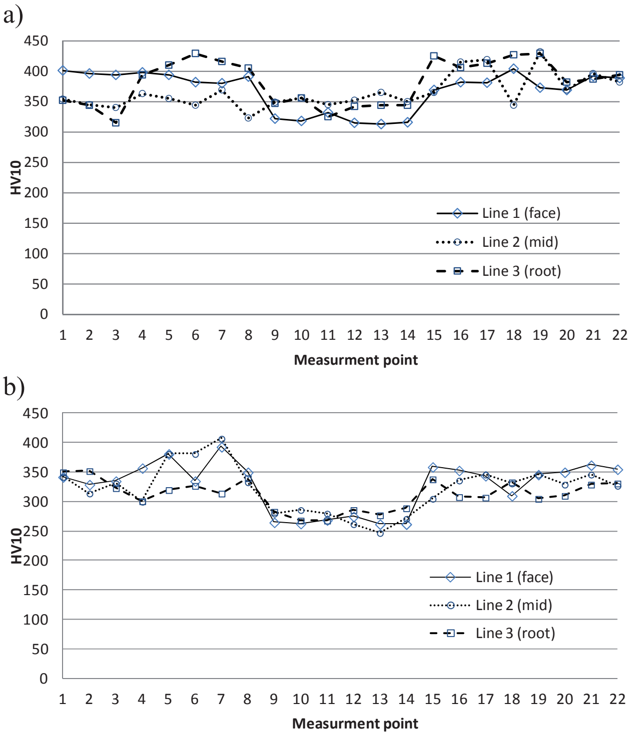

Fig. 11. Hardness measurements results on sample: a) 10A; b) 10B

Hardness in the weld in the 20A and 20B joints welded with the same filler metal remains unchanged. The change takes place in HAZ and, as it was the case with the previous instance, is caused by increased amount of heat supplied to the joint. In case of the 20A joint, hardness is above the acceptable value for joints of steel of group 3 which was determined not to be higher than 450 HV (Fig. 12).

All specimens that underwent static tensile test fractured in weld which constitutes the weakest spot in the joint in case of welding with undermatching materials.

The highest strength parameters were obtained in case of joints welded with filler of higher strength. Strength results of joints for X90 filler metal remain stable.

The 10A and 20A joints that were welded with lower linear energies and whose plasticity was unsatisfactory, achieved a negative result in a static bend test. Prolongation of t8/5 time in the joints enhanced the parameters to a degree which allowed for the test to end positively.

Due to varying thicknesses of specimens – 7.5 mm for the 10A and 10B joints and 10 mm for the 20A and 20B joints respectively – the comparison of impact strength (Table 4) is possible only with regard to one type of joint. Only a juxtaposition of impact strength results gives the full picture of crack resistance with regard to stresses of dynamic nature. Bend test results is shown in Table 5.

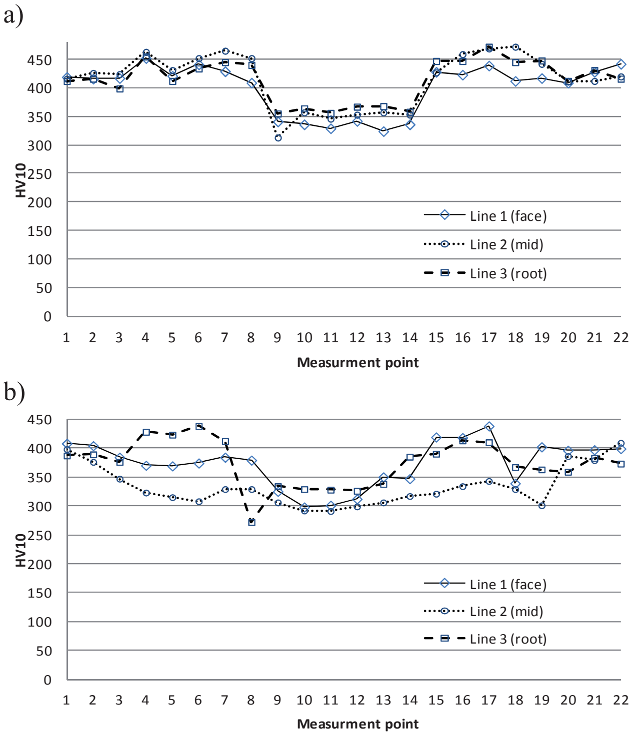

Fig. 12. Hardness measurements results on sample: a) 20A; b) 20B

Table 4.
Tensile tests results – crack location: weld

Sample	Yeld point 0.2%, MPa	Tensile strength, MPa
10A-1	1058.6	1127.8
10A-2	1109.6	1139.5
10B-1	884.3	980.1
10B-2	892.5	977.2
20A-1	1059.1	1120.2
20A-2	1028.4	1120.9
20B-1	1072	1110.3
20B-2	1057.8	1103.5

Table 5.
Bend test results

Weld ID	Kind of test	Result	Remarks
10A	2 x FBB	N	2 x rupture
	2 x RBB	N	2 x rupture
10B	2 x FBB	P	-
	2 x RBB	P	-
20A	4 x SBB	N	4 x rupture
20B	4 x SBB	P	-

Table 6.
Impact test results

Notch location	Impact strength, J/cm^2			
	10A	10B	20A	20B
weld	77.3	96.9	67.8	64.9
HAZ 2mm	102.3	115.4	193.6	145.4

The impact strength of weld in specimens of 10 mm thickness welded with fewer number of passes is considerably higher. It reaches maximum value for material SG700. In case of specimens of 20 mm thickness, the impact strength of weld reaches similar values (Tab. 6).

HAZ is characterised by a more diversified impact strength which in every case is higher than in the weld. Impact strength of HAZ in specimen of lower thickness increases along with the increase in linear energy, but it drops in case of specimen of 20 mm.

3. Conclusions

The thickness of the material welded bears an influence on the nature and size of thermal changes in parent material. It was proved by macroscopic examination in the first place. Since thinner sheets are more susceptible to overheating, the width of heat affected zone proves higher in case of specimens of lower thickness. It shows that the ability to abstract heat is lower in the 10A and 10B joints. As a result, HAZ temperatures are higher, and t8/5 cooling time is longer. In joints of 20 mm thickness, the structure of heat affected zone is different due to multi-pass manner of welding and higher heat abstraction ability of the material. Overlapping of thermal effects of subsequent passes can be observed here. The thermal characteristics described above influence further mechanical properties of joints that were tested.

The measurement of joint hardness clearly exhibits a lower level of HAZ hardening in 10 mm joints that results from lower cooling dynamics and higher values of t8/5 time. With the amount of heat supplied being 13 kJ/cm, the resultant SWC structure consists mainly of bainite of hardness around 350 HV.

In joints of material of 20 mm thickness, individual passes successively harden the adjacent HAZ and temper some part of heat affected zone of the previous pass. Cooling speeds are higher in this case due to greater disposition of thick sheet to abstract heat. In consequence, martensite areas of hardness exceeding the acceptable 450 HV appear in the heat affected zone. Only increased amount of heat supplied improves the t8/5 time, allowing for emergence of structures whose properties are acceptable.

The plasticity of joints tested behaves in a similar fashion, showing improvement with the increase in welding linear energy. Regardless of the thickness of parent material, when the value of linear energy is low, plasticity is insufficient and bent specimens fracture already at the value of angle of bend at the level of 100°.

No relation between the strength of a joint and any technological parameter was found in the course of tensile tests of the joints. Such a result was due to fracture point where the factor influencing the strength to the greatest extent constituted the filler used, characterised by constant parameters in the range of linear energy applied in the test.

From the point of view of static strength, the strength of the filler metal used proves fundamental in case of welded joints of high strength MART steels. In case of X90 materials, the strength is similar to the properties of X1100QL steel, while in case of SG700 material, the strength is lower. In case of fillet welds, the strength of a joint can be freely adjusted by changes in its thickness. In case of butt welds, there is no such possibility. In supporting structures made of S1100QL steel, joints welded with butt welds with the use of undermatching materials should be located in neutral zones exhibiting a lower state of stresses.

Another parameter that is susceptible to welding thermal cycle is the impact strength of a joint. In case of weld, the impact strength is directly proportional to the t8/5 cooling time and the filler metal used. In case of the 20A and 20B joints, the structure of multi-pass weld undergoes cyclic heat treatment and is shaped to such an extent that it is not influenced by welding linear energy. The impact strength of this area does not change significantly. In specimens 10A and 10B, different filler metals were used; therefore, the differences in the impact strength of this area of a joint are the function of filler metal properties.

In the heat affected zones of the joints tested, one deals with two mechanisms: grain growth at the fusion line resulting in the deterioration of impact strength as well as tempering of non-equilibrium structures that improves impact strength.

Depending on the HAZ structure, one of the abovementioned processes will prevail. In 10 mm specimens, heat affected zone consists of coarse grained bainite which slightly tempers at the increase in linear energy and thus improves the resistance to dynamic stresses. In specimens of 20 mm thickness, heat affected zone is more diversified in terms of structure and consists of fine grained martensite of tempering degree dependant on the orientation in regard to neighbouring passes. Increasing linear energy causes grain growth and decrease in impact strength of the zone.

The range of comprehensive tests that follows from the requirements of standards concerning approval of welding procedures is justified. This stance can be proved by instances when some tests give positive results, while the results of other tests disqualify the joint. The results of non-destructive testing for all the joints described in the article were positive. Good results were also obtained in macroscopic examination and impact strength tests. Hardness tests proved decisive, for they revealed the disposition of the joints to harden and bend and allowed to observe unfavourable changes in plasticity.

Greater technological regime of welding entails the necessity for automation which has to be taken into consideration in the process of planning the production of MART steel elements. The key factors from the point of view of utility of a joint are the amount of heat supplied as well as process stability which can be easily obtained and regulated without restraint in case of automatic welding and, in this way, exerting an influence on the properties of HAZ – the most critical zone in the joint.

Currently, the choice of filler constitutes major difficulty in terms of welding of high strength steel. Despite the emergence of new types of welding wires, the weldability of the wires is low, which considerably raises the costs of production. The tests conducted showed that the knowledge of properties of the joints welded with materials that are characterised by higher weldability and potentially better mechanical properties but remain nominally lower, is crucial for a properly produced joint.

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