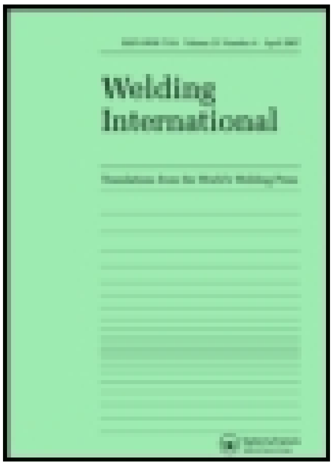

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Effect of heat input on the mechanical properties of welded joints in high-strength steels

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Experiments were carried out to determine the properties of the welded joints in 8 mm thick high-strength steels produced by quenching and tempering and thermomechanical rolling with accelerated cooling (tensile strength 821–835 MPa). The dependence of the strength, elongation, hardness, impact energy and crack opening displacement on the heat input in the range 1.0–0.7 kJ mm^{-1} was determined. The results show that the dependence of the strength of the welded joints decreases and that of the elongation increases. The heat input has only a slight effect on the impact energy and crack opening displacement in the heat-affected zone.

Keywords: high-strength steel; thermomechanical rolling; linear energy; welded joint

Introduction

At the present time, high-strength steels are steels with a tensile strength higher than 950 MPa. There are three main methods of production of high-strength steels: quenching and tempering (QT), thermomechanical rolling with accelerated cooling (TMCP) and direct quenching. The microstructure of the steel can be bainitic, martensitic and ferritic–bainitic.

In arc welding of the high-strength steels, the microstructure and mechanical properties of the welded joint are determined by the chemical composition of the weld and the parent metal and also by the cooling rate of the metal, especially in the heat-affected zone (HAZ). The latter depends mostly on the heat input, weld geometry and the thermophysical properties of the metal. The results of comparative analysis of the microstructure of the HAZ metal in welding of high-strength steels were published in [1]. The dependence of the mechanical properties on the welding conditions was studied in [2–5], but the effect of heat input has been studied insufficiently.

The aim of this study is the determination of the effect of heat input on the mechanical properties (tensile strength of the welded joint, hardness distribution, impact energy and crack opening displacement) in arc welding with a consumable electrode of steels produced by the QT and TMCP methods, with the tensile strength being higher than 800 MPa.

Materials

Experiments were carried out using two high-strength steels, produced by the QT method and TMCP method, greatly differing in the chemical composition (Table 1) but having similar mechanical properties (Table 2). The tensile strength of the filler material (OK Autrod 12.51 electrodes wired) in relation to the yield limit of the parent material was 67–68% (Table 2). The thickness of the welded sheets was 8 mm (Figure 1).

Welding technology

The sheets with V-shaped edge preparation (angle 60°, root face 1 mm, gap 1.5 mm) were welded with a wire with a diameter of 1.2 mm in a shielding gas (15% CO_2 and 85% Ar). The welding conditions are presented in Table 3. The heat input corresponds to the thermal efficiency of the arc equal to 0.8.[6,7] The cross-section at the heat input of 1.7 kJ mm^{-1} of the point of measurement of hardness and the area in which a Charpy notch was made in the specimen are shown in Figure 1.

Strength

The welded joint is an inhomogeneous body, consisting of the parent metal, the soft welded joint and the harder HAZ (Figure 1). The weakest zone of the welded joint is the weld zone.

The specimens with the cross-section of the welded joint were tensile tested in accordance with the ISO 4136:2001 standard 'Destructive tests on welding metallic materials. Transverse tensile test'. All the specimens failed through the welded joint. The strength of the welded joint in the steel produced by TMCP was slightly higher than that of the welded joint in the QT steel (Figure 2a). In all cases, the strength of the welded joint was higher than the strength of the electrode wire mainly as a result of inclusion of the harder parent material in the welded joint. The figure shows that the strength of the joint decreases with increasing heat input.

Elongation

Because of the high concentration of the plastic strains in the transverse soft welded joint, the elongation of the welded joint is only 4–10%, which is 2–4 times smaller than the elongation of the parent metal (Figure 2b). The elongation of the welded joints in the TMCP steel is considerably higher than the elongation of the welded joint in the QT steel. With increasing heat input the elongation increases (Figure 2b). It should be mentioned that the heat input had no effect on the strength and elongation of the welded joint when the ratio of the tensile strength of the weld metal to that of the high-strength parent metal of the QT type was equal to 85–92%.[2]

Table 1.

Steel	C	Si	Mn	Al	B	Nb	Ti	V	Cu	Cr	Ni	Mo	N	P	S
QT	0.137	0.28	1.39	0.061	0.0021	0.022	0.002	0.001	0.02	0.062	0.066	0.029	0.005	0.013	0.0013
TMCP	0.049	0.17	1.86	0.025	–	0.081	0.092	0.009	–	–	–	0.008	0.005	0.08	0.004
OK Autrod 13.51	0.07	0.89	1.45	0.061	–	–	0.01	–	(≤0.30	0.05	0.04	–	0.005	0.012	0.02

Hardness

The inhomogeneity of the welded joint can be determined on the basis of the hardness distribution. Vickers hardness HV5 was determined in the cross-section of the welded joint at a depth of 2 mm from the upper surface with a step of 0.5 mm according to the standard ISO 6507-1:2005 'Metallic materials. Vickers hardness test. Part 1: Test method'.

The hardness of the parent metal of the TMCP and QT steels was identical and equalled 270–290 HV5 (Figure 3). The hardness of the weld metal was 200–220 HV5 for the TMCP steel (Figure 3a) and 200–210 HV5 for the QT steel (Figure 3b).

The HAZ metal is subjected to double heating and cooling and, consequently, the microstructure is quite complicated (Figure 1). The microstructure of the TMCP steel with a low carbon content is bainitic, ferritic–pearlitic and ferritic. Hardness equals 220–230 HV5 and is almost completely independent of heat input.

After welding the QT steel, the HAZ microstructure in the vicinity of the boundary of the welded joint is coarse grained. At a high carbon content, quenching takes place with the formation of martensite and bainite and, consequently, the hardness may exceed the hardness of the parent metal.[3] With the heat input increasing from 1 to 1.7 kJ mm^{-1} (reduction of the cooling rate), the hardness in this zone decreases from 300 to 250 HV5 (Figure 3b). With a further increase of heat input (reduction of the cooling rate), the hardness in the coarse-grained zone may increase in comparison with the hardness of the parent metal.[2] The HAZ metal in the vicinity of the parent metal is heated below the temperature A_3 so that the metal is tempered and its hardness decreases to 190 HV5.

Figure 3 shows that the width of the HAZ and its components greatly increases with increasing heat input. The effect of softening of the welded joint is determined by the ratio of the width of the softened zone to the thickness of the sheet. This means that the increase of heat input results in a reduction of the strength of the welded joint, even if the weld metal has the same strength as that of the parent metal.

Table 2.

Steel	Yield stress (MPa)	Ultimate strength (MPa)	Elongation A5 (%)	Impact energy (J)
TMCP	793	835	16.3	103 (−40 °C)
QT	761	821	20	98 (−20 °C)
OK Autrod 12.51	470	560	min 26	26 (−30 °C)

Impact energy

The Charpy specimens with the size of 5 × 10 × 55 mm were tested at a temperature of −40°C in accordance with the standard ISO 148-1.2 to 9 'Metallic materials. Charpy pendulum impact tests. Part one: Test Method'. A V-shaped notch included the weld metal, the HAZ and the parent metal (Figure 1). The HAZ consists of the coarse-grained region, the fine-grained region, the zone of intercritical heating and the zone of sub-critical heating. The HAZ of both passes contains the coarse-grained region, subjected to repeated intercritical heating (to the maximum temperature in the range A1–A3). As shown in many investigations,[8–13] this region is characterized by the highest brittleness.

Increase in carbon content results in a reduction of the impact energy (Figure 4). This confirms the results obtained by other researchers.[14] The impact energy of the weld metal is higher than that of the HAZ.

Previously, it was reported that in welding niobium-containing steels, the impact energy increases if the heat input is low and decreases if the heat input is high.[14,15]

Crack opening displacement

The crack opening displacement was determined on specimens with a cross-section of 5 × 10 mm at a temperature of −40°C according to the ASTM 1290-2 standard: 'Standard test method for crack tip opening displacement fracture toughness measurement'. It is well known that the highest brittleness is recorded in the coarse-grained region.[4,12,16] The investigations of the

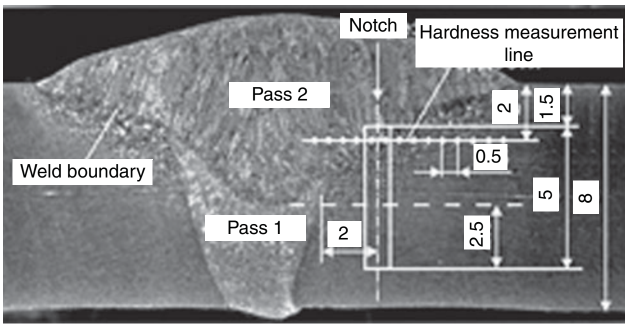

Figure 1. Position of the V-shaped notch in the Charpy specimen and the line of measurement of hardness in the cross-section of the welded joint.

Table 3.

No.	Current (A)	Arc voltage (V)	Welding speed (mm s^{-1})	Arc power (W)	Effective power (W)	Heat input (J mm^{-1})
1	230	25.6	4.53	5888	4710	1039
2	268	29.0	4.52	7772	6218	1376
3	258	30.6	3.71	7895	6316	1701

welded joint showed that it is very difficult to position and initiate the crack in this narrow region.[17] Therefore, the crack opening displacement was determined on specimens subjected to the same thermal cycle in equipment Gleeble 3800 as the metal in the coarse-grained region (maximum temperature 1623 K, cooling time from 1073 K (800°C) to 773 K (500°C) equal to 10–55 s, depending on the welding conditions). Comparison of the microstructure of the metal in the specimens in the coarse-grained region of the actual welded joint showed that it is approximately the same and consists of martensite and bainite. For example, at a heat input of 1.3–1.4 kJ mm^{-1}, the austenite grain size of the QT steel was equal to 3.5–4 in the specimens and 4–5 in the actual welded joint according to ASTM E 112-10: 'Standard test methods for determining the average grain size'. The small difference in the grain size is explained by the effect of the high temperature gradient in the actual

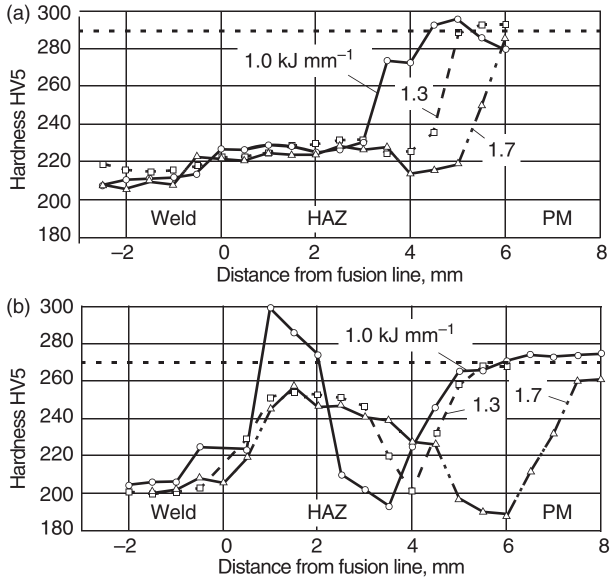

Figure 3. Effect of heat input on the hardness of TMCP (a) and QT (b) steel. The dotted line shows the hardness of the parent metal.

welded joint.[18] Thus, the metal of the samples represents quite efficiently the HAZ in the coarse-grained region.

Figure 4b shows that the crack opening displacement in the HAZ metal in the coarse-grained regions is considerably smaller than in the parent metal. The effect of heat input on the crack opening displacement in both steels

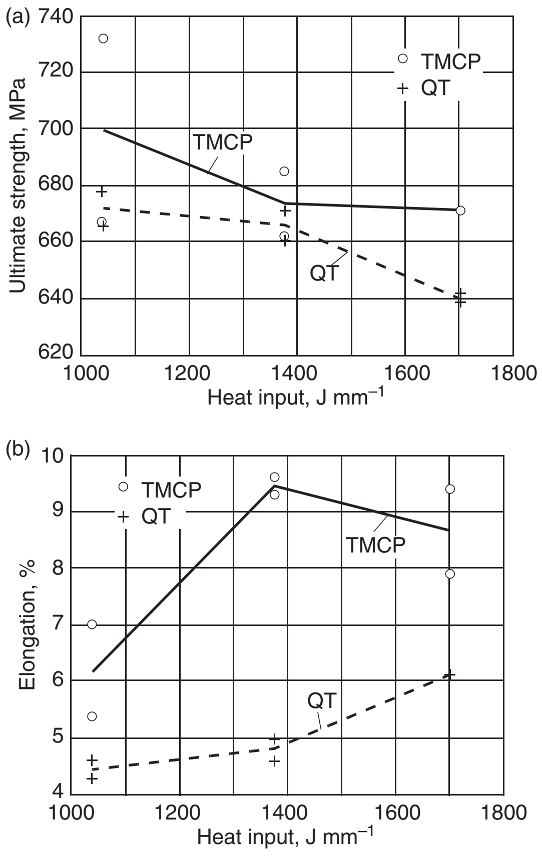

Figure 2. Dependence of the strength (a) and elongation (b) of the welded joint on heat input.

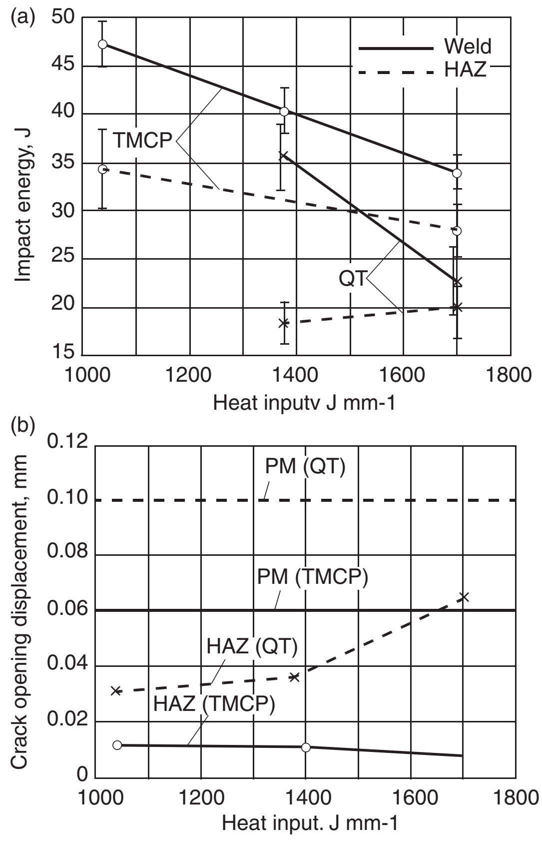

Figure 4. Dependence of the impact energy of the weld metal and the HAZ (a) and crack opening displacement in the HAZ metal (b) on heat input.

was only small. It should be mentioned that the same conclusion can be made on the basis of the results of investigating the dependence of the J-integral on the cooling time from 1073 to 773 K in a wide range.[4] Additional studies show that changes in the chemical composition, permissible for the same grade of the steel, may lead to large changes in the properties of the HAZ than the effect of the heat input in the investigated range.

Conclusions

(1) The tensile strength of the welded joint in the high-strength steels is more than 15% higher than the strength of the metal of the electrode wire which equals 67–68% of the tensile strength of the parent metal.
(2) Because of the high concentration of plastic strains in the weld metal, the elongation of the specimen reaches 4–10% which is 2–4 times smaller than the elongation of the parent metal.
(3) The dependence of the strength of the welded joint on the heat input becomes weaker and that of the elongation becomes stronger.
(4) In welding a high-strength steel with a thickness of 8 mm, the heat input in the range 1.0–1.7 kJ mm^{-1} has only a slight effect on the impact energy and the crack opening displacement in the HAZ.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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