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Electron Beam Welding of TMCP steel S700MC

Abstract: The article discusses tests aimed to determine the effect of electron beam welding on the properties of butt welded joints made in 10 mm thick TMCP steel S700MC. The welding process was performed in the flat position (PA) using an XW150:30/756 welding and surface processing machine (Cambridge Vacuum Engineering). The joints obtained in the tests were subjected to non-destructive tests including visual tests and magnetic particle tests. The joints were also subjected to destructive tests including static tensile tests, bend tests, toughness tests (performed at a temperature of -30°C), hardness tests as well as macro and microscopic metallographic tests. The destructive tests revealed that the joint represented quality level B in accordance with the PN EN ISO 13919-1 standard. The analysis of the destructive test results related to the electron beam butt welded joint (made in steel S700MC) revealed its high mechanical and plastic properties. The toughness tests revealed a decrease in toughness in the HAZ (27 J/cm²) in comparison with that of the base material (50 J/cm²). In addition, the hardness of the HAZ and of the weld increased up to approximately 330 HV; the hardness of the base material amounted to 280 HV.

Keywords: TMCP steel, electron beam welding, mechanical properties, plastic properties

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Introduction

Presently, increasingly many welded structures are made of high strength and high yield point steels, including steels made in the thermo-mechanical control process. The special controlled rolling process enables the obtainment of required mechanical properties without compromising plastic ones. The addition of alloying microagents of titanium, niobium and vanadium, not exceeding 0.22%, leads to grain refinement and precipitation hardening, thus improving mechanical properties. Steels made in the thermo-mechanical control process can be found in oil rigs and construction equipment. TMCP steels are also used in the shipbuilding industry, the nuclear power generation sector and in many other industries [1, 2]. Because of lowered preheating temperature or, in some cases, the elimination of the preheating process, decreased weld cross-sections and the reduced consumption of welding consumables, the use of high strength and high yield

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point steels lowers the costs and time of welding processes. In addition, reduced cross-sections of structural elements decrease the overall weight of welded structures. TMCP steels are usually welded using arc-based methods, yet high-energy processes such as laser, hybrid or electron beam welding, are becoming increasingly popular in the joining of high-strength steels [3, 4]. Although the electron beam has been known as the welding power source for many years, the electron beam welding technology has not exhausted its application potential [5, 6]. In spite of significant technological competition, primarily connected with laser beam-based processes, electron beam welding remains indispensable for the jointing of steels, primarily because of the high metallurgical purity of welds, high welding rates and significant penetration depth. In addition to welding, the electron beam is used for surfacing, surface alloying, remelting, making holes and in many other processes [7, 8]. The primary advantages of the electron beam welding include the very narrow heat affected zone (HAZ), very high electron beam power density, minimum stresses and strains as well as the possibility of joining steel materials having thicknesses restricted within the range of 0.01 mm to 250 mm and aluminium materials having thicknesses of up to 500 mm [9]. The disadvantages of the electron beam welding technology include limited dimensions of weldable structures, the emission of X-radiation as well as the relatively high costs of welding equipment and fixtures [10].

Individual research

Individual research-related tests aimed to assess the possibility of obtaining electron beam welded joints in 10 mm thick steel, meeting appropriate mechanical and plastic criteria. The chemical composition and the mechanical properties of the test steel are presented in Table 1, whereas the structure of the steel is presented in Figure 1.

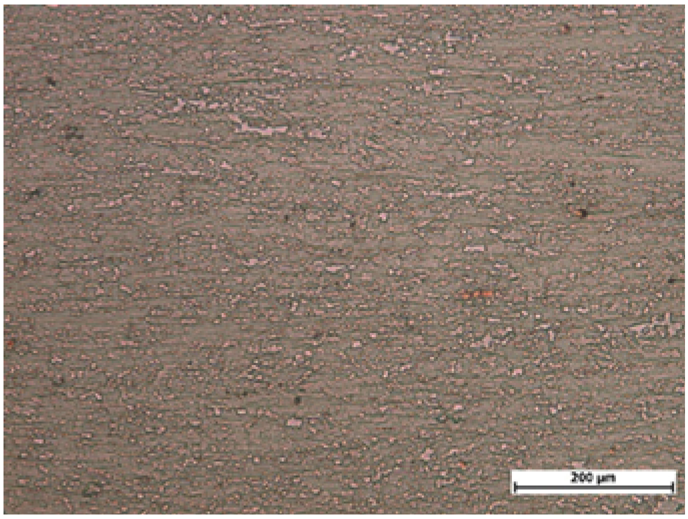


Fig. 1. Bainitic-ferritic structure of steel S700MC

Welding process

The tests involved electron beam butt welded joints made in 10 mm thick steel S700MC. The joints were made at Łukasiewicz – Instytut Spawalnictwa using an XW150:30/756 welding and surface processing machine (Cambridge Vacuum Engineering) having a power of 30 kW and equipped with a vacuum working chamber having a volume of 5 m3 (Fig. 2). The optimisation of welding parameters involved the performance of the electron beam remelting of steel S700MC. The process of remitting was performed using an accelerating voltage of 120 and 150 kV. The initial remelting tests, performed using a remelting rate of 800 mm/min, enabled the determination of parameters as presented in Table 2.

Table 1. Actual chemical composition of 10 mm thick steel S700MC

Chemical composition, %										
C	Mn	Si	S	P	Al	Nb	Ti	V	N*	Ce**
0.056	1.68	0.16	0.005	0.01	0.027	0.044	0.12	0.006	72	0.33
* N: content expresses in ppm; nitrogen content identified using the high-temperature extraction method ** Ce – carbon equivalent										

Table 2. Parameters used during the electron beam welding of 10 mm thick steel S700MC; beam energy: 2.6 kJ/cm

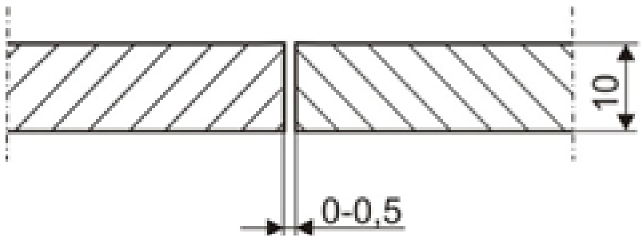
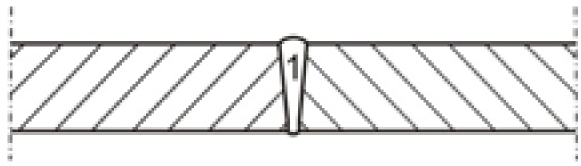
Pre-weld preparation of the test plates	Welding sequence
	
Accelerating voltage HV [kV]	120
Electron beam current [mA]	28.5
Focus [mm]	700
Working [mm]	210
Cathode filament current [A]	22
Welding rate [mm/min]	800
Rising ramp [mA/s]	100
falling ramp [mA/s]	100
Welding linear energy [kJ/cm]	2.6

Fig. 2. Electron beam welding machine: XW150:30/756

Tests of the welded joints

The test joint was subjected to the following non-destructive tests:
- visual tests performed in accordance with the requirements specified in PN-EN ISO 17637:2011;
- magnetic particle tests based on the guidelines contained in PN-EN ISO 3059:2005, PN-EN ISO 9934-2:2003 and PN-EN ISO 9934-3:2003.

After the above-presented NDTs, the welded joint was subjected to the following destructive tests:
- tensile tests performed in accordance with the requirements specified in PN-EN ISO 6892-1:2010;
- face bend test of the butt weld (FBB) and the root bend test of the butt weld (RBB) based on the requirements of the PN-EN ISO 5173:2010 standard. The bend tests involved the use of a bending mandrel having a diameter of 30 mm. The distance between the rollers amounted to 60 mm. The identification of the location of the weld axis required the etching of the fronts of the specimens using Adler's reagent;
- Charpy V-notch test performed at a temperature of -30 °C in accordance with PN-EN ISO 148-1:2010. The identification of the location of the weld axis required the etching of the fronts of the specimens using Adler's reagent;
- macroscopic metallographic tests performed using an Olympus SZX9 stereoscopic light microscope; the specimens were etched using Adler's reagent,
- microscopic metallographic tests performed using a NIKON ECLIPSE MA100 light microscope; the test specimens were etched in Nital,
- Vickers hardness tests performed using a WILSON WOLPERT 430 testing machine. The hardness measurements were carried out in accordance with the requirements specified in the PN-EN ISO 9015-1 standard. The hardness tests were performed along three measurement lines (presented in the schematic diagram in Figure 3).

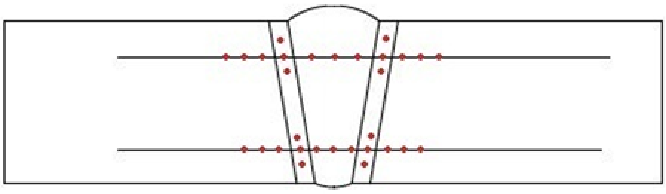


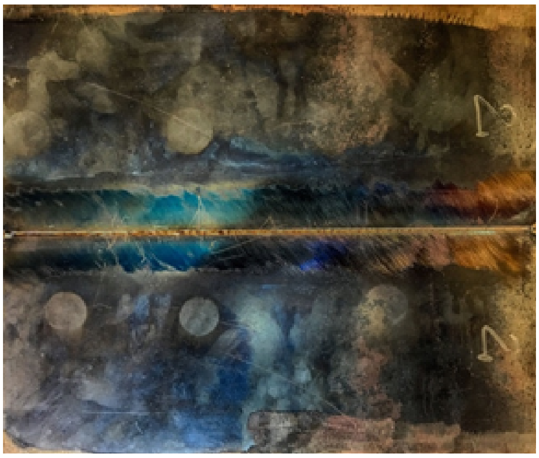
Fig. 3. Arrangement of hardness measurement points

Analysis of test results

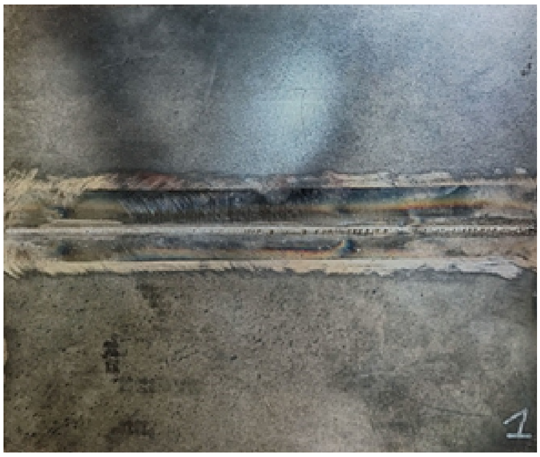
The non-destructive tests of the welded joint did not reveal the presence of any surface-breaking welding imperfections such as cracks, porosity, incomplete fusions or lacks of penetration. The visual tests performed in accordance with the PN-EN ISO 17637 standard revealed that the joint represented quality level B in accordance with PN-EN ISO 13919-1 (Fig. 4). The weld face was characterised by the proper excess weld metal and shape. The weld root was also properly shaped. The magnetic particle tests did not reveal surface-breaking cracks. The macroscopic tests did not reveal the presence of any welding imperfections in the weld or in the HAZ (Fig. 5).

The microscopic tests revealed the structure typical of TMCP steel S700MC, i.e. the fine-grained bainitic-ferritic structure. The HAZ was characterised by the partial grain growth and changes in the microstructure. The weld contained the martensitic structure, whereas the HAZ contained the bainitic structure (Fig. 6). The changes in the grain size in the HAZ were not significant, which could be ascribed to a considerable heat input to the welded joint.

The analysis of the destructive tests of the electron beam butt welded joint revealed the slight effect of the welding method on the mechanical and plastic properties of the butt joints made in steel S700MC (Table 3). The static tensile test revealed that the joint was characterised by high mechanical properties. The tensile strength of the welded joint exceeded the that of the base material (rupture took place in the base material). The bend test revealed that the butt welded joint was characterised by good plastic properties. The obtainment of a full



Weld face



Weld root

Fig. 4. Welded joint

Table 3. Results of the tensile test, bend test and impact strength tests of the electron beam welded joint

Extension*		**Bending*, bend angle, °**		**Toughness KCV*, J/cm² (test temperature: -30 °C)**					
				Weld		Fusion line		HAZ	
R_m, MPa	Area of rupture	Face	Root	KCV, J/cm²	Mixed fracture	KCV, J/cm²	Mixed fracture	KCV, J/cm²	Brittle fracture
830	BM	180	180	59		60		27	
* – average results of two measurements									

bend angle of 180° did not result in any damage to the specimen. In addition, the surface of the specimen did not contain any partial tear traces. The impact strength test performed at a temperature of -30°C revealed that the area characterised by the lowest toughness was the heat affected zone. The toughness in the HAZ was restricted within the range of 26 J/cm² to 28 J/cm², the toughness of the base material amounted to 50 J/cm², whereas the toughness of the weld amounted to 60 J/cm² (Fig. 7).

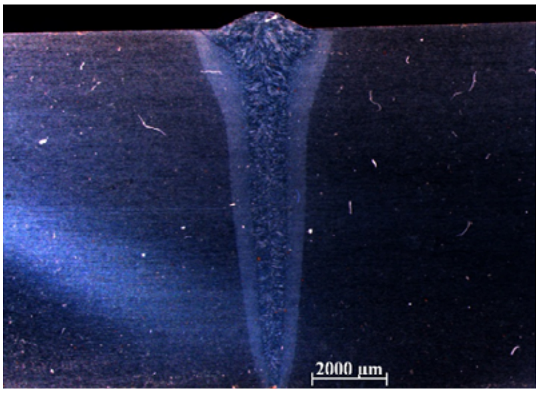


Fig. 5. Macrostructure of the welded joint

In comparison with the hardness of the base material, the electron beam welding process increased the hardness in the weld and that in the HAZ (Fig. 8). However, the aforesaid increase was not very high. The maximum hardness in the HAZ amounted to 334

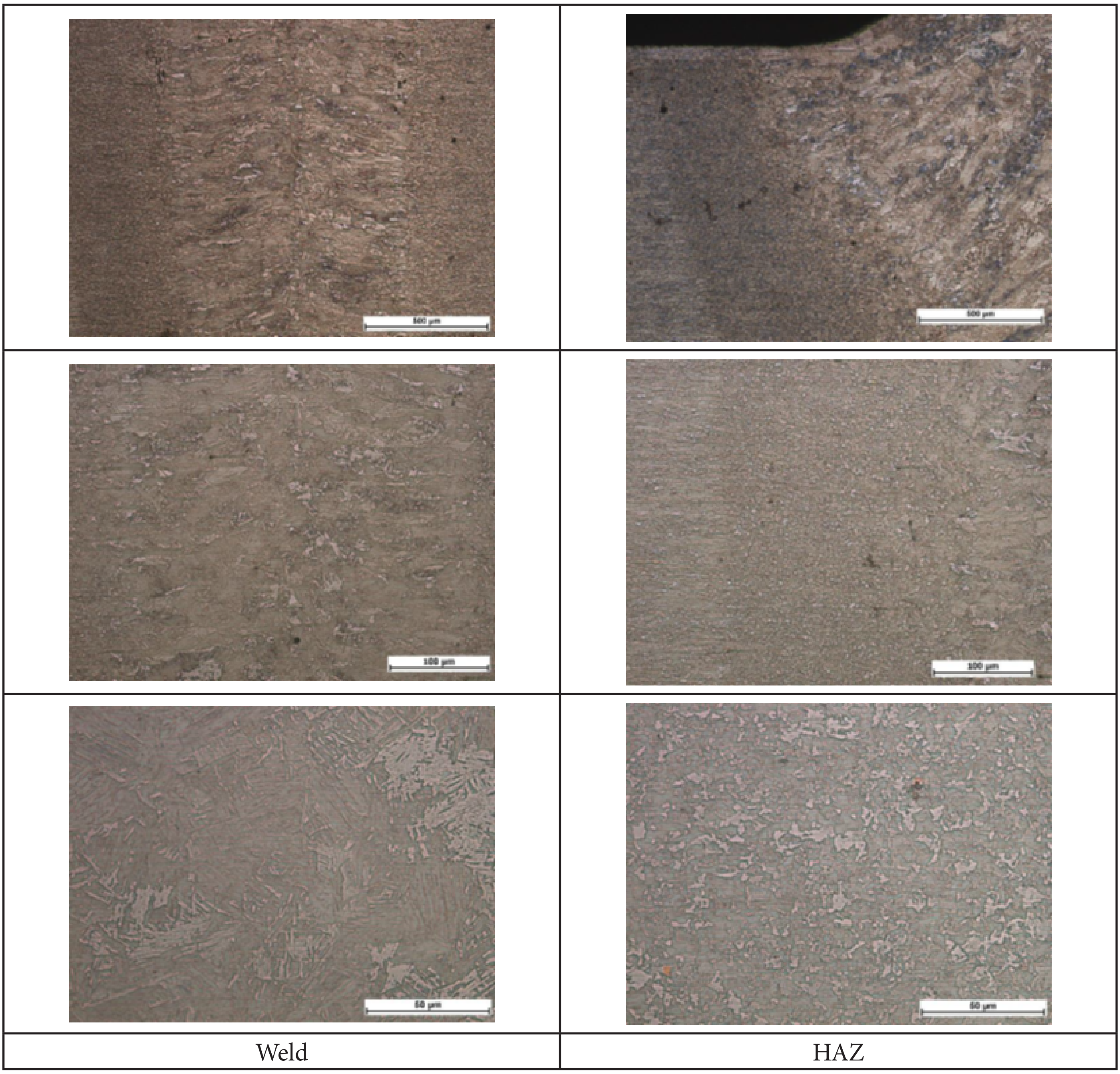


Fig. 6. Microstructure of the welded joint

HV0.2, whereas the maximum hardness in the weld amounted to 331 HV0.2. The hardness-related criterion states that the maximum hardness of welded joints made in unalloyed steels containing microagents should amount to a maximum of 350 HV. The above-named value was not exceeded in any area of the electron beam welded joint. In addition, the gradient of hardness between the individual zones amounted to 49 HV. As a result, the structural notch was not formed. The increase in hardness was primarily connected with the fast discharge of heat and the formation of the martensitic structure in the weld and in the HAZ.

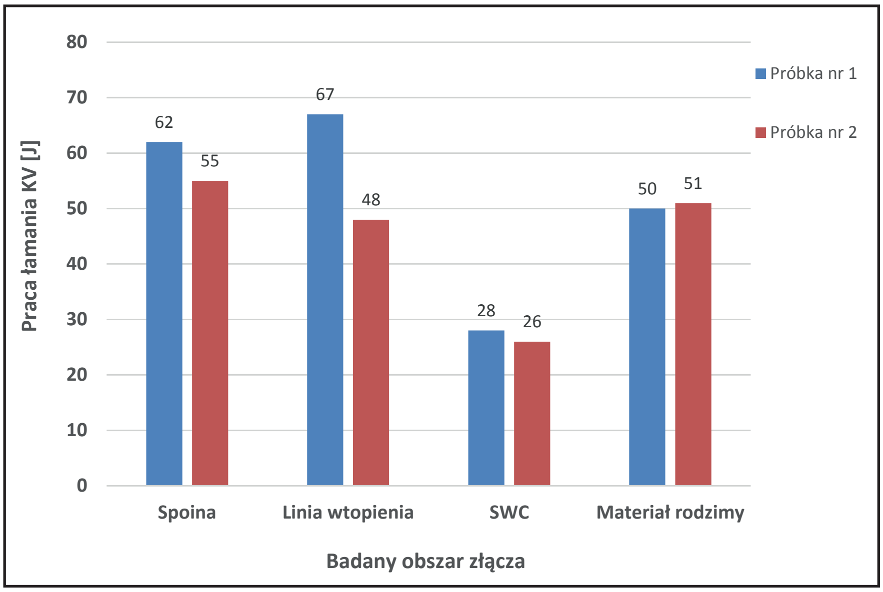


Fig. 7. Toughness of the welded joint

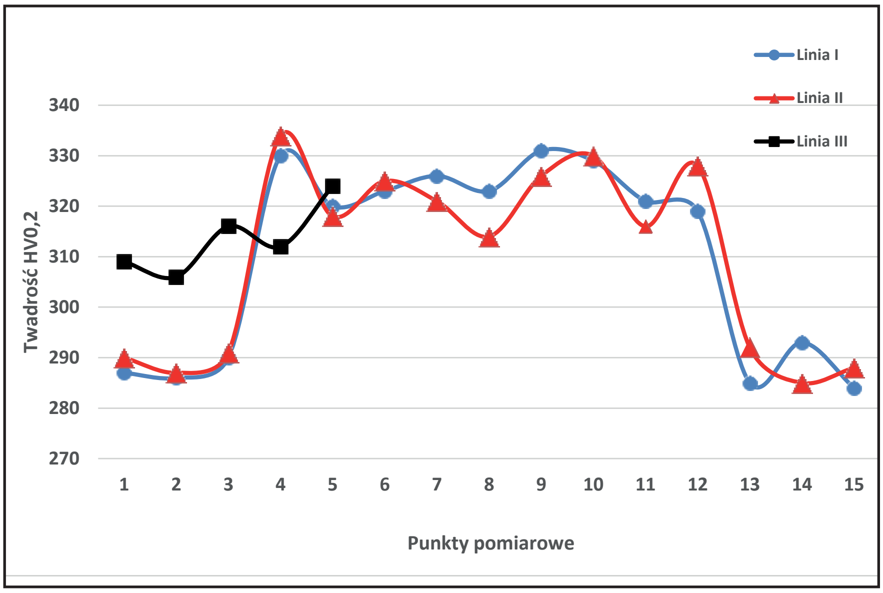


Fig. 8. Distribution of hardness in the welded joint

Summary

The electron beam remelting of the specimen made in steel S700MC enabled the optimisation of welding process parameters. The initial tests confirmed the effect of beam current and accelerating voltage on the depth and width of penetration. It was assumed that the joint would be made using an accelerating voltage of 120 kV and a beam current of 28.5 mA. The above-named parameters enabled the obtainment of a joint characterised by the properly formed root and the face having a proper shape and excess weld metal. The destructive tests revealed that the joint represented quality level B in accordance with PN EN ISO 13919-1. The static tensile tests revealed the high mechanical properties of the joint (rupture took place in the base material area). A full bend angle of 180° was obtained in the bend test; the specimen surface did not contain any partial tear or scratches. The toughness test revealed a decrease in toughness in the HAZ in comparison with that of the base material. The toughness of the HAZ dropped to 27 J/cm^2. The toughness of the base material amounted to 50 J/cm^2. The hardness of the HAZ increased to 330 HV. In none of the joint areas hardness exceeded 350 HV, i.e. the limit value for the type of steel used in the tests. The gradient of hardness between the individual areas of the joint did not exceed 100 HV, indicating that the structural notch had not been formed. The microscopic tests revealed the typical, i.e. fine-grained bainitic-ferritic, structure of TMCP steel S700MC. The weld contained the martensitic structure, whereas the HAZ contained the bainitic structure. The electron

beam butt welded joint made in 10 mm thick TMCP steel S700MC satisfied requirements of related standards. Both the above-presented destructive and non-destructive tests confirmed that the joint was made properly and that it was characterised by appropriate quality as well as mechanical and plastic properties satisfying related acceptance criteria.

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