

Article

An Approach to Assessing S960QL Steel Welded Joints Using EBW and GMAW

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Abstract: In recent years, ultra-high-strength structural (UHSS) steel in quenched and tempered (Q+T) conditions, for example, S960QL has been found in wider application areas such as structures, cranes, and trucks due to its extraordinary material properties and acceptable weldability. The motivation of the study is to investigate the unique capabilities of electron beam welding (EBW) compared to conventional gas metal arc welding (GMAW) for a deep, narrow weld with a small heat-affected zone (HAZ) and minimum thermal distortion of the welded joint without significantly affecting the mechanical properties. In this study, S960QL base material (BM) specimens with a thickness of 15 mm were butt-welded without filler material at a welding speed of 10 mm/s using the high-vacuum (2×10^{-4} mbar) EBW process. Microstructural characteristics were analyzed using an optical microscope (OM), a scanning electron microscope (SEM), fractography, and an electron backscatter diffraction (EBSD) analysis. The macro hardness, tensile strength, and instrumented Charpy-V impact test were performed to evaluate the mechanical properties. Further, the results of these tests of the EBW joints were compared with the GMAW joints of the same steel grade and thickness. Higher hardness is observed in the fusion zone (FZ) and the HAZ compared to the BM but under the limit of qualifying the hardness value (450 HV10) of Q+T steels according to the ISO 15614-11 specifications. The tensile strength of the EBW-welded joint (1044 MPa) reached the level of the BM as the specimens fractured in the BM. The FZ microstructure consists of fine dendritic martensite and the HAZ predominantly consists of martensite. Instrumented impact testing was performed on Charpy-V specimens at -40 °C, which showed the brittle behavior of both the FZ and HAZ but to a significantly lower extent compared to GMAW. The measured average impact toughness of the BM is 162 J and the average impact toughness value of the HAZ and FZ are 45 ± 11 J and 44 ± 20 J, respectively.



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1. Introduction

Ultra-high-strength low alloy steel (UHSS) is now widely used in practice for engineering structures and highly-loaded construction components such as cranes, heavy-duty trucks, and bridges, as well as in the automotive industry due to its outstanding combination of high strength and toughness [1–4]. Other important features that have attracted attention are its good weldability and a high strength-to-weight ratio, which is advantageous when energy-saving is focused on environmental and cost-saving aspects [5–7]. Increasing demand for higher-strength materials with these exceptional qualities has led to the development of several technological methods for enhancing their properties using heat-treatment processes or combining them with different alloying elements [8,9]. The quenched and tempered group is the most frequently-used high-strength structural steel category, and S960QL is the highest grade according to the EN 10025-6 standard, although nowadays higher-strength grades are available but not yet classified using the standard.

HSS can make a significant contribution to supporting sustainable development by reducing the weight of structures and vehicles with increased payload capacity, and by lowering fuel consumption and CO₂ emissions [10–13].

Electron beam welding (EBW) was invented as an innovative welding technological process with significant breakthroughs, with its greater depth of penetration and narrow fusion zone (FZ) being of particular importance [14–16]. It is a fusion welding process in which a high-energy density beam (10^7 W/cm²) [17,18] impinges on the surface of the materials to be welded and vaporizes metals (kinetic energy of high velocity of the electron is used to produce heat energy) [19,20]. It is a low-heat input process with a significantly small heat-affected zone (HAZ) and minimal distortion [21,22]. It was originally intended for use in the nuclear and aerospace industries, but the subsequent developments in the technology (process and equipment) have broadened the application area of EBW [17–23]. Nowadays, it is used in welding and material processing in the construction, automotive, shipbuilding, petrochemical, and medical industries [24].

These HSS could offer superior quality and performance if the EBW process is used, which has a narrower HAZ than is produced in conventional arc welding processes [21,25]. Zhang et al. studied EB-welded joints of 300M type UHSS composed of ferrite, bainite, and primarily austenite, finding that the HAZ is composed of ferrite and cementite, whereas this steel found extensive application in the aerospace industry [13]. Gáspár and Balogh [26] investigated gas metal arc welding (GMAW) of S960QL for a 15 mm thickness plate, identifying optimal mechanical properties obtained at a lower cooling time (5–6 s) with lower linear energy of 0.7 kJ/mm. A numerically simulated result of the EBW process using SYSWELD for a 15 mm thick butt-welded joint with a linear heat input of 0.6 kJ/mm and a welding speed of 14 mm/s obtained a shorter cooling time of $t_{8/5} = 2$ s compared to the GMAW, which predicts the chance for better mechanical properties of EB-welded joints [27].

Błacha et al. [4] in their study related to the EB-welded joint of S960QL for a thickness of 11 mm observed that the tensile strength of the welded joint is at the same level as that of the base material (BM). The maximum macro hardness was found in the HAZ. The different subzones could be distinguished clearly due to differences in morphology and level of hardness. The welding of HSS S960QL can be performed satisfactorily using the EB-welding process without compromising the mechanical properties of the weld. During the conventional arc welding of S960QL steel, the outstanding toughness of the base material is drastically reduced in the HAZ due to the welding heat input [28]; therefore, EBW could be the ultimate way to reduce the areas of the brittle HAZ subzones. Tomków et al. [29] showed that the HSS welding of 960 MPa strength grade is sensitive to heat input. Their study with three different heat input levels (0.63 kJ/mm, 0.72 kJ/mm, and 0.93 kJ/mm) found that cold cracking phenomena can be observed if the heat input is too low or too high.

The weldability of HSS consists of more challenges such as the hardening of the HAZ, and a higher cold cracking sensitivity (CCS), a reduction in strength, or a toughness of the HAZ [30,31]. Nowadays, with the increasing strength of the steels, higher amounts of alloying elements are used, which increases the tendency of higher hardenability resulting in cold cracking in the welded structure [32].

In this paper, an autogenous (without filler wire) single-pass EBW was performed. The main aim was to analyze the mechanical properties and, partially, the microstructural changes of an EB-welded butt joint of S960QL HSS. The microstructure, macro hardness, tensile strength properties, and the toughness with instrumented Charpy V-notch impact tests were examined to evaluate the microstructural changes and joint behavior in the FZ and HAZ. Furthermore, the results of an EB-welded high strength steel joint were compared to a GMA-welded joint for the same material grade and thickness.

2. Materials and Methods

2.1. The Investigated Base Material

The chemical composition of the investigated S960QL base material according to the material certificate and laboratory chemical analysis is summarized in Table 1. Based on the

available chemical composition, the carbon equivalents CEV (according to EN 1011-2:2001 Annex C, Method A) and CET (according to EN 1011-2:2001 Annex C, Method B) were calculated. The carbon equivalents CEV and CET are mentioned in Equations (1) and (2), respectively.

$$\text{CEV} = \text{C} + \frac{\text{Mn}}{6} + \frac{\text{Cr} + \text{Mo} + \text{V}}{5} + \frac{\text{Ni} + \text{Cu}}{15} \quad (1)$$

$$\text{CET} = \text{C} + \frac{\text{Mn} + \text{Mo}}{10} + \frac{\text{Cr} + \text{Cu}}{20} + \frac{\text{Ni}}{40} \quad (2)$$

Table 1. Chemical composition of the investigated S960QL steel in wt%.

	Chemical Composition (wt.%)													
	C	Si	Mn	P	S	Cr	Ni	Mo	V	Ti	Al	Nb	B	N
1	0.170	0.230	1.23	0.011	0.0010	0.200	0.04	0.588	0.041	0.004	0.061	0.017	0.0010	0.002
2	0.147	0.216	1.22	0.010	0.0007	0.178	0.04	0.576	0.031	0.001	0.054	0.011	0.0009	0.019

1. According to EN 10204 3.1 material certificate provided by the steel producer. 2. Laboratory chemical analysis (own measurement data).

The carbon equivalent values for the S960QL base material are CEV = 0.55, CET = 0.36. The microscopic images (OM and SEM) of the tempered martensite base material, S960QL, are presented in Figure 1.

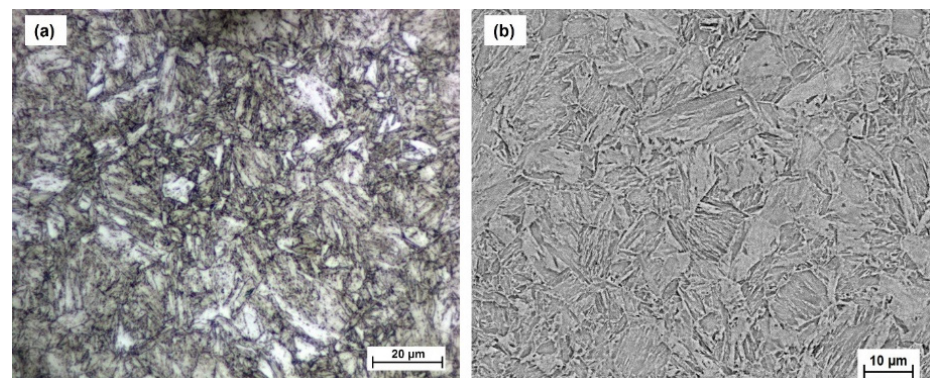


Figure 1. S960QL base material microstructure. (a) Optical micrograph; (b) SEM micrograph, M = 1000× (2% Nital).

The required and the measured mechanical properties of the examined S960QL HSS according to the material certificate are summarized in Table 2.

Table 2. Mechanical properties of the investigated S960QL steel.

S960QL	Mechanical Characteristics				
	R _{p0.2} MPa	R _m MPa	R _{p0.2} /R _m	A ₅ %	CVN (at −40 °C) J
Requirement EN 10025-6	≥960	980–1150	-	≥10	≥27
¹ Material certificate	1014	1053	0.96	14	75
Own measurement (BM)	996	1039	0.96	17	162

¹ According to EN 10204 3.1 material certificate provided by the steel producer.

2.2. Experimental Procedure

The base metal (BM), WELDOX 960 E (S960QL in EN 10025-6), a product of SSAB (Stockholm, Sweden), was used for the welding experiment. The steel plate of thickness 15 mm was cut into pieces of 300 mm × 150 mm each for a butt-welded joint (according

to EN 15614-11:2002) using a plasma cutting machine. The area of the HAZ of plasma cutting was removed by machining before the welding. A backing plate from the same thickness was used for EBW in single pass with not-through penetration mode to get better results, supporting the molten materials in the weld pool to ensure the welding of the full thickness of the material, and to exclude the possibility of root cavities and spiking [17], forming an assembled unit with the original butt-welded joint. The backing plate material was the same as the BM and was cut into the dimensions of 300 mm $\times$ 50 mm. Before welding, the edges of the samples were cleaned and milled, the base of the specimen from the joining edge on both samples and the surface of the backing plate was properly cleaned and carefully machined to secure precise assembly for EBW with the maximum allowable air gap of 0.15 mm along all the joint lengths, as shown in Figure 2a. Precise machining and proper assembling are the most important factors to obtain a good quality EB-welded joint. The sample was tack welded at a few positions by manual tungsten inert gas (TIG) welding using the copper-coated solid wire UNION X96 (G 89 5 M21 Mn4Ni2.5CrMo according to EN ISO 16834-A standard) filler material before final EBW. The clamping device was prepared according to the specimen size as shown in Figure 2b for the required EB-welded joint. The specimens to be welded were kept with welding fixture to hold the plate rigidly and minimize the distortion, as shown in Figure 2b.

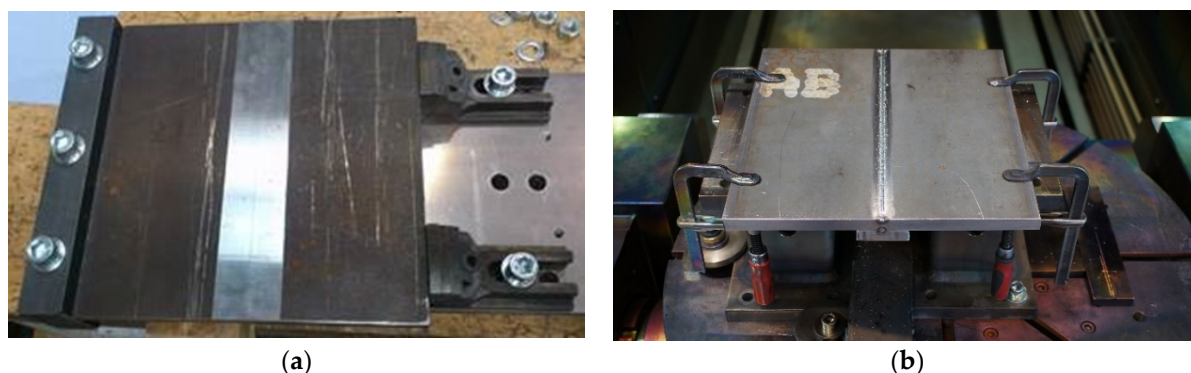


Figure 2. (a) Clamping device; (b) Clamp configuration in EB welding of S960QL specimen.

Several preliminary tests were conducted to determine the EBW parameters in full-depth penetration conditions. The optimal parameters used in the present study are mentioned in Table 3. The welding was performed at a speed (v) of 10 mm/s, accelerating voltage (V_a) of 150 kV, beam diameter (d_b) of 0.4 mm, and a beam current (I_b) of 49 mA. The working distance (WD) in the welding process was selected as 500 mm and chamber ceiling to surface of the workpiece distance was 284 mm.

Table 3. EBW optimal parameters.

Steel	Process	V_a (kV)	I_b (mA)	v (mm/s)	d_b (mm)	WD (mm)
S960QL	EBW	150	49	10	0.4	500

The welding was done in a single pass without a filler metal addition and with no preheating. The EBW was performed using EBOCAM EK74C–EG150–30BJ EBW in vacuum conditions, 2×10^{-4} mbar (1.97×10^{-7} atm), and the same level was maintained in the electron gun and work chambers. The EB-welded samples were then allowed to cool in chamber for a few minutes to avoid any oxidation and moved outside for further cooling. The linear heat input was calculated using Equation (3) [33,34] with parameters provided in Table 3 and efficiency ($\eta = 0.9$) [21] as 0.661 kJ/mm.

$$Q = \eta \frac{V_a I_b}{v} \quad (3)$$

GMAW experimental details of the resulted joints are presented in brief to understand the comparative results of EBW with GMAW process highlighted in this paper. The welded joints were made by GMAW (ISO 135) using M21 (82% Ar + 18% CO₂) shielding gas according to ISO 14175. The plate thickness was 15 mm, and single side butt welds were prepared with V-joint type. The filler wire used to produce the welded joint was UNION X96 (G 89 5 M Mn4Ni2,5CrMo according to ISO 16834), diameter 1.2 mm. The chemical composition and mechanical properties of the filler metal are depicted in Tables 4 and 5, respectively. The welding parameters for GMAW are summarized in Table 6.

Table 4. Chemical composition of filler metal (UNION X96) in mass percent.

C	Si	Mn	Cr	Ni	Mo	V	Ti	Cu	Al	Zr	B
0.11	0.76	1.90	0.35	2.23	0.57	0.004	0.057	0.002	0.002	0.001	0.000

Table 5. Guaranteed mechanical properties of investigated filler metal.

Filler Metal	R _{p0.2} , MPa	R _m , MPa	A ₅ %	CVN, (at −40 °C)
UNION X96 *	930	980	14	40

* Standard minimum values in EN 16834-A

Table 6. GMAW welding parameters.

Pass Number	T _{pre/interpass} , °C	v, mm/s	I, A	U, V	Q, kJ/mm	t _{8/5} , s
Root	190	3	117	18.5	0.6	5.5
2	150	7	247	24.6	0.7	6
3–9	150	9	285	27.8	0.7	5

After welding, microstructural and mechanical properties of the EBW joints were investigated. The samples for OM and SEM observations were sectioned through the weld in transverse direction. The sectioned samples were polished with SiC waterproof papers in series of 120, 400, 800, and 2000 ANSI grit and finally with a disc using diamond paste of 1 µm. The specimens were then etched with Nital (2% HNO₃) for 10 s. The sample preparation for EBSD [35,36] analysis was made by Technoorg's (Budapest, Hungary) SEMPrep (model SC-2000) noble gas ion mill using its focused high-energy ion source. To create large ion polished zones of about 1 cm² area, the steel samples were rotated for 26 min during low-angle (7°) argon ion bombardment. The high-energy ion source was operated in high-vacuum environment at dynamic argon pressure of 3.4×10^{-4} mbar, with anode voltage of 10 kV and focus voltage of 5 kV. The specimen for the metallography study was comprised of BM, HAZ, and FZ. The microstructural examination was carried out using an OM (Axio Observer D1m (Zeiss, Oberkochen, Germany) inverted microscope), SEM, and EBSD (Zeiss Evo MA10). The Vickers macro hardness (ISO 22826: 2005, Geneva, Switzerland) of the BM, HAZ, and FZ was tested by Reichert UH 250 Universal (BUEHLER Worldwide Headquarters, Lake Blu, IL, USA) hardness testers with a 10 kgf (or test force of 98.07 N) load and with a 10 s dwell time. Instrumented Charpy V-notch impact tests (according to EN ISO 14556) were done by PSD 300/150 instrumented impact testing equipment (WPM Werkstoffprüfsysteme GmbH, Markkleeberg, Germany). equipment and fractured surface was observed by SEM. Tensile test was executed with ZD 100 (1000 kN) hydraulic materials testing equipment at room temperature and the specimens used for mechanical tests were designed according to the ISO 4136:2012 standard.

3. Results and Discussion

3.1. Comparison of FZ and HAZ Shape Characteristics for EBW and GMAW

Figure 3 shows a comparison of experimentally observed (Stereo Microscope) fusion zone cross sections for the EB-welded and GMAW S960QL butt-welded HSS. The fusion

zone is indicated by a yellow marked line (liquidus temperature, T_{liq}). The black line indicates the A_1 line temperature, which represents the visible HAZ region of the welded joint [37]. The experimental results showed that the weld depth, average full weld width (FZ), and average HAZ width of the EB-welded joint were 17.9, 1.576, and 1.029 mm, respectively, and the corresponding values for GMA-welded joint were 17, 15.8, and 3.11 mm, respectively. Tümer et al. [38] observed that the CGHAZ width in EBW was only 0.5 mm at the face area, whereas the width of the same subzone obtained with a metal active gas (MAG) arc-welding process is about 3 times wider. The experimentally calculated EB weld fusion cross-section area and HAZ area are 28 mm^2 and 34 mm^2 , respectively, and the corresponding values for the GMA-welded joint are 257 mm^2 and 95 mm^2 , respectively. The process variables comparison of GMAW and EBW is presented in Table 7.

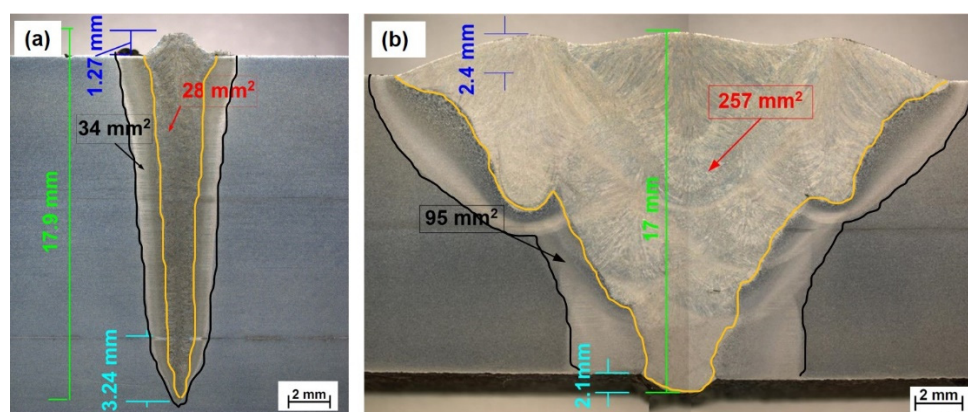


Figure 3. Calculated cross-section area of FZ, HAZ and depth of penetration. (a) EBW; (b) GMAW, $M = 6.5 \times (2\% \text{ Nital})$ data from [26].

Table 7. Comparison of GMAW and EBW process variables.

Steel	Process Variable	GMAW	EBW
S960QL	Weld pass	9	1
	Filler material	Yes	No
	Speed (mm/s)	3–10	10
	Linear heat input (kJ/mm)	0.6 (root pass) 0.7 (2nd–9th pass)	0.661
	Welding time (s)	$40 \times 9 = 360$ (9 passes)	30

The performed visual inspection of the welded joint and the macro test of the cut section through the weld in the transverse direction showed no imperfections or cracks.

3.2. Microscopic Tests

As illustrated in Figure 4, the HAZ can be divided into subregions: coarse-grained HAZ (CGHAZ), fine-grained HAZ (FGHAZ), and intercritical HAZ (ICHAZ). Energy dispersive X-ray spectroscopy (EDS) was performed in the FZ to study the distribution of chemical elements and to determine the precipitates behavior.

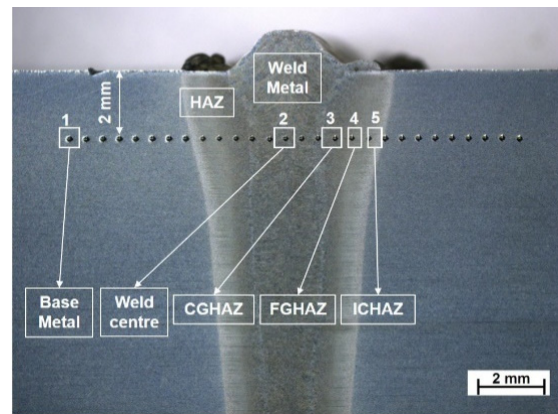


Figure 4. Schematic photograph from welded cross section showing the areas where SEM micrographs were taken (2% Nital).

The microstructure of the as-received S960QL base material consists of tempered martensite as shown in Figure 1a,b.

The SEM micrograph of the fusion zone in Figure 5(2) shows that it consists of a fine dendritic martensitic microstructure whose orientation is nearly perpendicular to the weld centerline (weld pool). This happened during fusion zone solidification when grains tend to grow in the direction of the maximum heat extraction. The nucleation of prior austenite grains at the fusion boundary is caused because it is energetically more favorable [13,39]. The different subzones of the HAZ (CGHAZ, FGHAZ, and ICHAZ) are clearly identified by their distance from the weld face. However, the microstructure of the HAZ depends on the distance from the fusion boundary line, as different heating cycles and temperatures are experienced by the HAZ. The CGHAZ area, Figure 5(3) near the fusion boundary line, is fully composed of rough lath martensite. The FGHAZ area, Figure 5(4), primarily constitutes martensite in accordance with the hardness measurement. The area near the vicinity of the base material, i.e., the ICHAZ, Figure 5(5), is composed of a mixture of tempered martensite and M-A parts. Thus, the HAZ microstructure predominantly consists of martensite.

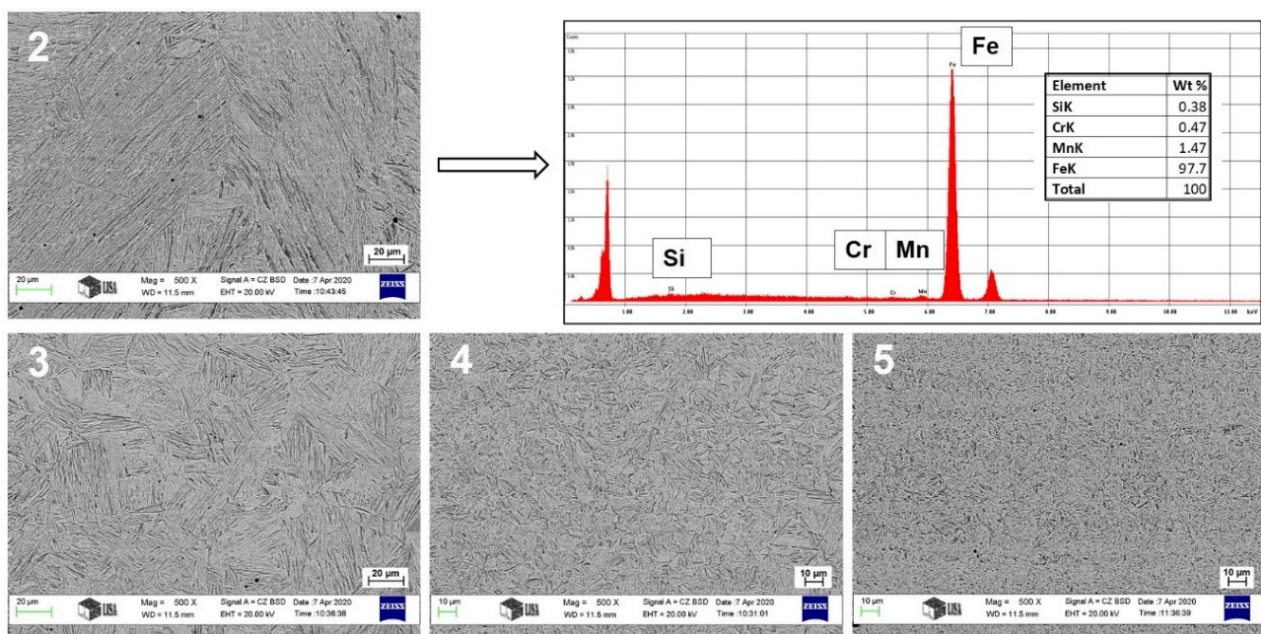


Figure 5. SEM micrographs of different subzones of the EB-welded joint, S960Q steel. 2—Fusion zone and EDS spectrum of FZ; 3—CGHAZ; 4—FGHAZ; 5—ICHAZ (2% Nital).

The EBSD figures of the BM, FZ, and HAZ are presented in Figure 6. The orientation inverse pole figures (IPF) color-patch map of the microstructure of the grain in the BM (top), the FZ (middle), and the HAZ (bottom) are shown in Figure 6a. The image quality (IQ) figures of the microstructures of the grains in the BM (top), the FZ (middle), and the HAZ (bottom) are shown in Figure 6b. In Figure 6c, a stereographic triangle represents the connection between the colors and crystal orientations. Equiaxed grains are observed near the weld centerline, as shown in Figure 6b. Compared with the base material, the HAZ grains are very fine, long lath types, whereas the FZ grains are coarser crystals (both the columnar and equiaxed structures). The characteristics of lath martensite morphology can be seen in a clearer way in EBSD compared to OM and SEM. Precise quantitative analysis of the grain-size distribution cannot be provided due to the complexity of the microstructure having a mixture of grains, subgrains, and lath boundaries.

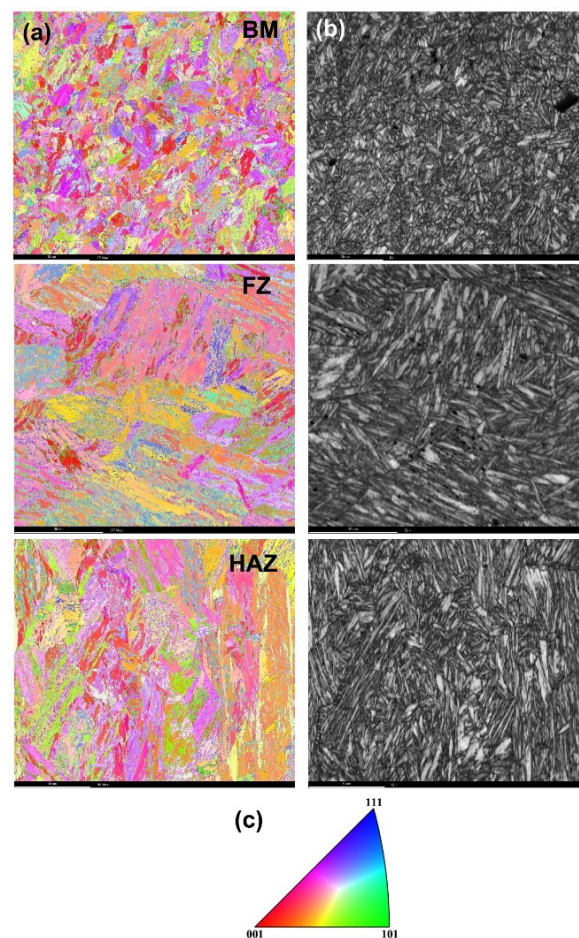


Figure 6. EBSD images EB-welded joint, S960QL steel; Top: BM, Middle: FZ, and Bottom: HAZ, (a) Inverse pole figures; (b) Image quality figures; (c) Inverse pole figure key.

3.3. Hardness Test

The macrohardness tests were performed in accordance with the ISO 22826:2005(E) standard practices of EB-welded joints using a Reichert UH250 universal macro hardness tester with a 10 kg load and a 10 s dwell time. The evaluation was performed according to the EN ISO 15614-11 standard which permits $HV_{max} = 450 HV_{10}$ for the non-heat-treated welded joints (including HAZ) of quenched and tempered high-strength steels belonging to the 3rd group of CR ISO 15608. The macro hardness value was measured over the weld cross-section in three lines (top, middle, and bottom) of a simple macro test specimen with dimensions of $67 \times 14 \times 15$ mm from the transversal cross-section of the welded joint after the surface preparation using grinding and polishing. The macro indentations taken

in three horizontal directions of different regions (BM, HAZ, and FZ) of an EB-welded specimen for S960QL are shown in Figure 7a, and the GMAW hardness graph for the face and root side is shown in Figure 7b.

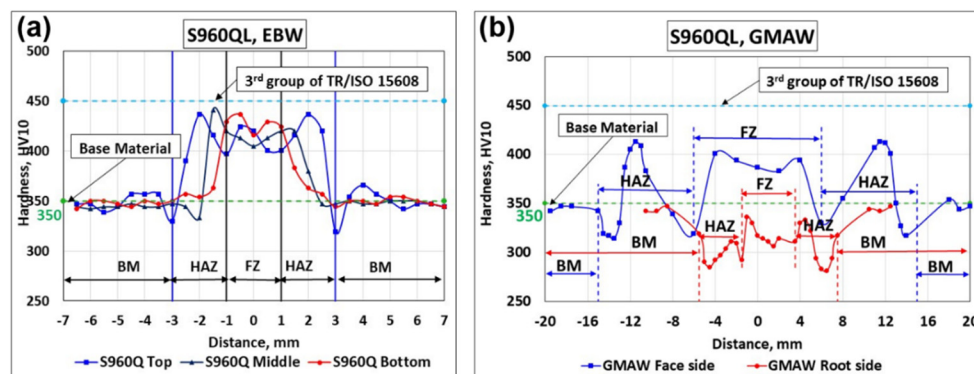


Figure 7. The macro hardness distribution. (a) Macro hardness graph, EBW; (b) Macro hardness graph, GMAW data from [26].

The measured macro hardness of the as-received base metal S960QL was approximately 350 ± 7 HV10. The macro hardness measurement obtained in all three lines of the welded joint follows a similar trend. However, the average hardness in the FZ is slightly less than in the HAZ; the hardness in the HAZ was highest among the three zones (BM, HAZ, and FZ). This variation in hardness value is closely associated with the microstructural transformation. The average hardness at the centerline of the FZ was 414 ± 6 HV10, which is approximately 20% higher than the average hardness of the BM. Tümer et al. [38,40] demonstrated in their study that for EBW of S1100 HSS, the average hardness of the EBW fusion zone is about 420 HV0.2, which is approximately 10% higher than the average hardness of the BM, mainly due to the martensitic microstructure resulting from the high cooling rate during the EBW process. The highest hardness of the HAZ near the fusion line was observed in all three lines which corresponds to the FGHAZ, and the hardness values decreased further as we moved along the BM. An increased hardness in the CGHAZ and FGHAZ was observed since the base metal fully transformed into martensite after austenitization.

The hardness measurement values for the EBW and GMAW joints are presented in Tables 8 and 9, respectively.

Table 8. Hardness test (HV10) results of EB-welded S960QL joint.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Top	347	347	339	344	357	357	357	330	390	437	416	397	424	420	401
Middle	344	342	344	344	347	344	344	347	344	333	441	420	413	405	413
Bottom	342	350	350	347	344	350	347	350	357	354	363	429	437	416	429
	16	17	18	19	20	21	22	23	24	25	26	27	28		
Top	401	416	437	420	319	354	366	357	350	342	347	347	344		
Middle	420	420	380	347	347	350	347	347	350	350	350	347	344		
Bottom	424	383	363	357	344	350	350	347	354	354	350	347	344		

Table 9. Hardness test (HV10) results of GMA-welded S960QL joint.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Face	342	347	347	342	319	317	314	330	387	405	413	409	383	339	319	401
Root	342	342	347	319	290	285	292	297	304	311	309	292	336	330	317	314
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Face	394	387	383	394	330	355	407	413	412	401	350	327	317	354	344	347
Root	311	306	314	311	330	333	322	294	283	281	294	317	344	342	347	

The highest hardness in the HAZ was 441 HV10 measured in the middle line and the second highest in the top line at 437 HV10, which can be clearly observed in Figure 7a.

Blacha et al. [4] found that the maximum hardness value in the HAZ was 447 HV10 and the average hardness value of the FZ was 433 HV10, while considering the top-line hardness measurement at the same material grade. Gáspár and Balogh [26] observed a maximum hardness value of 413 HV10 in the HAZ and the average hardness in the FZ was 370 HV10 for the face side of the GMAW S960QL joint, whereas in the case of the root HAZ the maximum hardness was 333 HV10 and the average FZ hardness was 315 HV10 with a linear energy of 0.7 kJ/mm and a shorter cooling time (5–6 s). Here, a modest variation in the hardness value in the top, middle, and bottom of the EB-welded specimen was observed, which was mainly related to the different thermal gradients in the thickness. However, a little softening can be seen in the ICHAZ area close to A₁ due to the tempering of the martensite and the small number of brittle zones. In the GMAW-welded joint, the FZ also has a higher average hardness compared to the HAZ in both the face side and the root side, although in this case the higher hardness was achieved by the use of filler metal. It can be seen in Figure 7b that the average hardness decreased drastically in the root side, both in the HAZ and the FZ, even below the level of the BM, due to the tempering effect of multipass welding, which did not occur during EBW due to the single-pass weld.

3.4. Transverse Tensile Test

The transverse (perpendicular to welding direction) tensile tests were performed on EB-welded specimens in accordance with the ISO 4136:2012 standard. Butt-welded joints were used to make tensile test specimens. The schematic view of the transverse tensile specimen with its dimensions is given in Figure 8. The tensile test was conducted at room temperature with ZD 100 (1000 kN) hydraulic tensile testing, and the ultimate tensile strength of all the welded specimens was determined. The specimens were milled and etched to view the FZ and the HAZ from the welded sheets to see the fracture along the welded specimens. The fractured specimen of the tensile tests is shown in Figure 9.

Table 10. Tensile properties of EBW and GMAW S960QLwelded joints.

Steel	Sample No.	EBW			GMAW [26]		
		Force (kN)	Tensile Strength (Mpa)	Fracture Location	Avg. Tensile Strength (Mpa)	Linear Energy (kJ/mm)	Fracture Location
S960QL	1	397	1038	BM	1030	0.7	BM
	2	384	1049	BM	977	1	ICHAZ

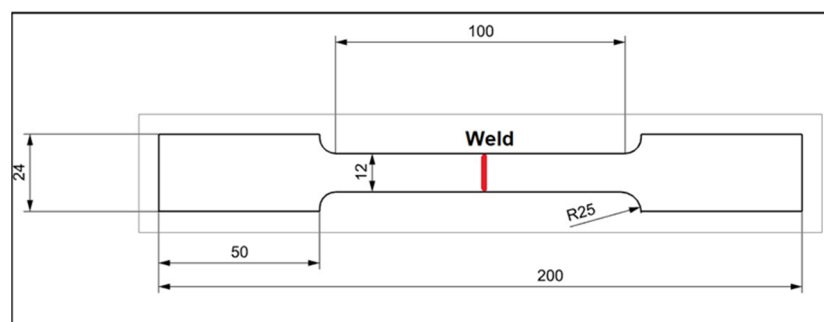


Figure 8. Schematic representation of tensile tested specimen (all dimensions in mm).

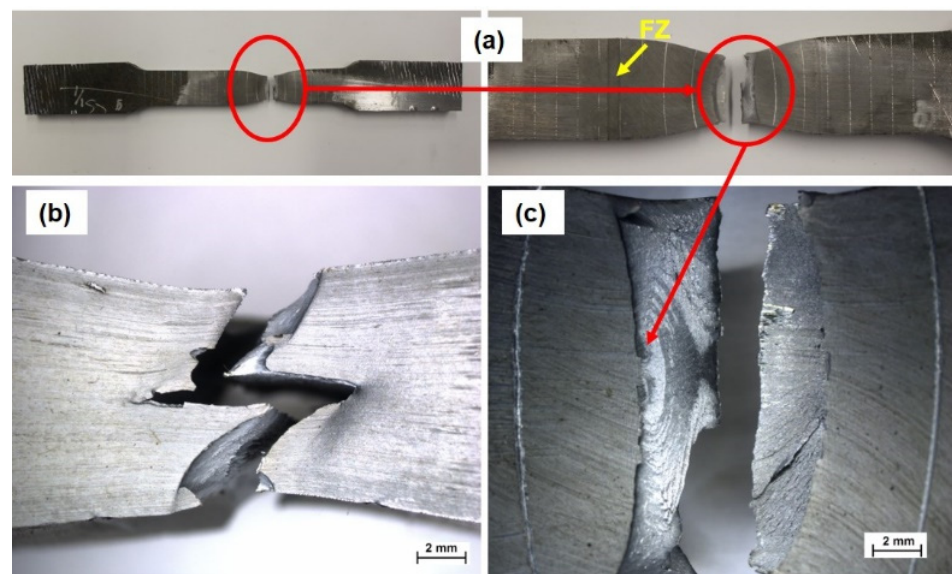


Figure 9. Tensile test specimen. (a) fractured sample; (b) side view of fractured section; (c) front view.

The comparative tensile test results of EBW and GMAW joints are given in Table 10.

The tensile strength of the BM was 1053 MPa, according to the EN 10204 3.1 material certificate provided by the steel producer; however, we measured 1039 MPa during our own investigations. According to EN 15614-11, the tensile strength of the test specimen should not be less than the corresponding specified minimum value for the base metal, which is 980 MPa in this case (according to EN 10025-6). However, the measured tensile strengths of the EBW samples were 1038 MPa and 1049 MPa, which were approximately the same as the BM strength. Also, it was observed that all failures in the tested EB-welded samples occurred in the BM, not in the welded part, as shown in Figure 9. Blacha et al. [4] in investigating EBW of HSS S960QL, also observed that the tensile strength of the EBW-welded joints was at the same level as the BM, and rupture took place out of the weld. Gáspár and Balogh [26] showed that the average tensile strength of an S960QL GMAW joint for the same thickness was 1030 MPa, the cooling time was ($t_{8/5}$) 5–6 s, and the linear energy was 0.7 kJ/mm, which is quite close to the experimental linear energy used in this paper for EBW, i.e., 0.6615 kJ/mm. When the GMAW linear energy was increased to 1 kJ/mm, the cooling time was 10 s, and the corresponding average tensile strength of the welded joints was 977 MPa [26]. Therefore, it can be concluded from the above comparison that the average tensile strength of GMAW is nearly the same level of linear energy input as that of the EBW process, whereas in the case of the GMAW joint for a higher linear energy input with a cooling time of 10 s, the corresponding average tensile strength of the welded joint decreased to 977 MPa, which is below the required minimum limit of 980 MPa. The effect of the softened HAZ subzone (ICHAZ) is less significant due to its limited extension of EBW and overlapping of different HAZ subzones, especially in the GMAW joint at shorter cooling times. The results are in accordance with some previous investigations. Hochhauser et al. [41] showed that in HSS the tensile strength is not significantly compromised by a softening in the HAZ, which can be explained by the narrow HAZ size, the constraint effect of the base metal, and the high strength of the weld metal. According to their conclusions, low-heat-input welding processes keep the soft zone small and the strength high. Therefore, using EBW the same strength welded joint was prepared as in GMAW but without the application of filler material.

3.5. Instrumented Charpy V-Notch Test

The instrumented Charpy V-notch pendulum impact test was performed in accordance with EN ISO 14556 standards to evaluate the impact toughness of the BM, HAZ, and FZ using PSD 300/150 instrumented equipment. Specimens incised in the FZ are marked

VWT, and specimens incised in the HAZ are marked VHT. The standard dimensions and incised position in the specimens are illustrated in Figure 10. In the figure, the notation “a” is the distance of the center of the notch from the reference line, $a = 0.75$ mm, and “b” is the distance from the weld joint face side to the nearest face of the test specimen, $b = 3$ mm. The Charpy V-notch impact test was done to quantify the toughness of the welded joints at the guaranteed operating temperature of the base material [42]. For S960QL steel, in accordance with EN 10025-6 the required minimum impact energy is 27 J at -40 °C. According to the material certificate, the investigated steel plate has a 75 J CVN, although 162 ± 46 J was measured during the performed impact test of the base material. The five Charpy V-notch specimens with dimensions of $10 \times 10 \times 55$ mm at -40 °C for BM, HAZ, and FZ were tested. The fracture surfaces of the tested samples (whose average value is nearest among one of the five tested samples) were obtained for the BM, HAZ, and FZ and examined via SEM equipped with three-dimensional (3D) fractographic imaging analysis; results are shown in Figures 11–13.

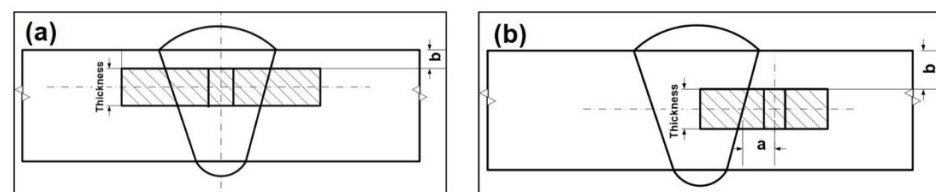


Figure 10. Charpy V-notch impact test specimen sizes per EN ISO 9016:2011. (a) VWT; V-notch in fusion zone; (b) VHT; V-notch in HAZ (all dimensions in mm).

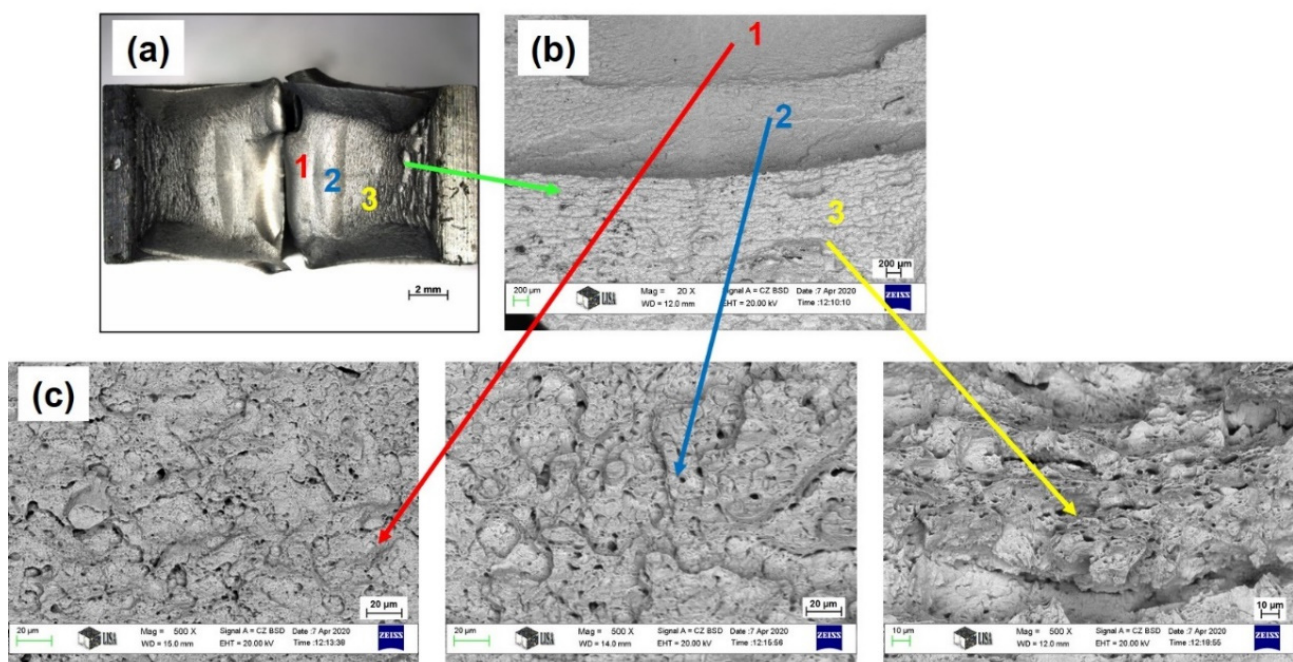


Figure 11. (a). BM Charpy V specimen at a test temperature of -40 °C; (b) SEM photo of full-fractured surface having three zones; (c) fractographs of three zones.

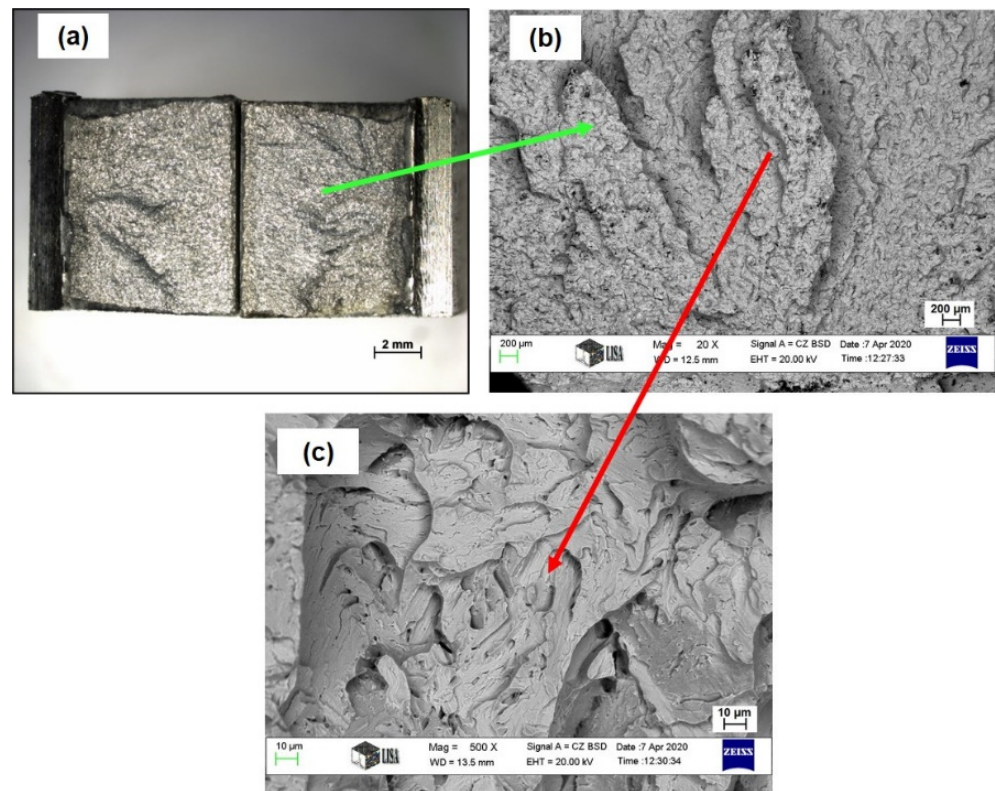


Figure 12. (a). HAZ Charpy V specimen at a test temperature of $-40\text{ }^{\circ}\text{C}$; (b) SEM photo of full-fractured surface; (c) fractograph.

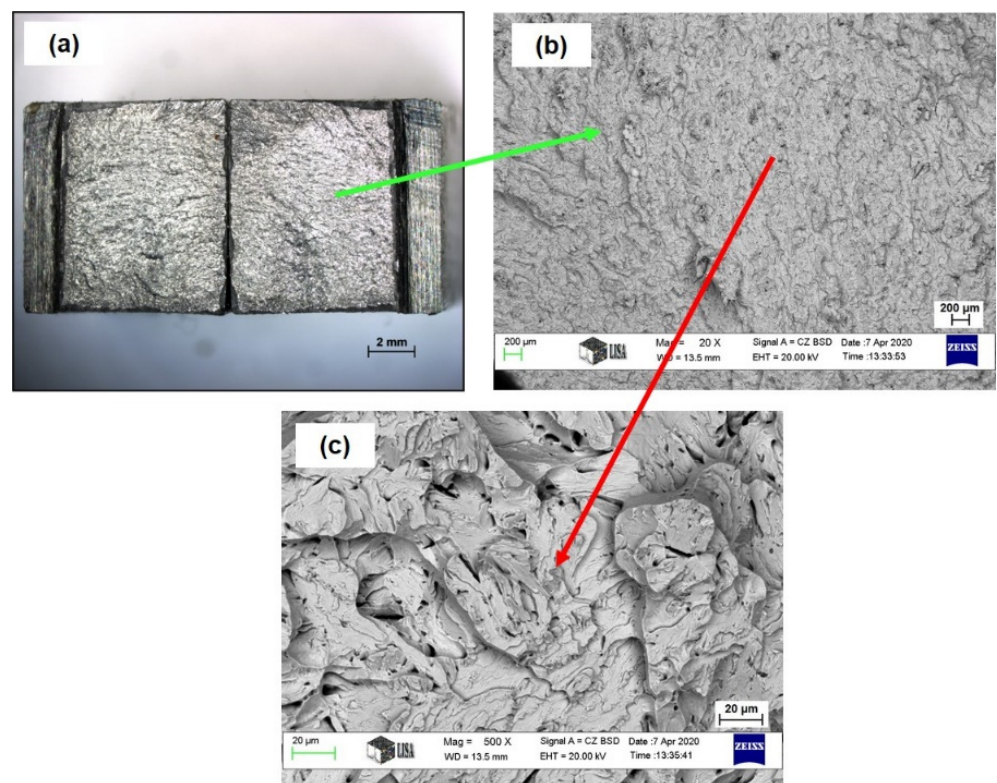


Figure 13. (a). FZ Charpy V specimen at a test temperature of $-40\text{ }^{\circ}\text{C}$; (b) SEM photo of full-fractured surface; (c) fractograph.

In Table 11, the CVN values of the real EB-welded joints from the investigated S960QL material are presented with the average (Avg.) CVN and the standard deviation (Std. Dev.) of CVN, where, W_i is the crack initiation, W_p is the crack propagation, and “e” is the expansion in mm. In Table 12, the CVN values of the S960QL GMA-welded joints are presented.

Table 11. Measured CVN values of EB welded S960QL joints.

Zone	S. No.	CVN, J	CVN, Avg. (J)	CVN, Std. Dev. (J)	F_{max} , kN	W_i , J, (%)	W_p , J, (%)	e (mm)
BM	1	206	162	46	29	41 (20)	165 (80)	2.01
	2	135			29	36 (27)	99 (73)	1.33
	3	85			28	17 (20)	68 (80)	0.83
	4	184			32	39 (21)	145 (79)	0.84
	5	199			30	38 (19)	161 (81)	1.29
HAZ	1	43	45	11	34	35 (82)	8 (18)	0.11
	2	39			31	34 (88)	5 (12)	0.31
	3	27			29	25 (94)	2 (6)	0.3
	4	57			33	50 (88)	7 (12)	0.39
	5	57			33	48 (85)	9 (15)	0.45
FZ	1	64	44	20	34	61 (96)	3 (4)	0.55
	2	20			31	17 (87)	3 (13)	0.07
	3	55			34	41 (74)	14 (26)	0.32
	4	62			32	37 (59)	25 (41)	0.43
	5	20			28	17 (83)	3 (17)	0.18

Table 12. Charpy V-notch impact test results on GMA-welded S960QL joints data from [26].

Zone	$t_{8/5}$, s	F_{max} , kN	CVN, J	W_i , J, (%)	W_p , J, (%)
HAZ	5–10	-	44	-	-
HAZ	20–30	-	26	-	-
FZ	5–10	-	43	-	-
FZ	20–30	-	38	-	-

The average impact toughness of the BM is 162 J and the average impact toughness value of the HAZ and FZ are 45 ± 11 J and 44 ± 20 J, respectively. This clearly shows that there is a decrease in HAZ and FZ toughness values compared to the BM, and the average toughness values of the HAZ and FZ are similar. In particular, the weld metal toughness depends upon many factors such as the amount of martensite transformation, carbide precipitation, and grain size. By comparing the impact test results of the EBW and GMAW joints, it can be concluded that the measured impact energy values are in the same range since the 43 J average value was measured in the weld zone and the 44 J average value in the HAZ at the low-heat-input GMAW process. With the increase in welding heat input (and therefore the value of $t_{8/5}$), the impact energy values decrease both in the weld and the HAZ of the GMAW joints [26]. It can be remarked that the same toughness level can be achieved in the weld zone with EBW as with GMAW without the application of filler metal.

The instrumented Charpy V-notch impact testing was used because it provides more detailed information about the fracture process and the ductile/brittle behavior of the material than the conventional Charpy V-notch impact test, which can only provide the whole energy absorbed during the fracture. The experimental set-up of the instrumented Charpy V-notch pendulum impact tests is shown in Figure 14a. With the strain gauge measurement technique, the load-time graph was obtained and the characteristic points of the fracture process were identified (the start of the plastic strain, maximal force, start and end of the unstable crack propagation). In the registered graph, the unstable crack propagation stage was correlated with the amount of brittle fracture on the fracture surface. From the load-time graph, the force-displacement graph was calculated. Considering that the crack initiation occurs at the maximal force, the registered graph was divided into two parts according to the maximal force. Until the maximum force, the area under

the curve was considered as the absorbed energy for crack initiation (W_i), whereas the rest for crack propagation (W_p). The toughness of the examined material reduces with the increase of the absorbed energy ratio for the crack initiation [43]. The edges show the cleavage cracking in all subzones; however, the fractured surface appears completely smooth due to its polycrystalline structure. The different fracture features can be clearly seen in Figures 11–13. A brittle fracture with a low number of ductile parts was detected in the registered force–displacement diagrams (VWT and VHT) despite the fulfillment of the 27 J CVN criteria at $-40\text{ }^{\circ}\text{C}$ since the absorbed energy mostly consisted of the crack initiation energy. Previous studies [28] verified that the critical, local toughness reduction in the HAZ of the investigated S960QL cannot be avoided by the simple modification of the welding parameters (by the modification of $t_{8/5}$ cooling time range), therefore one possible solution is to minimize the extension of the HAZ. By using EBW, the area of the HAZ, including the brittle subzones CGHAZ and ICHAZ, can be reduced by three times.

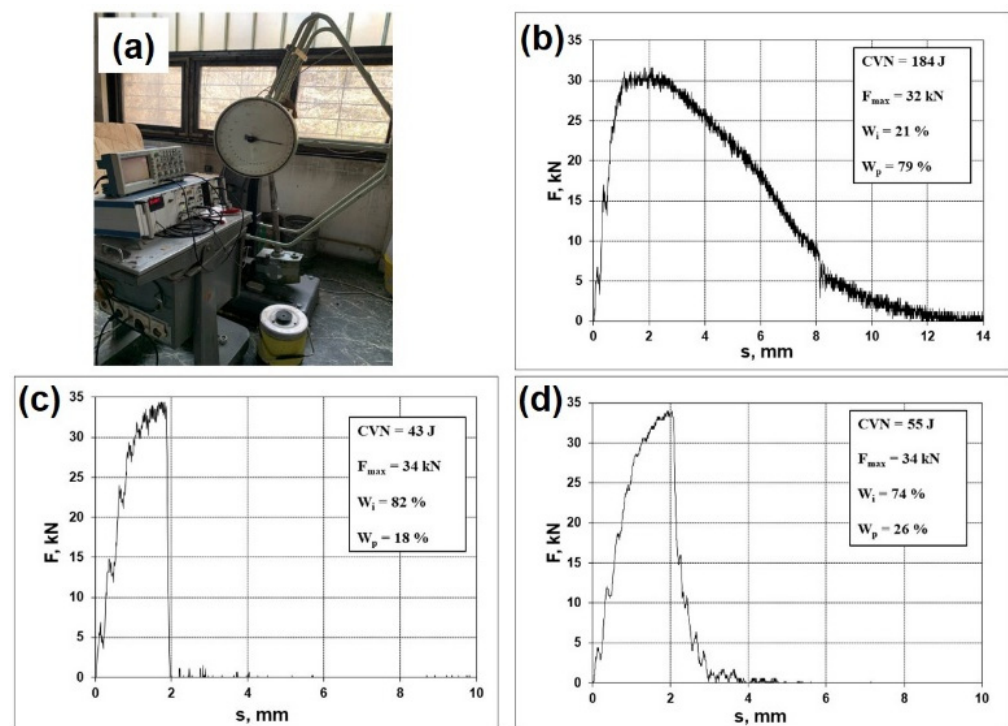


Figure 14. (a) Experimental setup of Instrumented Charpy V-notch impact test; Force displacement graphs; (b) BM; (c) HAZ; (d) FZ.

During the instrumented Charpy V-notch impact tests, the force–displacement graphs were determined for the BM, HAZ, and FZ and are shown in Figure 14.

The lateral expansion of the fractured surfaces was measured and evaluated; this is a measure of test sample ductility. When ductile materials fracture, the materials become deformed. The amount of specimen deformation is measured (in mm) as the difference between the deformed width (b_m) and the original measured width (b) and is expressed as a lateral expansion ($b_m - b$), or it is defined as the increase in the fractured sample width as measured opposite the side of the notch on the striking side. Therefore, as the ductility of the material decreases, the lateral expansion decreases, and vice versa [44]. The schematic diagram and the expansion graph of the lateral expansion measurement on the Charpy V-notch impact tested specimen are shown in Figure 15.

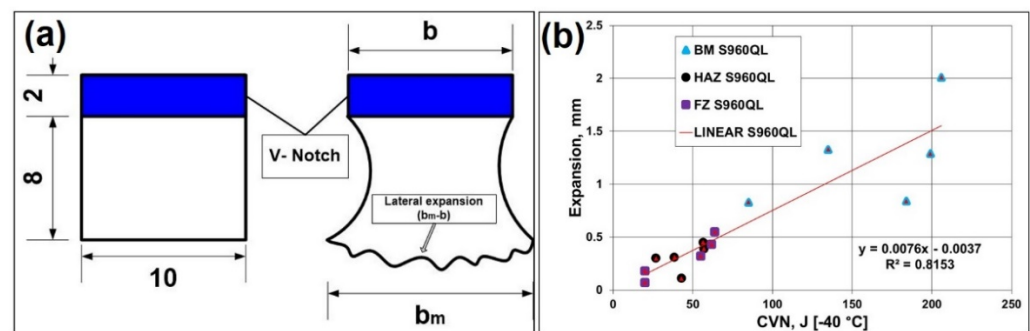


Figure 15. (a) Lateral expansion on CVN test specimen (all dimensions in mm) data from [44]; (b) Expansion graph.

The relationship between the CVN and the expansion shows that in the weld (FZ) and the HAZ mostly brittle fracture occurred, whether or not the CVN values fulfilled the 27 J requirement. This is due to the fact that during the impact testing of high-strength steels, generally higher maximum force values are measured compared to mild steels, which results in a relatively high CVN; however, the value of the CVN mostly includes the W_i and not the W_p , which is almost zero. Therefore, the CVN is higher because of the high W_i , and not, unfortunately, because of the high W_p . Therefore, if the CVN is around or above the requirement but the expansion is almost zero, this means that the material is brittle. It can be concluded that the HAZ of the EB-welded joint is brittle, as with the HAZ of the GMAW joint. However, the major advantage of EBW is that the area of brittle zone is much lower, especially in the HAZ, as compared to that of the GMAW process. The toughness will be reduced but not in as large a cross section as in conventional GMAW.

4. Conclusions

Based on the experimental study, microstructural examination (SEM, EBSD, and fractography), and mechanical tests (hardness test, tensile tests, and instrumented Charpy V-notch impact test) of the electron beam-welded butt joint of S960QL, the conclusions are summarized:

- Electron beam welding of S960QL was performed with the highest quality without any loss of mechanical strength. The tensile strength of the experimentally tested EB-welded joint is nearly similar to the as-received base material tensile strength of S960QL steel. Cracks and other imperfections were not observed during the visual inspection and macro photo observation. The same strength welded joint could be prepared with EBW as with GMAW without the application of alloyed filler material.
- The BM is generally composed of tempered martensite. The microstructure of the S960QL welded joint consists of fine dendritic martensitic, whereas the HAZ predominantly constitutes a relatively rough lath martensite microstructure in the CGHAZ, and a mixture of tempered martensite and M-A constituents in the ICHAZ.
- In the EB-welded joint, the average width of the FZ is 1.576 mm, which is 10 times lower than the width of the GMA-welded FZ. The area of the FZ was 28 mm² for EBW, whereas the GMAW FZ area was 257 mm², which is approximately 9 times larger than the EBW FZ area.
- The average calculated width of the EB-welded HAZ was 1.029 mm, which is 3 times smaller than the GMA-welded HAZ. However, the HAZ area of the GMAW was 3 times larger than that of the EBW.
- The hardness of the as-received base material was measured at 350 HV₁₀, whereas the maximum hardness value (441 HV₁₀) was observed in the HAZ and the average hardness of the FZ was 417 HV₁₀. However, the hardness values of the BM, HAZ, and FZ are under a prescribed limit of HV_{max} = 450 HV₁₀. In the case of GMAW, the maximum hardness in the HAZ was 413 HV₁₀ and the average hardness of the FZ

was 370 HV10 for the face side, whereas for the root, the HAZ maximum hardness was 333 HV10 and the average FZ hardness was 315 HV10.

- (f) In comparison with a GMAW-welded joint of the same thickness and steel grade, the average tensile strength of GMAW-welded joints was found to be close to that of the EB-welded joint for a shorter cooling time (5–6 s) with linear energy of 0.7 kJ/mm. However, for a longer cooling time (10 s) with linear energy of 1 kJ/mm, the average tensile strength of the welded joints was below the required minimum limit, i.e., 980 MPa as per the recommended standard EN 10025-6.
- (g) Whenever the 27 J requirement at $-40\text{ }^{\circ}\text{C}$ for the CVN was fulfilled, a brittle fracture with a low number of ductile parts was detected in the registered force–displacement diagrams (VWT and VHT), since the absorbed energy mostly consisted of the crack initiation energy. Since the previous studies verified that the critical, local toughness reduction in the HAZ of the investigated S960QL cannot be avoided by the simple modification of the welding parameters (by the modification of $t_{8/5}$ cooling-time range), one of the possible solutions is to minimize the extension of the HAZ. With EBW, the area of the HAZ including the brittle subzones (CGHAZ, ICHAZ) was significantly reduced.

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