Investigations

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Welding of High Strength Toughened Structural Steel S960QL

Abstract: The article discusses the effect of the thermal conditions applied during the MAG welding of steel S960QL and the mutual annealing of runs on the mechanical properties as well as on the macro and microstructure of welded joints made using various values of cooling time $t_{8/5}$. The research described in the article also involved the comparison of the above-named results with those obtained during a thermal simulation. In addition, the article presents the test results concerning the examination of the coarse and fine-grained areas of the HAZ of welded joints. The test results made it possible to optimise the value of cooling time $t_{8/5}$ when welding steel S960QL.

Keywords: high strength steels, S960QL steel, mechanical properties of welds, microstructure of welded joints

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Introduction

Fine-grained high strength toughened steels are primarily used in structures characterised by high strength and light weight (Fig. 1).

The technical requirements of the above-named steels having the yield point within the range of 460 to 960 MPa are specified in standard PN-EN ISO 10025-6. Recent years have seen the use of steels having higher yield points, i.e. 1100 MPa and even 1300 MPa. In spite of their high strength, the above-named steels are regarded as readily welded, yet, in terms of technology, the obtainment of optimum properties of welded joints remains a crucial issue.

Fig. 1. Exemplary applications of high strength toughened steels [1, 2, 3]

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To this end, it is often necessary to use the characteristic of cooling time $t_{8/5}$ making it possible (based on the CCT diagram for welding conditions) to appropriately interpret the structure and some mechanical properties of the HAZ.

The article presents the mechanical and structural properties of joints made in steel S960QL obtained using various values of time $t_{8/5}$ and compared with analogous results obtained in specimens after thermal simulation. In accordance with the above-named standard, the steel should be characterised by the following mechanical properties:

$$R_e \geq 960\ MPa;\ R_m = 950\text{-}1180\ MPa;$$
$$A_5 \geq 15\%;\ KV(-40°C) \geq 30\ J$$

CCT Diagrams for Welding Conditions in Relation to Austenite

Welded joints characteristics concerning strength, hardness, plasticity and toughness related to the weld and HAZ (heat affected zone) should diverge from the analogous properties of the base material as little as possible. In cases of toughened steels, the above-mentioned level of coincidence is significantly dependent on welding thermal conditions, the exponent of which is the cooling time of the HAZ area within the range of 800°C to 500°C (time $t_{8/5}$). Therefore, the CCT diagram for welding conditions in relation to austenite is of great importance, both in theory and practice [4]. If the CCT diagram for welding conditions is not available, it is possible, to some extent, to take advantage of the continuous TTT diagram, often used in heat treatment. An exemplary CCT diagram for welding conditions related to steel Weldox 1100 with marked structural areas in the function of cooling time $t_{8/5}$ is presented in Figure 2.

CCT diagrams for welding conditions are used to forecast the structure and to assess the HAZ hardening susceptibility as well as to aid in the design of welding technologies (arc linear energy and preheating temperature) enabling the obtainment of joints characterised by good plasticity and ductility, protecting the above-named area against brittle cracking.

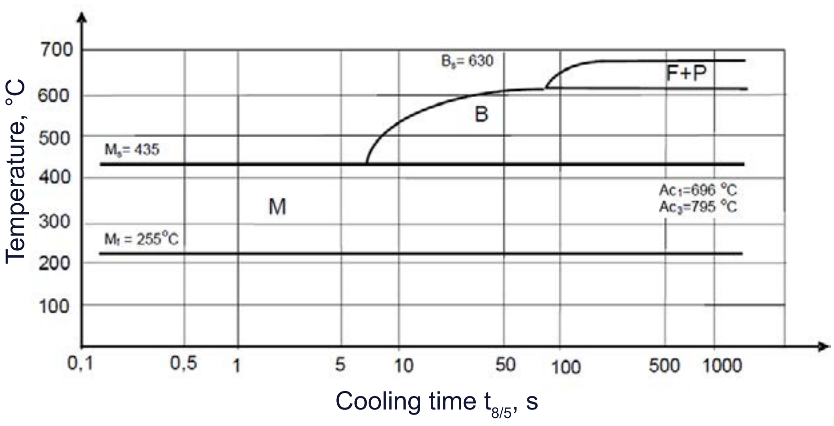


Fig. 2. Exemplary CCT diagram for welding conditions in relation to steel Weldox 1100 [5]

Thermal Simulation of Steel S960QL

The primary objective of simulation tests is usually the determination of the effect of time $t_{8/5}$ on the structure, hardness and toughness of steels. In cases of high strength steels, an important factor is tensile strength, and, in particular, the dependence of this characteristic on cooling time $t_{8/5}$. The course of this dependence enabling the identification of a more significant decrease in strength for given time $t_{8/5}$ could, along with the above-named properties, result in the welding-related optimisation of time $t_{8/5}$ [4-6]. For this reason, the simulated specimens were used for making non-standard specimens used in static tensile tests (Fig. 4b), the strength of which (after using various cooling times $t_{8/5}$) could only be interpreted through comparison.

It was interesting to answer the question, whether within the range of time $t_{8/5}$ values determining the area of martensite (lines M_s – M_F in the CCT diagram for welding conditions), the properties of steel having an unequivocally martensitic structure varied depending on the above-named time and what the nature of these differences was. There are CCT diagrams for welding conditions characterised by the significant time extent of the presence of these lines, yet welding practice indicates that in cases of such long $t_{8/5}$, the strength of joints is definitely overly low. The simulation tests were performed using a modern Gleeble 3500 simulator being in Instytut Spawalnictwa's possession (Fig. 3). The tests were performed using standard specimens (10×10×50 mm) heated up to 1250°C and cooled using $t_{8/5}$ amounting to 4, 8, 15, 30 and 40 seconds.

The specimens with simulated HAZ areas (Fig. 4) were subjected to hardness, toughness and strength tests. Strength was determined using the specimens with the radial notch and the diameter of the specimens subjected to tension amounting to 5 mm. The tests also involved the simulation of a specimen with a double thermal cycle for cooling time $t_{8/5}$ = 4 s (in each case). The test results related to the mechanical properties of the specimens are presented in Table 1.

Interpretation of Thermal Simulation Results

Hardness

For $t_{8/5}$ = 4, 8 and 15 seconds, hardness was nearly the same and amounted to approximately 410 HV; the hardness decreased along with the further extension of $t_{8/5}$; for $t_{8/5}$ = 30-40 seconds,

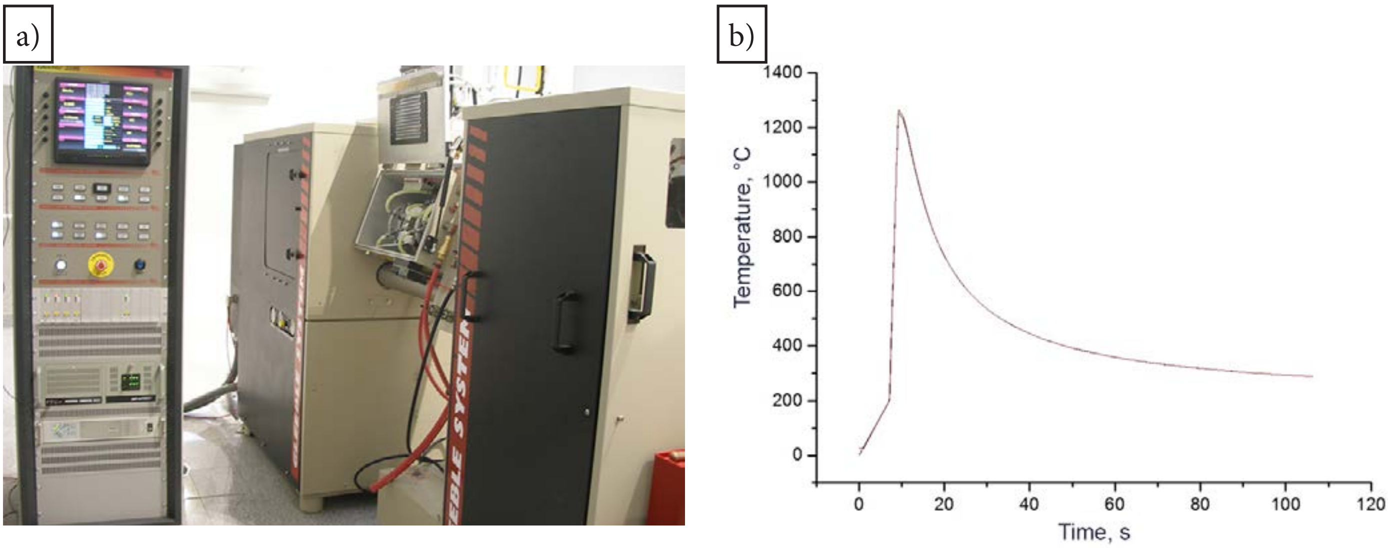


Fig. 3. Gleeble 3500 simulator (a) and the exemplary curve of specimen heating and cooling cycle (b)

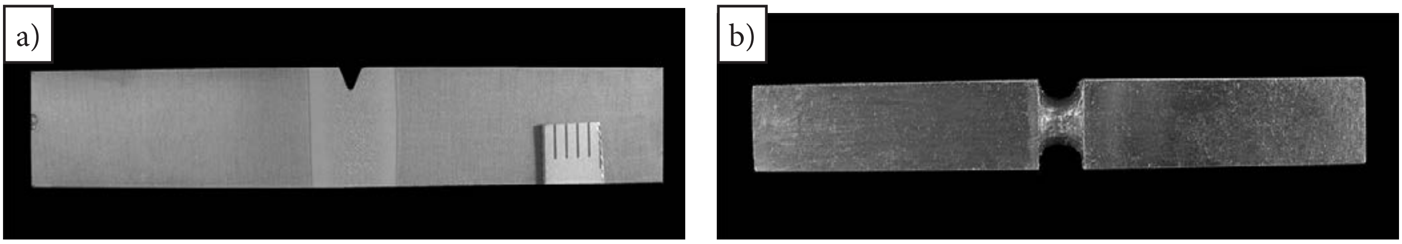


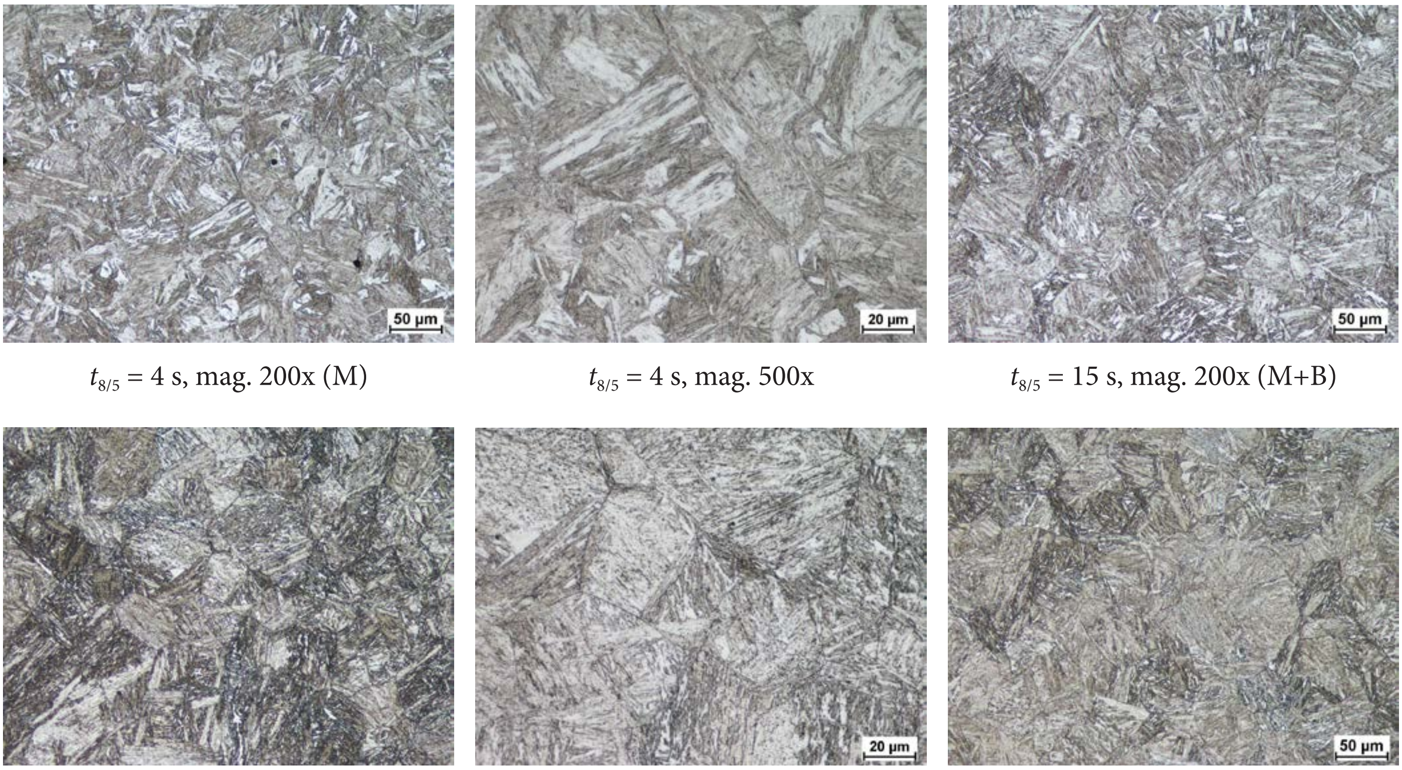
Fig. 4. Specimens with the simulated HAZ area used in the toughness and hardness (a) as well as tensile strength (b) tests

Table 1. Mechanical properties of the specimens after thermal simulation

Cooling time $t_{8/5}$	Impact energy, J, (-40°C)			Hardness, HV10			Rm*, MPa		
4 s	32	32	48	408	409	408	1852	1868	1851
8 s	46	24	52	405	411	405	1923	1917	1904
15 s	44	38	54	410	412	412	1767	1788	1755
30 s	38	22	50	362	353	346	1655	1660	1734
40 s	26	36	32	372	371	371	1648	1657	1667
2 × 4 s	40	42	42	402	409	412	1830	1802	1804

*Solely comparative interpretation

Microscopic metallographic tests of the specimens with the simulated HAZ areas



$t_{8/5}$ = 4 s, mag. 200x (M) $t_{8/5}$ = 4 s, mag. 500x $t_{8/5}$ = 15 s, mag. 200x (M+B)

$t_{8/5}$ = 30 s, mag. 200x (M+B) $t_{8/5}$ = 30 s, mag. 500x $t_{8/5}$ = 40 s, mag. 200x (B+M)

Fig. 5. Microstructures after the thermal simulation (M – martensite, B – bainite, etchant: Nital)

the hardness amounted to 350-370 HV (seemingly because of martensite tempering).

Impact energy

It was difficult to unequivocally assess the effect of time $t_{8/5}$ on this characteristic; it was only possible to try to identify a tendency. In cases of short cooling time values ($t_{8/5}$ = 4-15 s) and the double cycle, the toughness was slightly higher than in cases of longer cooling time values, i.e. $t_{8/5}$ = 30-40 s.

Tensile strength

An increase in $t_{8/5}$, particularly above 8 seconds, was accompanied by a clearly visible decrease in tensile strength; also as regards the double simulation.

Structure

An increase in $t_{8/5}$ was accompanied by the gradual replacement of martensite with bainite; when $t_{8/5}$ = 40 s, the amount of bainite exceeded that of martensite. It could be stated that to maintain high strength without compromising constant hardness and toughness, time $t_{8/5}$ should be limited to 4-8 seconds (maximum to 15 seconds).

Tests of Welded Joints Made of Steel S960QL

The tests aimed to determine the effect of MAG welding thermal conditions and of mutual annealing of runs on the mechanical properties as well as on the macro and microstructure of the welded joints made using various values of cooling time $t_{8/5}$ and to compare these results with those obtained in the thermal simulation tests.

Conditions Accompanying the Making of the Welded Joints

- Base material: sheets made of steel S960QL (15 mm thick) having the chemical composition based chemical analysis, in %: C = 0.16; Si = 0.36; Mn = 1.45; P = 0.013; S < 0.001; Cr = 0.57; Mo = 0.47; Ni = 0.026
- Filler metal: Union X90 filler metal wire

having a diameter of 1.0 mm and the following chemical composition in%: C = 0.10; Si = 0.81; Mn = 1.79; P = 0.006; S = 0.009; Cr = 0.3; Mo = 0.59; Ni = 2.28; and the following mechanical parameters: $R_e \geq$ 890 MPa; R_m = 950–1180 MPa; $A_5 \geq$ 15%; KCV(-60°C) ≥ 47 J and KV (-20°C) ≥ 90 J according to the quality certificate
- Shielding gas: grade M21
- Bevelling of sheet edges: bevelling – Y, edge – 2.5 mm, bevel angle – 55°
- Welding thermal conditions: joints were made using constant current parameters and welding rate. The diversification of welding thermal conditions (cooling time $t_{8/5}$) was obtained using various values of preheating temperature and of interpass temperature.

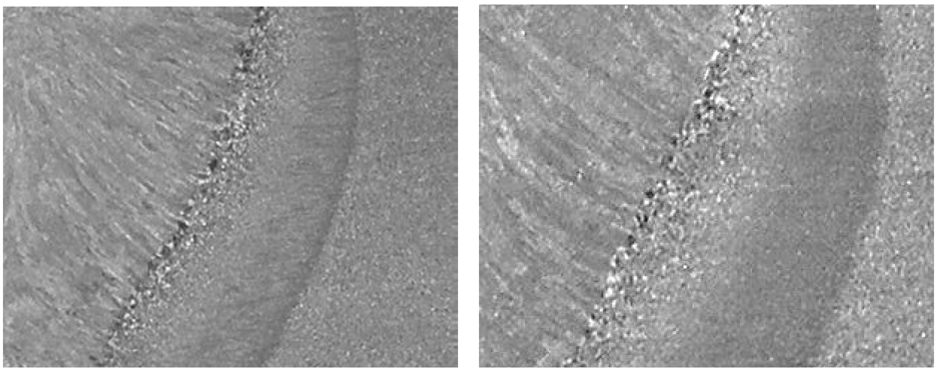
Cooling time $t_{8/5}$ was previously determined according to SEW 088 [9]. The parameters adopted when making the welded joint were the following:
- current parameters and welding rate: I_{sp} = 220 A; U_l = 26 V; V_{sp} = 40 cm/min,
- preheating temperature (equal to interpass temperature) decisive for cooling time $t_{8/5}$: T = 20°C → $t_{8/5}$ = 4 s; T = 120°C→ $t_{8/5}$ = 6 s; T = 220°C→ $t_{8/5}$ = 11 s,
- number of runs in the welded joints: 1, 2 and 4, where each run in a given joint was made using the same previously determined time $t_{8/5}$.

The actual values of characteristics related to the making of the joints are presented in Table 2.

Table 2. Test joint welding parameters

Number of runs	Temperature $T_p = T_m$, °C	Welding current I_{sp}, A	Arc voltage, V	Welding rate, cm/min	Linear energy, kJ/cm	Time $t_{8/5}$ [s]
1	20	220	27	40	8.58	4
1	225	220	26	40	8.58	11.0
2	20	225	27	40	9.14	4.0
2	220	220	26	40	8.58	11.0
4	20	220	26.5	40	8.75	4.0
4	120	230	26	40	8.97	6.0
4	220	222	26.5	40	8.82	11.0

T_p, T_m –pre-heating and interpass temperature



1-run; T = 20°C; $t_{8/5}$ = 4 s   1-run; T_p = 220°C; $t_{8/5}$ = 11 s

Fig. 6. Macroscopic metallographic photographs of the HAZ areas in the test joints; Adler's reagent

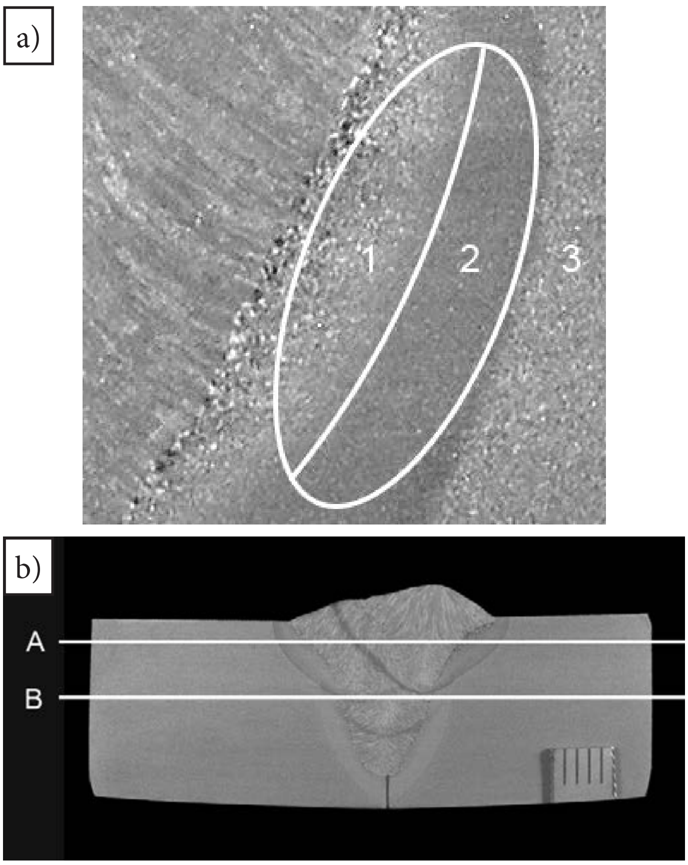


Fig. 7. HAZ areas a) 1 – area of superheating – coarse-grained; 2 – area of normalising –fine-grained; 3 – area of partial recrystallisation; b) hardness measurement lines

Macroscopic Metallographic Tests

The heat affected zone of welded joints made in toughened steels, particularly of those characterised by the highest strength, (Fig. 6) is clearly visible, complex and composed of the following areas (Fig. 7): 1 – area of superheating – coarse-grained; 2 – area of normalising – fine-grained and 3 – area of partial recrystallisation. The tests involved two, i.e.: coarse (1) and fine-grained (2) HAZ areas. The macroscopic metallographic photographs presented below concern the upper areas of the HAZ.

Hardness of Welds and HAZ

Table 3 presents the results concerning hardness measurements of the base material, weld and HAZ in the coarse and fine-grained structure areas according to the measurement lines in the upper (A) and lower (B) parts of the one and multi-run test joints made using various values of $t_{8/5}$. In certain cases, only hardness change-related trends were observed. In general, it could be stated that hardness differentiation on lines A and B of the weld and HAZ respectively for the same values of $t_{8/5}$ was relatively small. This could indicate the uniform strength of the entire welded joint, where the strength assessed on the basis of hardness was higher in the upper part of the joint.

Mechanical Properties of Welded Joints

The tests involved the use of joint specimens (complete filling of the weld groove) with a previously milled edge having a thickness of 10 mm.

The strength (R_m) and impact energy concerning the test joints in relation to $t_{8/5}$ amounting to 4 and 6 seconds were almost identical. Time $t_{8/5}$ = 11 s was accompanied by a slight decrease in strength and a slight increase in impact energy. In each case, the HAZ-related impact energy was higher than that of the weld. This fact could be ascribed to the presence of the cast dendritic structure of the weld, less favourable even in comparison with the coarse and fin-grained structure of the HAZ.

Table 3. Hardness of welded joints (runs) of steel S960QL

Number of runs	Hardness measurement line	Temperature $T_p = T_m$, °C	Time $t_{8/5}$, s	Hardness HV1			
				Base material	Weld	Coarse-grained HAZ area	Fine-grained HAZ area
1	A	20	4	360-369	389-422	425-448	404-466
1	A	220	11	343-350	347-359	379-401	298-339
2	A	20	4		387-408	365-422	404-430
	B				411-422	382-441	313-376
2	A	220	11		351-363	367-401	322-364
	B				355-362	327-360	325-339
4	A	20	4		403-435	409-454	400-460
	B				370-424	352-400	349-406
4	A	120	6		373-402	405-440	403-415
	B				359-369	320-377	314-349
4	A	220	11		339-377	362-426	316-366
	B				332-353	307-356	304-322

Table 4. Mechanical properties and impact energy of welded joints

Number of runs	$T_p = T_m$, °C	$t_{8/5}$, s	R_m, MPa	Impact energy/toughness, -40°C			
				weld, J	weld, J/cm²	HAZ, J	HAZ, J/cm²
4	20	4	1096-1100	42-50	52-62	76-86	95-107
4	120	6	1093-1103	44-48	55-60	78-132	97-137
4	220	11	1041-1049	64-70	80-87	88-146	110-182

Metallographic Tests

Presented below are the microscopic metallographic photographs of the weld and HAZ areas in one and four-run joints made using $t_{8/5}$ amounting to 4, 6 and 11 seconds. The photographs present both the coarse and fine-grained areas. The microscopic metallographic tests were performed in accordance with the requirements of standard PN-EN ISO 17639 using Nital.

Metallographic Tests – commentary:

- The Heat Affected Zone was very clear; each HAZ in all of the joints contained coarse and fine-grained areas.
- The further from the weld, the finer the grain (originally coarse, adjacent to the fusion line).
- Weld. Ain increase in time $t_{8/5}$ was accompanied by the increasingly refined structure. This could be attributed to the growing content of bainite at the cost of martensite. In addition, the annealing of the runs led to the formation of finer grains.
- The coarse-grained area was characterised by a typical martensitic structure and by tempered martensite in the lower areas of the weld. The structure contained small amounts of ferrite. Slightly more ferrite was present in the annealed area. It was difficult to identify the variously sized martensite formed from austenite in relation to various values of time $t_{8/5}$.
- The grains of the fine-grained area neighboured the coarse-grained area. The grains grew smaller along with a growing distance from the weld. The structure contained fine martensite and some bainite as well as small amounts of ferrite. The similarity of the nature (not granularity) of the structures in the coarse and fine-grained areas was manifested by their hardness.

Welding Procedure Qualification Results

Table 5 presents the properties of the butt welds obtained within welding procedure

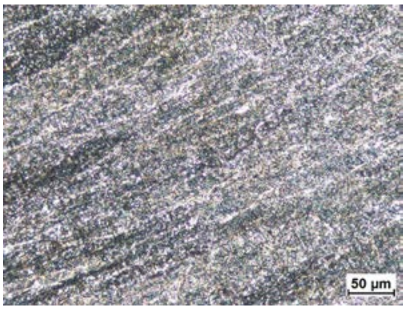
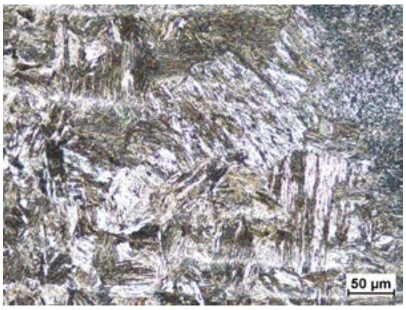
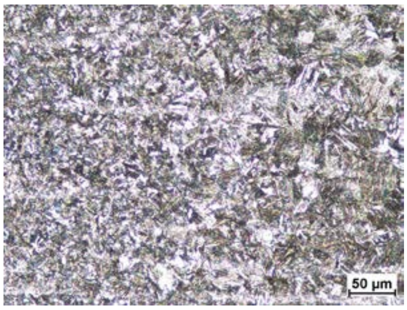
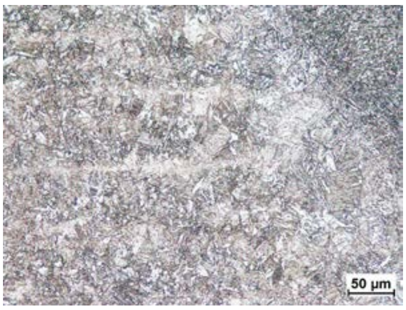
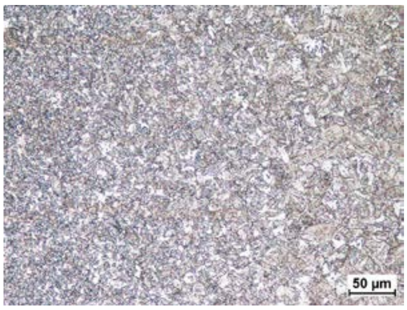
$t_{8/5}$	One-run weld		
4 s			
	Weld, mag. 200x (M+B)	Coarse-grained HAZ, mag. 200x (M)	Coarse and fine-grained HAZ, mag. 200x (M)
11 s			
	Weld, mag. 200x (B)	Coarse-grained HAZ, mag. 200x (B+M)	Fine-grained HAZ, mag. 200x (B)
Key: M- martensite; B- bainite; HAZ – heat affected zone; coarse-grained., fine-grained.- coarse and fine-grained zone respectively			

Fig. 8. Microstructure of welded joints made of steel S960QL with one-run weld

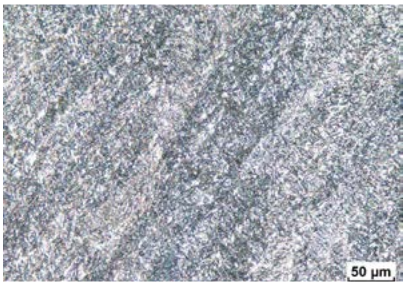
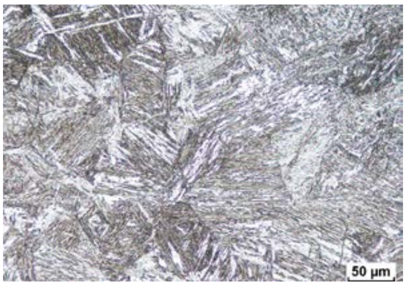
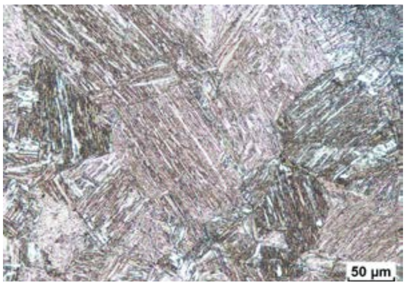
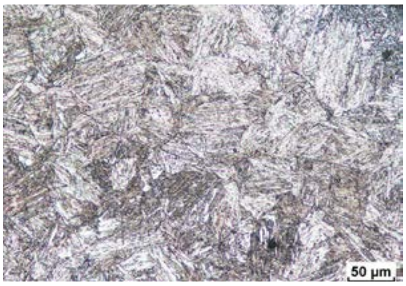
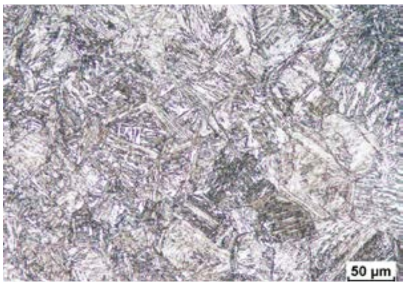
Multi-run weld (4 runs)		
$t_{8/5}$ = 4 s	$t_{8/5}$ = 6 s	$t_{8/5}$ = 11 s
		
U Weld, mag. 200x (M+B)	**U** Weld, mag. 200x (M+B)	**U** Weld, mag. 200x (B)
		
L Weld, mag. 200x (B+M)	**L** Weld, mag. 200x (M+B)	**L** Weld, mag. 200x (B)
		
U Coarse-grained HAZ mag. 200x (M)	**U** Coarse-grained HAZ mag. 200x (M)	**U** Coarse-grained HAZ mag. 200x (M)
		
L Coarse-grained HAZ mag. 200x (M)	**L** Coarse-grained HAZ mag. 200x (M)	**L** Coarse-grained HAZ mag. 200x (M)
		
U Fine-grained HAZ mag. 200x (M)	**U** Fine-grained HAZ mag. 200x (M)	**L** Fine-grained HAZ mag. 200x (M)
Key: U, L – upper (near the face) and lower (near the rot) run or weld area respectively; M- martensite; B – bainite; HAZ – heat affected zone; coarse-grained., fine-grained.- coarse and fine-grained zone respectively		

Fig. 9. Microstructure of welded joints made of steel S960QL with four-run weld

qualification. The properties revealed that welding processes performed maintaining values of time $t_{8/5}$ restricted within the range of 4.3 seconds to 8.0 seconds enabled the satisfaction of the requirements specified in PN-EN ISO 10025-6 and PN-EN ISO 15614-1 (R_m 980-1150 MPa, impact energy min. 30 J at a temperature of -40°C and a maximum hardness of 450 HV10).

Summary

Simulation Tests

– Within time $t_{8/5}$ range of 4 s to 8 s and with the dominant presence of martensite, the mechanical properties of the joint did not change. Time $t_{8/5}$ = 15 s was only accompanied by a decrease in strength. This indicates that, when making welded joints in steel S960QL, the above-named time should not be exceeded (to maintain strength).
– CCT diagrams for welding conditions related to toughened steels, particularly those having strength above 690 MPa, constitute an important source of information concerning the effect of time $t_{8/5}$ on the character of austenite structural transformations and HAZ properties. For this reason, even if the above-named diagrams do not directly concern specific steels, they should be used along with other welding technological guidelines when determining welding process parameters including welding current, arc voltage, welding rate, preheating temperature, interpass temperature etc.
– Instytut Spawalnictwa is in possession of appropriate resources for performing thermal simulations of steels in welding conditions enabling the fast and precise performance of austenite transformation analyses and adjusting appropriate time $t_{8/5}$ for given steels.

Table 5. Properties of welded joints obtained within the welding procedure qualification of 15 mm and 30 mm thick steel S960QL (data from companies)

Material thickness, mm	$t_{8/5}$, s	T_p, °C	R_m, MPa	Hardness, HV10			Impact energy, J		Welding parameters		
				Material	HAZ	Weld	Weld	HAZ	I_{sp}, A	U_l, V	V_{sp}, cm/min
15	6.4-7.5	150-180	1021-1027	340-350	340-380	300-340	70-76	90-122	235-250	26-27	33-36
15	5.0-5.4	120-150	1062-1063	320-340	330-410	310-400	46-50	104-112	225-228	28	36-39
15	4.5-6.1	120-150	1033-1038	335-350	330-430	330-385	49-56	126-175	210-225	28	33-41
15	4.8-5.4	130-140	1060-1064	350-380	385-440	380-410	48-62	54-60	230	27	36-42
30	4.6-5.8	150-180	1078-1097	380-430	370-515	380-490	54-64	30-48	230-270	26-27	36-48
30	4.5-7.0	180-200	1024-1046	330-360	320-420	330-390	74-78	96-118	190-210	24-25	30-40
30	4.3-7.8	130-180	1033-1051	345-360	370-450	330-400	62-68	150-170	240-270	27-29	35-56
30	5.3-8.0	150-170	985-1028	340-350	300-450	350-436	40-49	61-74	210-230	28-29	30-42
30	5.7-7.0	140-160	1065-1068	310-340	320-420	360-395	36-40	54-80	230-250	28	28-42

Tests of Welded Joints Made of Steel S960QL

- The hardness of the individual zones of the welded joints (runs) decreased along with an increase in time $t_{8/5}$.
- The strength and the impact energy of the test joint were nearly identical for $t_{8/5}$ amounting to 4 s and 6 s. Time $t_{8/5}$ = 11 s was accompanied by a slight decrease in strength and a slight increase in impact energy. In each case, the impact energy of the HAZ was higher than that of the weld. Such a fact could be ascribed to the presence of the cast dendritic, i.e. less favourable, structure in comparison with the coarse and fine-grained structure of the HAZ.
- The metallographic tests revealed that differences in time $t_{8/5}$ within the range of 4 to 11 s did not trigger visible structural transformations at any levels of the joint, which correlated with the slight diversification of mechanical properties. However, it was possible to notice differences between annealed and not annealed layers.
- It could be anticipated that in cases of $t_{8/5}$ = 4-9 s, the properties of joints made of steel S960QL should meet the requirements of PN-EN ISO 10025-6 and PN-EN ISO 15614-1 in terms of strength, plasticity, toughness and hardness. The above-named satisfaction was confirmed by the results obtained within welding procedure qualification. The proper quality of the joint was also demonstrated by the appropriate properties of the weld and those of the HAZ.

Correlation of Thermal Simulation results with Welded Joint Properties Results

The comparison of the properties of steel S960QL after thermal simulation with the welded joints made of the same steel using time $t_{8/5}$ restricted within the range of 4-15 s (Table 6) revealed the following:

- correlation of the hardness of the simulated specimens and that of the welded joints (in their upper ranges),
- correlation of structure within time $t_{8/5}$ range of 4 seconds to 11 seconds,
- greater impact energy of the welded joints than that of the simulated specimens.

References

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Table 6. Properties of steel after thermal simulation and of welded joints

	Time $t_{8/5}$, s	Hardness HV10		Impact energy, J	Structure
		Line	HAZ	HAZ	HAZ
Thermal simulation	4	-	408	32-48	M
	8	-	407	34-52	M
	15	-	411	38-54	M + B
Welded joint	4	A	400-460	76-86	M
		B	350-400		
	6	A	405-430	78-132	M
		B	315-370		
	11	A	360-430	88-146	M
		B	307-350		

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