Mirosław Łomozik

Mechanical Properties of Joints Made in Steel S1300QL Using Various Welding Methods

Abstract: The article presents applications of high-strength quenched steels in various industrial sectors and the chronological development of various grades of the aforesaid steels. The research-related tests involved flat butt joints made in 7 mm thick steel grade S1300QL, welded using the following methods: TIG, A-TIG, MAG involving the use of a hard flux-cored surfacing wire, MAG method involving the use of a solid wire, T.I.M.E. method involving the use of a solid wire, laser welding method without the use of the filler metal, hybrid (HLAW) method involving the use of a metallic flux-cored wire, electron beam welding without using the filler metal. The research also involved the performance of the mechanical properties of the welded joints made in quenched steel S1300QL using various welding methods. The joints made using the laser welding method, hybrid welding method and the electron beam welding method were characterised by tensile strength higher than the minimum yield point of steel S1300QL, amounting to 1300 MPa. In turn, the tensile strength of the joints made in steel S1300QL using arc welding methods was lower than the minimum yield point of the steel. All of the test joints were subjected to non-destructive digital radiographic tests. The tests concerning the mechanical properties of the joints with respect to various welding methods were subjected to comparative analysis. The research work finished with the formulation of concluding remarks concerning the mechanical properties of the joints.

Keywords: S1300QL, high-strength steels, welding methods, properties of joints

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Introduction

Quenched steels characterised by high and very high strength and a low nil ductility transition (NDT) temperature are enjoying a continuous interest among design engineers. The aforesaid popularity is related to developmental trends concerning steel structures as the latter are increasingly complex, large and confronted with increasingly high performance requirements. At the same time, design engineers

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and manufacturers attempt to reduce both the weight and the cost of structures. These apparently conflicting requirements can be satisfied by materials characterised by increasingly high mechanical properties [1, 2]. Presently, high yield point quenched steels belong to materials most commonly used in the production of critical welded structures exposed to significant loads, e.g. road vehicle chassis frames, poles and supports, hoisting equipment, oil rig elements, special bridge structures etc. Reference publications [3] and information obtained from companies producing elements of lifts, cranes, gantry cranes and other large-sized load-carrying elements indicate the increased use of steels having a yield point of 1300 MPa [4].

Examples of modern steels having a yield point of over 900 MPa include steels manufactured by SSAB Oxelösund (Sweden) [5]. The aforesaid steels not only satisfy but also surpass requirements presently formulated by producers of crane structures exposed to high loads. Because of a technologically advanced metallurgical process, steel grades S960, S1100 and S1300 are characterised by high metallurgical purity as well as by favourable weldability, bendability and machinability [6].

In recent years the development of high and very high yield point structural steels has concerned both quenched steels such as S690Q, S890Q and S960Q as well as TMCP steels characterised by lower mechanical properties but higher toughness, e.g. S355M, S460M and S500M. The year 2000 saw the advent of technologically advanced structural steels having a yield point of more than 1000 MPa. The chronological development of structural steels is presented in Figure 1.

Figure 2 presents the correlation between the value of carbon equivalent C_e and the yield points of steels obtained in various manufacturing processes (coloured areas). Figure 2 reveals that steels made using the Thermo-Mechanical Control Process (M) are characterised by a lower carbon equivalent than steels after normalising (N) characterised by the same yield point. Also within the yield point range above 550 MPa, steels subjected to the Thermo-Mechanical Control Process with accelerated cooling and tempering (A+T) are characterised by a lower carbon equivalent than quenched steels (Q). As can be seen, steels made using the Thermo-Mechanical Control Process are characterised by better weldability than normalised steels or quenched steels having a similar yield point.

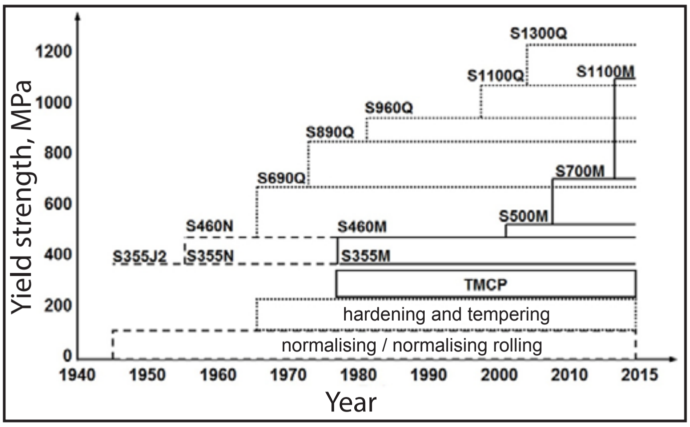


Fig. 2. Development of structural steels (TCMP – Thermo-Mechanical Control Process) [7]

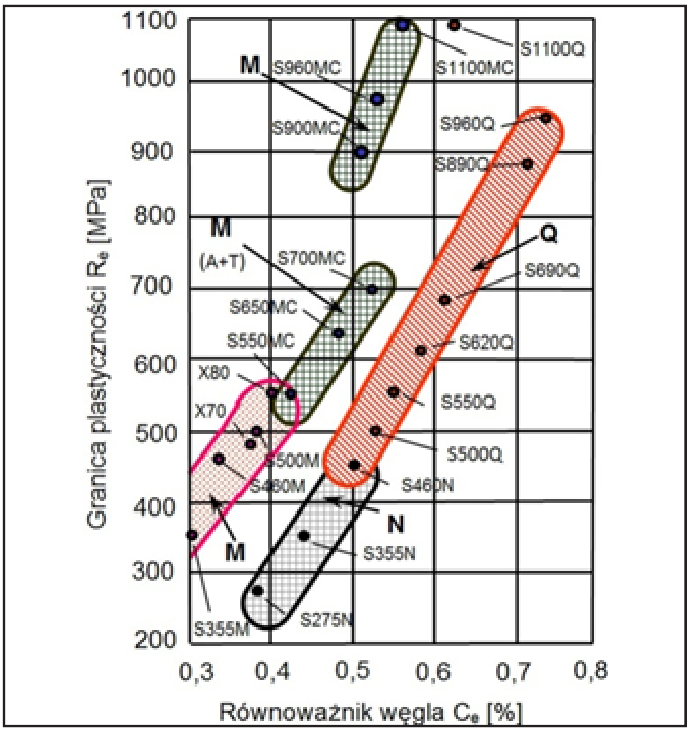


Fig. 2. Correlation between carbon equivalent Ce, and yield point Re of steels obtained in various manufacturing processes [8]: N – steels subjected to normalising or normalising rolling, M – steels subjected to the Thermo--Mechanical Control Process (MC – steels subjected to the cold Thermo-Mechanical Control Process), Q – quenched steels

Table 1. Chemical composition of steel S1300QL

C	Si	Mn	P	S	Cr	Cu	Ni	Mo	B	V
Chemical element content, % by weight in accordance with check analysis										
0.236	0.220	0.885	0.0047	0.0008	0.493	0.017	1.348	0.401	0.0012	0.020
Chemical element content, % by weight according to the producer [5]										
C	Si	Mn	P	S	Cr	Cu	Ni	Mo	B	-
max 0.25	max 0.50	max 1.40	max 0.020	max 0.005	max 0.80	max 0.30	max 3.00	max 0.70	max 0.005	-

Presently, in Poland welding processes are performed in relation to structures made of steel S960 and S1100 subjected to significant operating loads. Because of the lack of the filler metal intended for steel S1300, the aforesaid grade is not in common use. The foregoing issue inspired the search for alternative methods enabling the making of welded joints (characterised by high mechanical properties) in steel S1300. The tests along with their results are presented in the remainder of the article.

Tests materials and methodology

The tests involved the use of 7 mm thick high-strength quenched steel grade S1300QL. The analysis of the chemical composition of steel S1300QL was performed using a Q4 TASMAN spark spectrometer. The results of the analysis are presented in Table 1. The mechanical properties of steel S1300QL are presented in Table 2.

The test programme included the making of flat butt joints in steel S1300QL using the following methods:

a) TIG method involving the use of the filler metal the chemical composition of which was similar to that of the base material (process 141). The plate of the base material was subjected to mechanical working aimed to make bars used in the welding process. Joint TIG01 was made using two runs (root run + filling run), whereas joint TIG02 was made using three runs (root run + 2 filling runs). The joints were welded in the flat position (PA), in a groove having a bevel angle of 80°,

b) A-TIG (process 141 + flux) – single-run joint with full penetration without the addition of the filler metal and with the use of an activating flux in the form of the mixture of SiO2+-TiO2. The joint, welded in the flat position, was made using one run. The edges of the weld grove were not bevelled but prepared as the square butt weld,

c) MAG involving the use of various filler metals:
   - ROBODUR K 350 hard flux-cored surfacing wire having a diameter of 1.2 mm (process 138). The joint was welded in the flat position (PA), in a groove having a bevel angle of 60°
   - THERMANIT X 96 solid wire having a diameter of 1.2 mm (process 135). The joint was welded in the flat position (PA), in a groove having a bevel angle of 40°,

d) T.I.M.E method involving the use of the filler metal in the form of a THERMANIT X 96 solid wire having a diameter of 1.2 mm. The joint, welded in the flat position, was made on a ceramic backing strip using one run. The edges of the weld grove were not bevelled but prepared as the square butt weld,

e) laser method without using the filler metal (process 521). The two test joints were numbered L01 and L02. Welded joint L02 was made using a finishing

Table 2. Mechanical properties of steel S1300QL

Yield point $R_{e0,2}$, MPa	Tensile strength R_m, MPa	Elongation A_5, %	Impact energy KV at -40°C, J
1460	1600	11	34
Specifications provided by the manufacturer [5]			
min. 1300	1400–1700	min. 8	27

layer, the finishing layer was made directly after welding – Figure 3. The finishing layer was made to improve the geometry of the weld, i.e. by removing weld face undercuts (if any), smoothening the weld face surface and obtaining a gentle toe. In addition, the finishing layer was made to verify if it affected the mechanical properties of the joint in comparison with the joint made using one run.

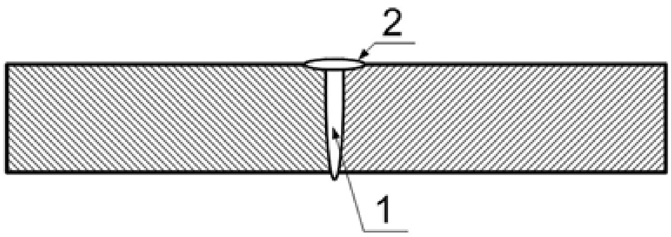


Fig. 3. Welding sequence in the laser welding method: 1 – filling run, 2 – finishing layer

f) HLAW method (laser Nd:YAG + MAG, i.e. process 521 + 138) involving the use of a STEIN-MEGAFIL 1100M metallic flux-cored wire having a diameter of 1.2 mm. The joint was made in the flat position. The edges of the weld grove were not bevelled but prepared as the square butt weld,
g) electron beam welding without using the filler metal (process 511). The two welded test joints were numbered EWB1.1 and EBW2. The edges of the weld grove were prepared as the square butt weld. Joints EBW1.1 was welded using one run. In addition to the filling run, joint EBW2 was also provided with a finishing layer aimed to improve the geometry of the weld, fill weld face undercuts (if any) and obtain a gentle toe.

Technological parameters applied when making welded joints using individual methods are presented in Tables 3–9. Main view of the welded joints from the weld face and weld root side is presented in Table 10.

The determination of the quality of the joints required the performance of radiographic tests in accordance with the requirements of the PN-EN ISO 17635 [9], PN-EN ISO 17636-2 [10], PN-EN ISO 13919-1 [11], PN-EN ISO 10675-1 [12], PN-EN ISO 6520-1 [13] and PN-EN ISO 19232-1 [14] standards. The range of the radiographic tests included 100% of the weld in the butt joints except the initial and final fragments of 35 mm in length each.

Afterwards, the joints were subjected to static tensile tests performed in accordance with the requirements of the PN-EN ISO 4136 standard [15], using an MTS 810 testing machine. The shape and the dimensions of the specimens are presented in Figure 4.

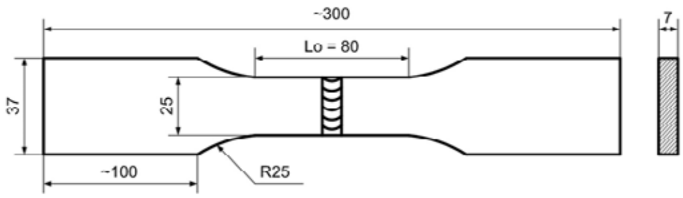


Fig. 4. Shape and dimensions of the specimens used in the static tensile tests

Test results

Radiographic tests

The results of the radiographic tests are presented in Table 11.

Static tensile tests

The results of the static tensile tests involving joints made using various welding methods are presented in Tables 12–18.

Discussion

The filler metal used in the TIG welding of steel S1300QL had the form of bars made of the base material of the aforesaid steel. The bars were square in cross-section (3 mm x 3 mm). The above-presented geometry and dimensions of the bars ensured the proper stability of arc burning and only slight porosity. Joint TIG01 was made using two runs, i.e. the root run + the filling run, whereas joint TIG02 was made using three runs, i.e. the root run + 2 filling runs. The radiographic tests revealed the presence of linear porosity and the cluster of porosity in joint TIG01 as well as the presence

Table 3. Technological parameters used in the TIG welding of the joints

Welded layer	Current A	Arc voltage V	Welding rate cm/min	Interpass temperature °C	Heat input Q kJ/cm
Root run	90–95	13.7–14.5	10	-	4.43–4.95
Filling runs	125–130	13.7–14.5	12	220	5.14–5.66

Table 4. Technological parameters used in the A-TIG welding of the joints

Joint	Current A	Arc voltage V	Welding rate cm/min	Interpass temperature °C	Heat input Q kJ/cm
A-TIG	270	-	10	-	-

Table 5. Technological parameters used in the MAG welding of the joints

Joint	Welded layer	Current A	Arc voltage V	Welding rate cm/min	Interpass temperature °C	Heat input Q kJ/cm
MAG350	Root run	195–200	20–21	15	-	12.48–13.44
	Filling run	235–240	22–23	25	220	9.85–10.51
MAG X96	Root run	195–200	18–19	15	-	11.23–12.16
	Filling run	230–240	22–23	30	150	8.10–8.83

Table 6. Technological parameters used in the T.I.M.E welding of the joints

Joint	Current A	Arc voltage V	Welding rate cm/min	Interpass temperature °C	Heat input Q kJ/cm
T.I.M.E. X96	475–490	46–47	70	16	14.94–15.75

Table 7. Technological parameters used in the laser welding of the joints

Joint	Layer number	Power *P*, W	Welding rate *v*, m/min	Beam focus position *f*, mm	Shielding gas flow rate, l/min	Heat input Q kJ/cm
L01	1	5300	1.5	0	16	2.12
L02	1	5800	1.5	0	16	2.32
	2	2000	1.5	30	16	0.80

Table 8. Technological parameters used in the hybrid laser welding (HLAW) of the joints

Parameter:	Value:
Laser beam power – P, kW	4.5
Welding rate – V_S, m/min	1.1
Filler metal wire feeding rate – V_d, m/min	8.5
Welding current – I, A	250
Arc voltage – U, V	20
Heat input – Q, kJ/cm	5.1
Position of the focus in relation to the surface of the plates subjected to welding – f, mm	0 (focus on the surface of the plate)

Table 9. Technological parameters used in the electron beam welding of the joints

Joint:	EBW1.1	EBW2
Accelerating voltage HV, kV	120	120
Beam current I, mA	16,5	16,75
Beam focal length, mm	720	720
Work distance, mm	210	210
Welding rate V, cm/min	80	80
Heat input Q, kJ/cm	1,41	1,44
Cathode burning current, A	22	22
Beam increase ramp, mA/s	100	100
Beam decrease ramp, mA/s	100	100
Remarks:	The joint was made using the finishing layer	
Parameters of the finishing layer:	Accelerating voltage HV: 120 kV Beam current: 10 mA Welding rate V: 50 cm/min Heat input Q: 1,37 kJ/cm Beam oscillation type: circular Beam oscillation amplitude: 5% Beam oscillation frequency: 400 Hz	

Table 10. Main view of the welded joints from the weld face and weld root side

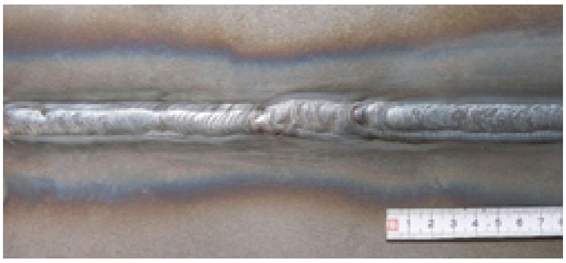
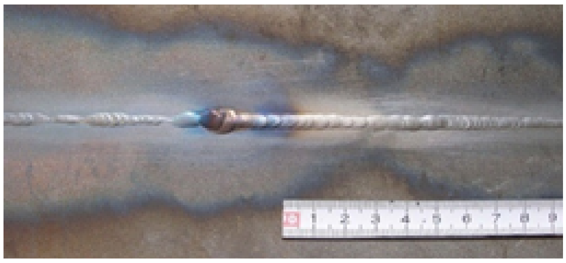
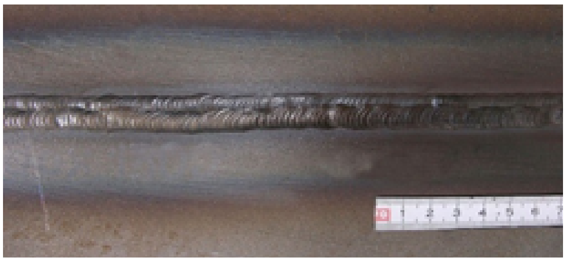
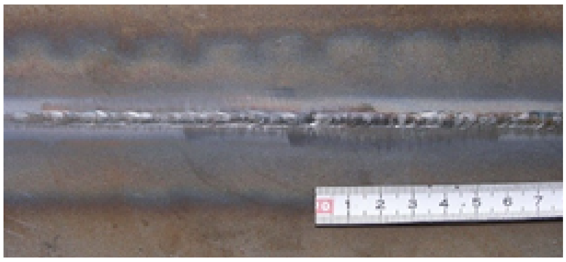
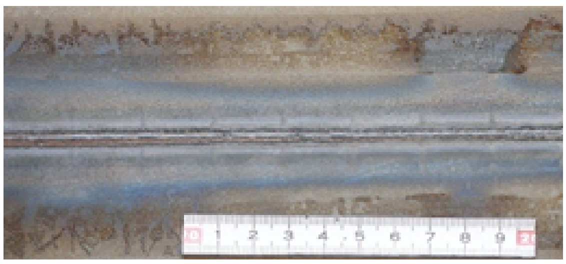
Joint	**View from the weld face side**	**View from the weld root side**
TIG01		
TIG02		
A-TIG		
MAG350		

Table 10. Main view of the welded joints from the weld face and weld root side (continued)

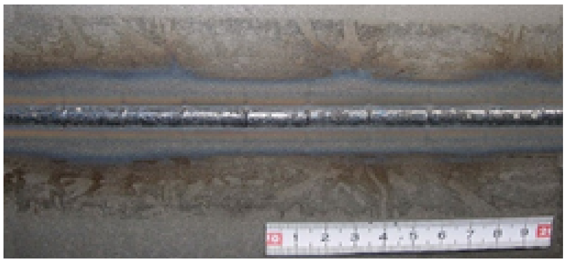
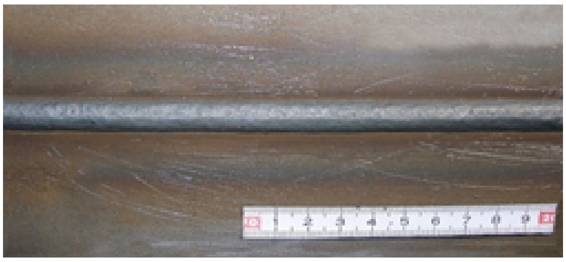
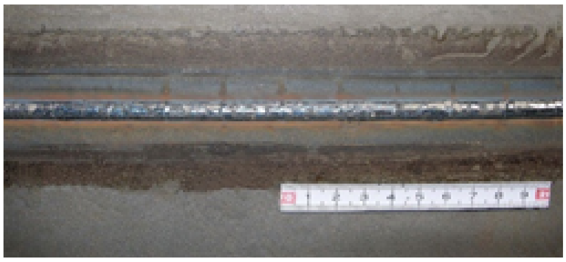
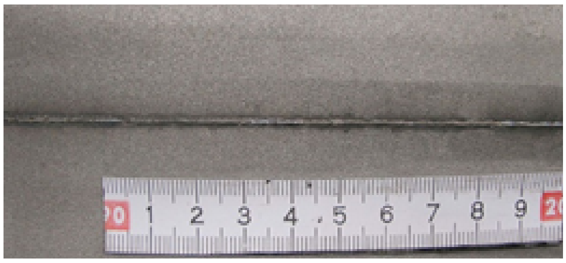
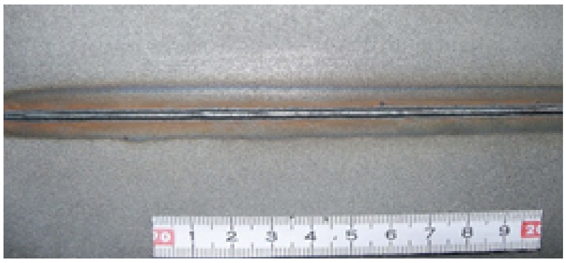
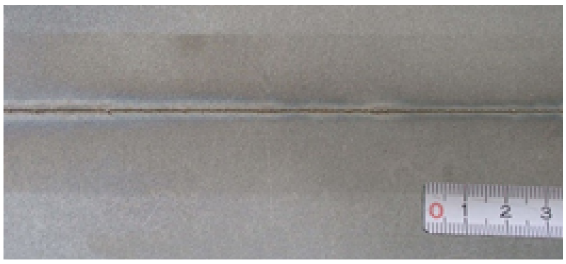
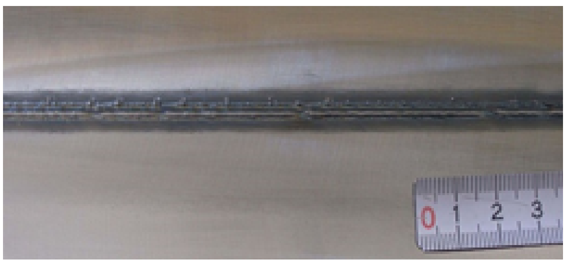
Joint	View from the weld face side	View from the weld root side
MAG X96		
T.I.M.E. X96		
L01		
L02		
HLAW		
EBW1.1		
EBW2		

Table 11. Results of the radiographic tests concerning the welded joints made in steel S1300QL

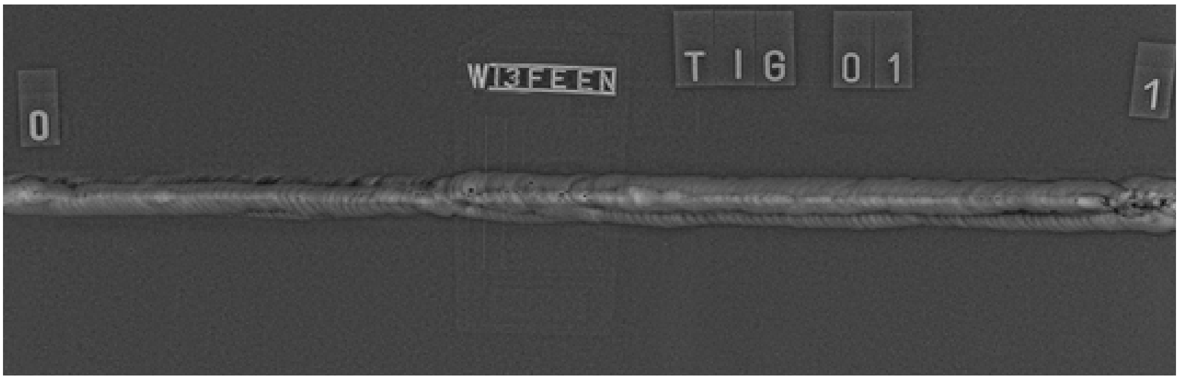
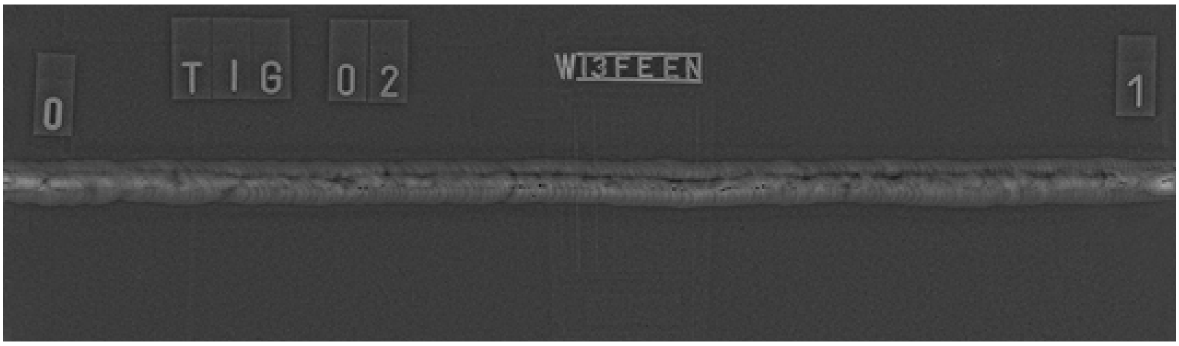
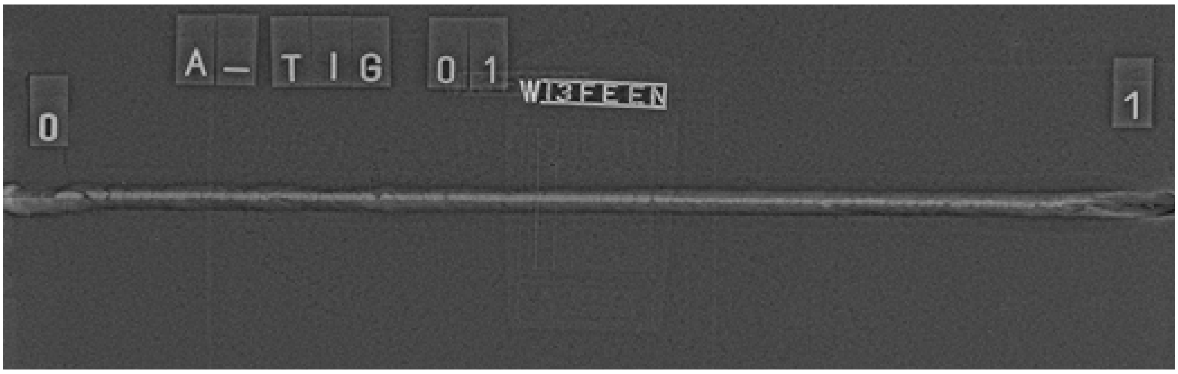
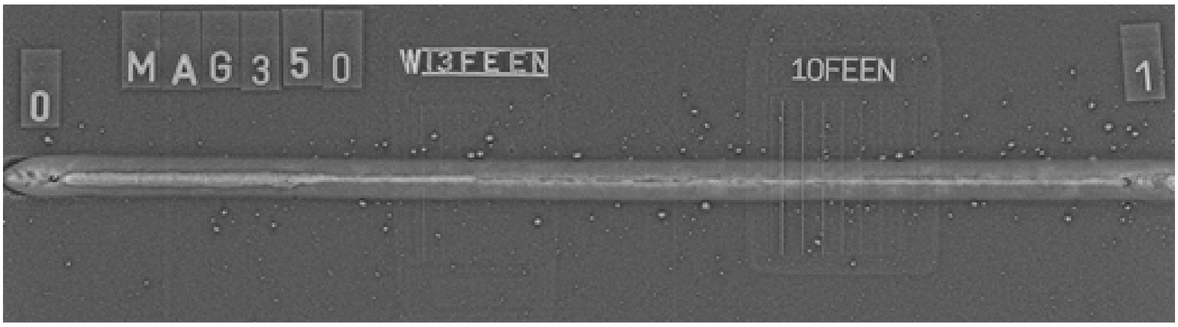
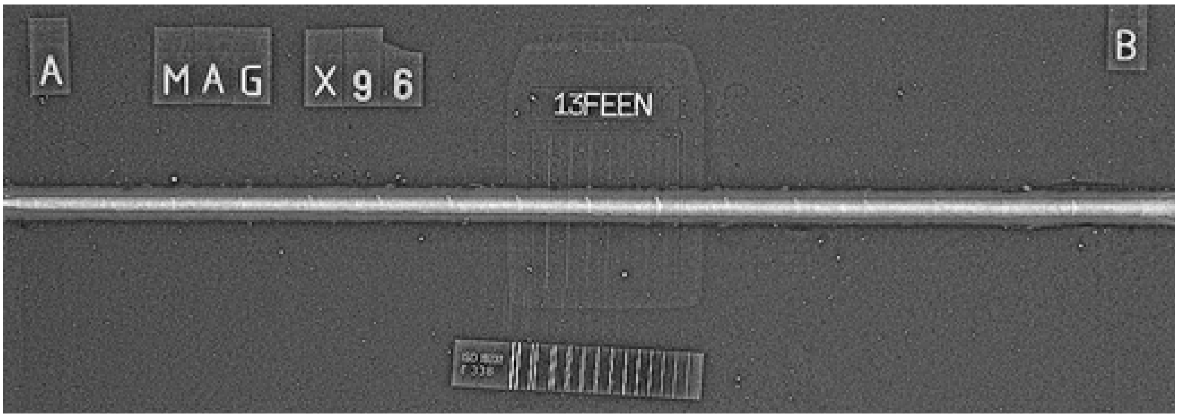
Joint	**Radiogram**
TIG01	
TIG02	
A-TIG	
MAG350	
MAG X96	

Table 11. Results of the radiographic tests concerning the welded joints made in steel S1300QL (continued)

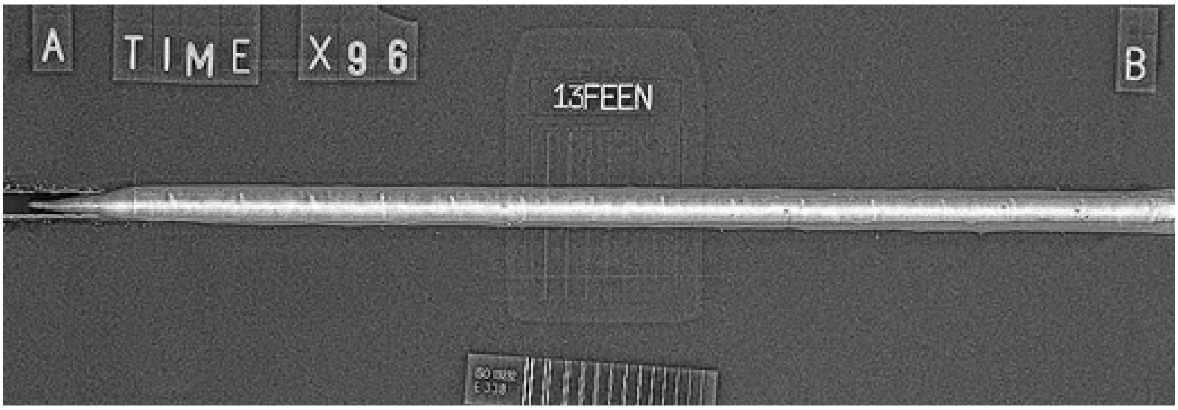
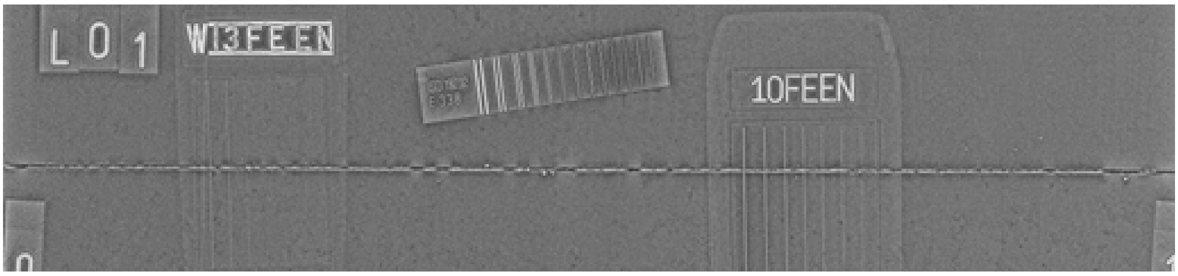
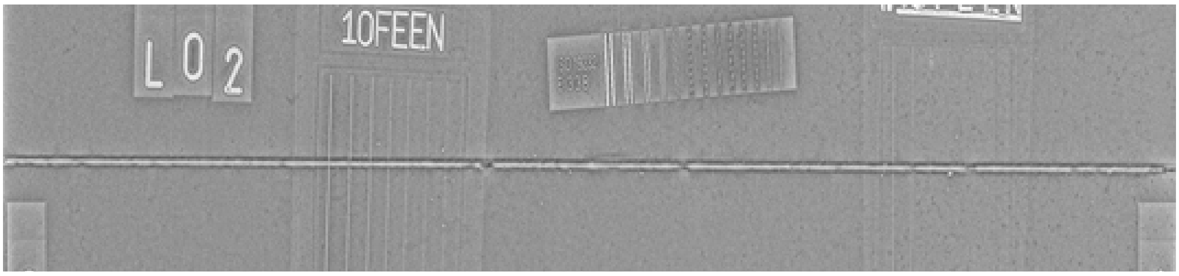
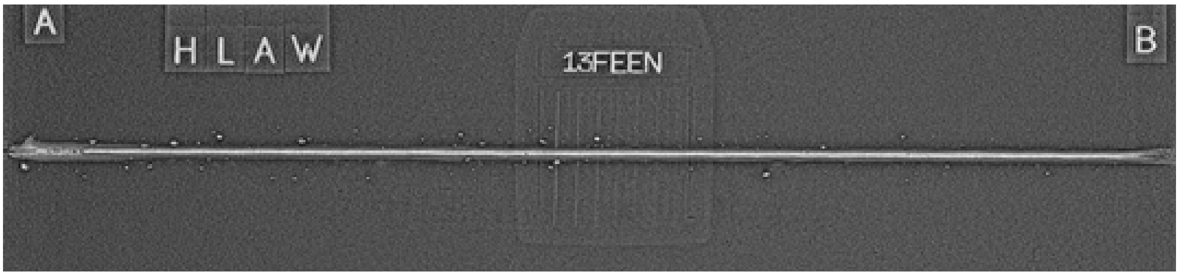
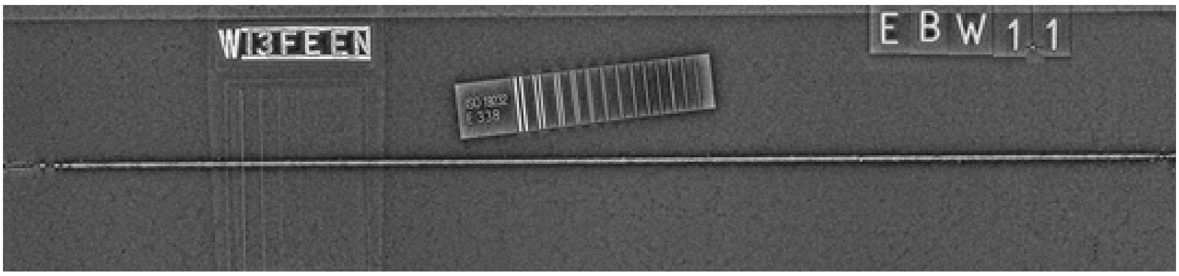
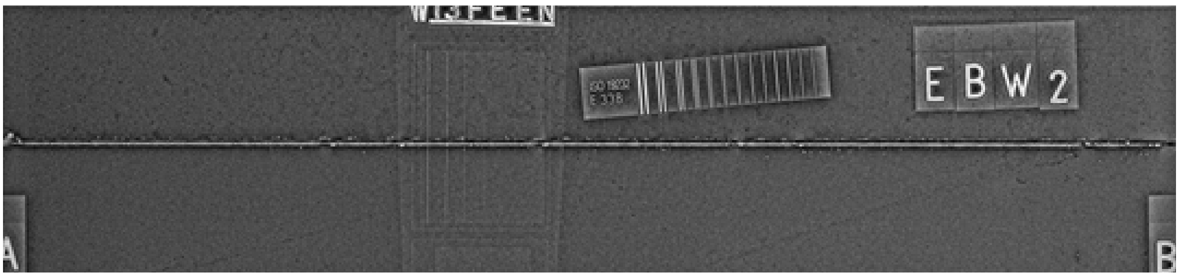
Joint	Radiogram
T.I.M.E. X96	
L01	
L02	
HLAW	
EBW1.1	
EBW2	

Table 12. Tensile test results concerning the joints in steel S1300QL made using the TIG method

Specimen	F_m, kN	R_m, MPa	$R_{mav.}$, MPa	Remarks:
TIG01/1	177.6	1048.8	1045.7	rupture outside the weld, mat fracture
TIG01/2	179.1	1042.5		rupture outside the weld, mat fracture
TIG02/1	181.6	1061.5	1062.7	rupture outside the weld, mat fracture
TIG02/2	182.8	1063.9		rupture outside the weld, mat fracture

Table 13. Tensile test results concerning the joints in steel S1300QL made using the A-TIG method

Specimen	F_m, kN	R_m, MPa	$R_{mav.}$, MPa	Remarks:
A-TIG/1	206.2	1204.8	1201.9	rupture in the weld-HAZ interface, mat fracture
A-TIG/2	202.2	1199.0		rupture in the weld-HAZ interface, mat fracture

Table 14. Tensile test results concerning the joints in steel S1300QL made using the MAG method

Specimen	F_m, kN	R_m, MPa	$R_{mav.}$, MPa	Remarks:
MAG350/1	193.0	1123.6	1117.0	rupture outside the weld, mat fracture
MAG350/2	190.8	1110.4		rupture outside the weld, mat fracture
MAGX96/1	196.9	1141.3	1143.0	rupture in the weld-HAZ interface, mat fracture
MAGX96/2	197.5	1144.6		rupture in the weld-HAZ interface, mat fracture

Table 15. Tensile test results concerning the joints in steel S1300QL made using the T.I.M.E. method

Specimen	F_m, kN	R_m, MPa	$R_{mav.}$, MPa	Remarks:
T.I.M.E.X96/1	195.5	1149.8	1150.2	rupture in the weld-HAZ interface, mat fracture
T.I.M.E.X96/2	195.6	1150.6		rupture in the weld-HAZ interface, mat fracture

Table 16. Tensile test results concerning the joints in steel S1300QL made using the laser welding method

Specimen	F_m, kN	R_m, MPa	$R_{mav.}$, MPa	Remarks:
L01/1	239.5	1431.7	1380.3	rupture in the weld, mat fracture
L01/2	225.6	1328.8		rupture in the weld, mat fracture
L02/1	260.9	1534.7	1534.3	rupture in the weld-HAZ interface, mat fracture
L02/2	260.8	1533.9		rupture in the weld-HAZ interface, mat fracture

Table 17. Tensile test results concerning the joints in steel S1300QL made using the hybrid (HLAW) method

Specimen	F_m, kN	R_m, MPa	$R_{mav.}$, MPa	Remarks:
HLAW/1	235.0	1397.3	1394.3	rupture in the weld-HAZ interface, mat fracture
HLAW/2	234.0	1391.3		rupture in the weld-HAZ interface, mat fracture

Table 18. Tensile test results concerning the joints in steel S1300QL made using the electron beam welding method

Specimen	F_m, kN	R_m, MPa	$R_{mav.}$, MPa	Remarks:
EBW1.1/1	246.4	1488.6	1472.9	rupture in the weld-HAZ interface, mat fracture
EBW1.1/2	242.1	1457.2		rupture in the weld-HAZ interface, mat fracture
EBW2/1	228.3	1373.9	1407.6	rupture in the weld, mat fracture
EBW2/2	238.5	1441.2		rupture in the weld, mat fracture

linear porosity in joint TIG02. The static tensile test results revealed that joint TIG01 (made using two runs) was characterised by average tensile strength $R_{mav.}$ = 1046 MPa (Table 10). In turn, joint TIG0 (made using three runs) was characterised by average tensile strength $R_{mav.}$ = 1063 MPa (Table 12). As regards joint TIG02, the making of two smaller (in terms of volume) filling runs led to higher tensile strength than that of joint TIG01.

The A-TIG method was used to make a single-run joint with full penetration, without the filler metal and with activating flux in the form of the SiO_2+TiO_2 mixture. The radiographic tests revealed a crack in the A-TIG welded joint. In the static tensile test, the average tensile strength of the joint amounted to 1202 MPa (Table 13).

The MAG method was applied to weld steel S1300QL using two processes, i.e. 138 and 135. As regards, the MAG (138) process, the filler metal used in the process was a ROBODUR K 350 hard surfacing flux-cored wire (Welding Alloys). Joint MAG350 was made using two runs (i.e. the root run + the filling run) and a ceramic backing strip (used to form the weld root). The joint-related radiographic tests revealed the lack of penetration and the presence of spatter. In the static tensile test, the tensile strength of the joint amounted to $R_{mav.}$ = 1117 MPa (Table 14).

The subsequent MAG welded joint in steel S1300QL was made using a THERMANIT X 96 solid wire having a diameter of 1.2 mm. The aforesaid wire is recommended by the manufacturer for the welding of high-strength steels having a yield point of 960 MPa (process 135). Joint MAG X96 was made using two runs (i.e. the root run + the filling run) and a ceramic backing strip. The radiographic tests did not reveal the presence of any welding imperfections in joint MAG X96. In the static tensile test, the average tensile strength of the joint amounted to $R_{mav.}$ = 1143 MPa (Table 14).

The T.I.M.E method was used to make a single-run joint designated as TIME X96. The filler metal was a THERMANIT X 96 solid wire having a diameter of 1.2 mm. The joint was welded in the groove, without bevelled edges, i.e. as the butt joint with square preparation. The joint-related radiographic tests revealed the presence of single gas pores. The average tensile strength of joint TIME X96 amounted to 1150 MPa (Table 15).

The laser welding method was used to make two joints numbered L01 and L02. The joints were made without the filler metal. The edges of the plates were not bevelled (square butt weld preparation). Joint L02 was made using a finishing layer, made to improve the geometry of the weld face. In joint L01, the radiographic tests revealed the incompletely filled groove, root concavity, and the lack of penetration. In joint L02, the radiographic tests revealed and undercut and the lack of penetration. In the static tensile tests the average tensile strength of joint L01 amounted to $R_{mav.}$ = 1380 MPa, whereas that of joint L02 amounted to $R_{mav.}$ = 1534 MPa (Table 16).

The hybrid welding method (laser Nd:YAG + MAG; process 521 + 138) was used to make one welded joint designated as the HLAW joint. The filler metal used in the process was a STEIN-MEGAFIL 1100M metallic flux-cored wire (Drahtzug Stein). The edges of the weld groove were not bevelled (i.e. square butt weld preparation). The joint was made using the A-L technique, i.e. "drag" arc welding. The above-named technique was selected because of the fact that the upper area of the joint was melted both by arc and the laser beam (leading to the formation of the convex weld face), whereas the central area of the joint and the root area were melted primarily by the laser beam (making them relatively narrow). The joint-related radiographic tests revealed the incompletely filled groove and the presence of gas pores. The average tensile strength of the HLAW joint amounted to 1394 MPa (Table 17).

The electron beam welding method was used to make joints numbered EBW1.1 and EBW2. The joints were made without the filler metal;

the edges of the plates were not bevelled (square butt weld preparation). Joint EBW1.1 was made using one run. In turn, in addition to the filling run, joint EBW2 was made using a finishing layer, the purpose of which was the same as that in the laser welding of joint L02. In terms of joint EBW1.1, the radiographic tests did not reveal any welding imperfections. In turn, as regards joint EBW2, the radiographic tests revealed the incompletely filled groove. The average static tensile strength $R_{mav.}$ of joint EBW1.1 amounted to 1473 MPa, whereas that of joint EBW2 amounted to 1408 MPa (Table 18). In joint EBW2, the finishing layer did not improve the weld geometry. On the contrary, it led to the formation of a notch-like imperfection, probably responsible for the lower tensile strength of the joint than that of joint EBW1.1, made without the finishing layer.

The results of the static tensile tests presented in Tables 12–18 were used to prepare the graphic comparison of average tensile strength values Rm in relation to the minimum yield point of the base material of steel S1300QL, i.e. 1300 MPa. The results of the static tensile tests are presented in Figure 5.

As can be seen in Figure 5, the joints made using arc welding methods (TIG, A-TIG and MAG) were not characterised by tensile strength equal to the minimum yield point of steel S1300QL, amounting to 1300 MPa.

In terms of the joints made using the TIG method and the filler metal having the form of bars made of the base material of steel S1300QL it was possible to observe slightly improved tensile strength in the joint made using two filling runs (joint TIG02) in comparison with that of the joint made using one filling run (joint TIG01). However, in general, the results obtained in the static tensile test do not justify a more optimistic prognosis. The probable reason for the above-named situation is the fact that the chemical composition of the filler metal was identical as that of the steel subjected to welding. During welding, hardening components such as chromium or molybdenum (strongly carbide-forming elements), as a result of diffusive processes, migrated towards carbide precipitates located along grain boundaries or burnt out, weakening the matrix of the microstructure not only in the weld area but also in the HAZ areas adjacent to weld. The aforesaid process worsened the mechanical properties of the joints.

The strength tests concerning the welded joint made using the A-TIG and the SiO2+-TiO2 flux revealed that tensile strength of the aforesaid joint amounted to approximately 1200

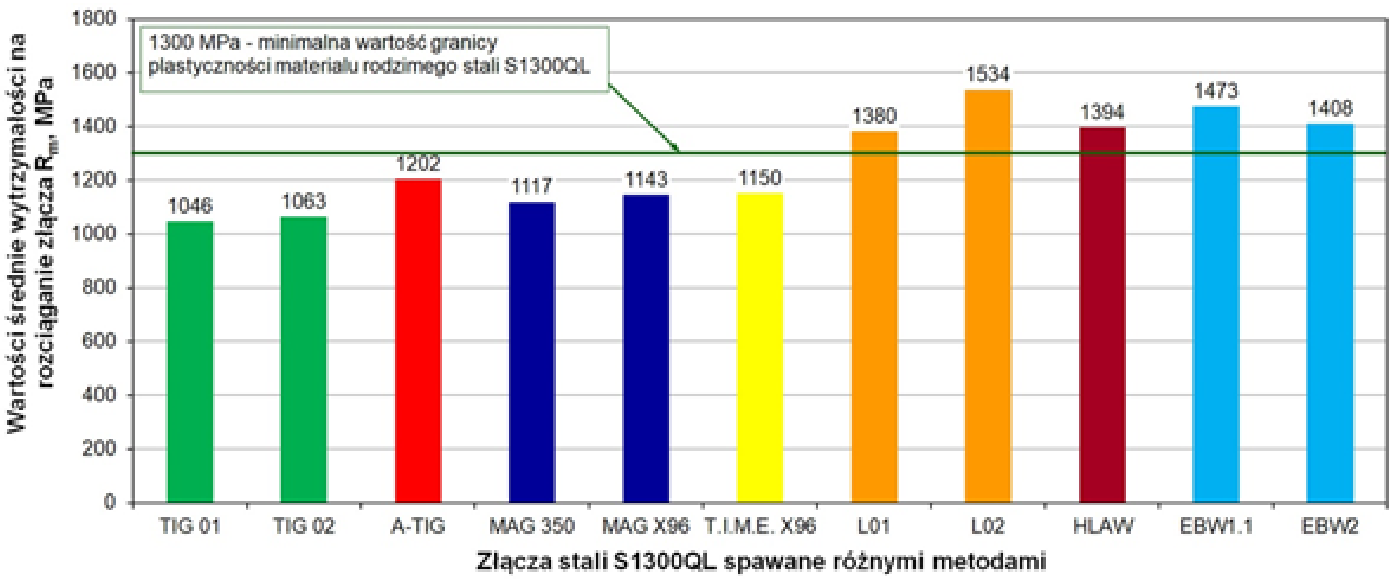


Fig. 5. Average tensile strength values (Rm) of the joints made in steel S1300QL using various welding methods and the comparison of the test results with the minimum yield point of the base material of steel S1300QL

MPa and was by 15% lower than the minimum declared strength of steel S1300QL (1300 MPa).

The comparison presented in Figure 5 reveals that, in terms of the MAG welded joints, the best results were obtained in relation to the joints made using the Thermanit X 96 solid wire.

The tensile test results concerning the joints in steel S1300QL, made using the concentrated energy of the laser beam and electron beam revealed that all of the joints made using the laser welding, hybrid welding (laser + MAG) and the electron beam welding method were characterised by tensile strength R_m exceeding 1300 MPa, i.e. the value of the minimum yield point of the base material of steel S1300QL. The above-presented observation is also important because of the fact that a value of 1300 MPa was exceeded in relation to all of the specimens (made using laser, hybrid and EBW methods) subjected to tensile tests (not just average R_m). Figure 5 reveals that the best result was observed in the laser welded joint made using the finishing layer (joint L02). The tensile strength of the joint made using the HLAW method was nearly the same as that of the laser welded joint made in one run (L01). The welding tests and the results obtained in the static tensile test justify an optimistic assumption that both welding methods, i.e. laser welding and hybrid welding (laser + MAG), because of high welding rates (above 1m/min), will constitute a competitive alternative to classical arc welding methods and, as a result, will be found attractive by potential users also in terms of the welding of high-strength steels.

In turn, the tests revealed that the electron beam welding of steel S1300QL enables the obtainment of good quality joints characterised by high tensile strength, higher than the minimum yield point of the base material. However, because of the very high cost of EBW equipment it can be expected that the aforesaid method will be used for comparative purposes (with other welding methods) and will not find many applications among producers of welded structures made of high-strength steels.

Conclusions

The above-presented tests and results justified the formulation of the following conclusions:

1. The making of joints using the TIG method and two filling runs enables the obtainment of higher tensile strength than that of welded joints made using one filling run.
2. The TIG welding of steel S1300QL involving the use of the filler metal in the form of bars made of the base material of the steel provides the stable and uniform burning of electric arc and, consequently, enables the obtainment of good quality welded joints. However, the filler metal having the chemical composition identical to the chemical composition of steel S1300QL precludes the obtainment of the tensile strength of joints similar to the minimum yield point of the steel.
3. The A-TIG welding of steel S1300QL without the filler metal enables the obtainment of welded joints characterised by tensile strength by approximately 15% lower than the minimum yield point of the base material.
4. The laser welding of steel S1300QL involving the making of the finishing layer (joint L02) enables the obtainment of significantly higher (by more than 100 MPa) tensile strength of joints than that of joints made without the finishing layer (joint L01).
5. The electron beam welded joint made using the finishing layer (joint EBW2) was not characterised by higher tensile strength than that of the joint made using one run.
6. The joints made using arc welding methods (TIG, A-TIG and MAG) were not characterised by tensile strength equal to the minimum yield point of steel S1300QL, amounting to 1300 MPa.
7. All of the joints in steel S1300QL made using laser welding, hybrid welding (laser + MAG) and electron beam welding (L01, L02, HLAW, EBW1.1 and EBW2) were characterised by tensile strength Rm exceeding 1300 MPa, i.e. the minimum yield point of the

base material of steel S1300QL. The highest tensile strength, i.e. Rmav. = 1534 MPa, was obtained in the laser welded joint made using the finishing layer (joint L02).

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