

# Effect of Preheating on the Structure and Mechanical Properties of Steel S1300QL

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**Abstract:** The use of advanced structural materials entails the necessity of adapting typical welding processes to special requirements resulting from the limited weldability of new materials, often tied to their complex chemical composition or unique mechanical properties obtained in technological processes used in the production of steels and alloys. An example of steel characterised by limited weldability is steel having a guaranteed yield point of 1300 MPa, where such high strength is obtained by adding slight amounts of carbide-forming elements and using complex heat treatment processes. As a result, not only a heat input accompanying the process of welding but also any additional procedures connected with the pre-weld preparation of edges or preheating could adversely affect the above-named properties. The tests described in the article involved the simulation of preheating combined with various cooling conditions. The tests enabled the identification of a permissible temperature, at which no unfavourable changes took place as well as the determination of critical temperatures, the exceeding of which could significantly alter mechanical properties.

**Keywords:** unalloyed steel, preheating, welding, structure, hardness

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## Introduction

Because of the necessity of decreasing the weight of products and reducing the energy consumption of manufacturing processes, high-strength steels will enjoy increasing popularity in the years to come [1-4]. The replacement of classical structural steels with steels having a yield point of more than 500 MPa makes it possible to reduce the weight of a structure two or even three times, or looking at the issue otherwise, makes it possible to increase the load capacity of a structure without increasing its weight (wall thickness) [2,5]. To make the foregoing possible, it is necessary to develop appropriate

welding technologies. Because of the presently limited weldability of high yield point steels (particularly those having a yield point of more than 1000 MPa), the use of classical welding processes seems unjustified [6-10]. In cases of unalloyed steels, high yield point values are achieved by adding carbide-forming elements (e.g. vanadium, titanium or niobium), hardening elements (e.g. copper), the obtainment of fine-grained structures and the use of appropriate heat treatment procedures during metallurgical processes. All of the above-named factors are difficult to achieve in welding conditions. As a result, welded joints of high-strength steels

are usually characterised by mechanical properties similar or slightly less favourable than those of the base material [7, 9, 10]. The loss of the aforesaid properties results from the effect of welding thermal cycles and heat treatment procedures accompanying welding processes, e.g. preheating, excessively high interpass temperature, post-weld holding (where only the temperature is controlled) or post-weld heat treatments (where time-temperature conditions are controlled). This study aims to assess the effect of preheating on mechanical properties of steel having a yield point of 1300 MPa and evaluate structural changes (if any) triggered by the preheating process.

### Test materials

Materials used in the tests were 4 mm thick sheets made of steel having a guaranteed yield point of 1300 MPa. Table 1 presents the primary mechanical properties declared by the manufacturer in the material certificate. The chemical composition analysis was performed using spark spectroscopy and compared with data provided by manufacturers (Table 2). The comparison of the chemical compositions provided by TyssenKrupp (Xabo) and SSAB (Strenx) revealed that the steels satisfied the requirements

of the EN ISO 10025-6 standard, yet they differed as regards alloying agents in the declared chemical composition. An addition of vanadium was declared in relation to Xabo, whereas additions of copper and boron were declared in relation to Strenx. As additions of copper and boron increase susceptibility to hot cracking, the tests were performed using steel Strenx 1300 (commercial name).

Because of the fact that in spark spectroscopy the contents of oxygen, nitrogen, carbon or sulphur are rather inaccurate, the analysis of the chemical composition was extended to include carbon and sulphur, and performed using a spectrometer made by LECO. The tests performed using spark spectrometry involved specimens subjected to mechanical grinding (abrasive papers of granularity grades from 100 to 600) and washing. The analysis was performed using the LECO-made spectrometer and chips obtained using a laboratory drill.

Table 1. Selected mechanical properties of steel S1300QL in the as-received state according to EN 10204, p. 3.1

Yield point $R_{p0.2}$ , MPa	Tensile strength $R_m$ , MPa	Elongation $A_5$ , %	Impact energy KV, J at -40°C
1300	1400 ÷ 1700	8	27

Table 2. Chemical composition of steel S1300QL according to data provided by the producers (maximum % by weight according to heat analysis) [1,2], in accordance with PN-EN ISO 10025-6 in relation to the product and individual tests

Steel grade/ name	C	Si	Mn	P	S	Cr	Mo	Ni	V <sup>a</sup>	Cu	B	N	Nb <sup>a</sup>	Ti <sup>a</sup>	Zr <sup>a</sup>
XABO 1300	0.25	0.5	1.4	0.015	0.005	0.8	0.7	2.0	0.08	-	-	-	-	-	-
Strenx 1300	0.25	0.5	1.4	0.020	0.005	0.8	0.7	3.0	-	0.3	0.005	-	-	-	-
According to the standard*	0.22	0.86	1.8	0.025	0.012	1.6	0.74	2.1	0.14	0.55	0.006	0.016	0.07	0.07	0.17
Spark spectrometer	<b>0.23</b>	<b>0.23</b>	<b>0.83</b>	<b>0.009</b>	<b>0.004</b>	<b>0.46</b>	<b>0.39</b>	<b>1.23</b>	<b>0.017</b>	<b>0.009</b>	<b>0.0016</b>	-	<b>0.011</b>	<b>&lt;0.002</b>	<b>&lt;0.002</b>
LECO	<b>0.23</b>	-	-	-	<b>0.0012</b>	-	-	-	-	-	-	-	-	-	-

\*- indicated values related to the products designated as QL, i.e. characterised by guaranteed toughness at a temperature of -40°C

<sup>a</sup> – chemical elements added (at least 0.01%) to refine grains; additions of aluminium are permissible, where the minimum content of dissolved aluminium should amount to 0.01%, which corresponds to a minimum of 0.013% of total aluminium

## Testing methodology

The tests involved specimens in the as-received state as well as after a heat treatment, i.e. holding in a chamber furnace:

- a) at a temperature of 100°C, 150°C, 200°C and 250°C for 30 minutes and cooled in air and water (stage 1);
- b) at a temperature of 250 °C and 500°C for 30 minutes and 80 minutes and cooled in air (stage 2)

The above-named manner of heating enabled the simulation of preheating and post-weld holding. The specimens used in the tests were 20 mm wide, 130 mm long and 4 mm thick. All of the specimens were cut out using the abrasive blasting process and, afterwards, subjected to grinding by means of an intensively-cooled oscillating grinding machine. The outer surfaces were left in the as-received state. Neither treatment led to the heating of the metal, thus not triggering any changes in mechanical properties.

The assessment of the microstructure was based on metallographic observations, including the use of light microscopy. The specimens, subjected to holding in the transverse plane, were sampled at the half of the length. The specimens were cut out using a water-cooled disc cutter and included in chemically bonded resin. The specimen surfaces were subjected to grinding performed using increasingly graded waterproof abrasive papers. Afterwards, the specimen was subjected to mechanical polishing in the slurry of aluminium oxide and chemical etching performed using 4% Nital (alcoholic solution of nitric acid).

The analysis of the mechanical properties was based on results obtained in the Vickers hardness test performed under an indenter load of 49.03 N and 98.1 N. The specimen used in the tests was subjected to grinding, polishing and including in epoxy resin,

maintaining the parallelism of the test surface with the opposite side.

## Microscopic tests

The microstructure of steel S1300QL in the as-received state is presented in Figure 1. The steel fine-grained microstructure contained tempered martensite and bainite.

Holding at a low temperature, i.e. restricted within the range of 100°C to 250°C and cooling both in water (quenched) and in air (free) did not trigger any noticeable structural changes. Exemplary microstructures of the specimens subjected to cooling in air and in water are presented in Figure 2. In relation to a temperature of 250°C, the extension of hold time from 30 minutes to 80 minutes enabled the observation of the precipitation of iron carbides in the steel. The precipitates were probably carbides  $\epsilon$ , formed as a result of martensite decomposition.

Only after using a temperature restricted within the range between medium and high annealing, i.e. 500°C, it was possible to observe the annealing of martensite occurring during a hold time of 30 minutes (Fig. 3). At the above-named temperature, the supersaturation with carbon decreased and led to a greater amount of fine carbide precipitates seen on the metallographic specimen. Carbide  $\epsilon$  formed at the first stage transformed into cementite. It was possible to observe the first indications of the coagulation of carbides.

The microscopic tests did not reveal any significant effect of a hold time on the steel

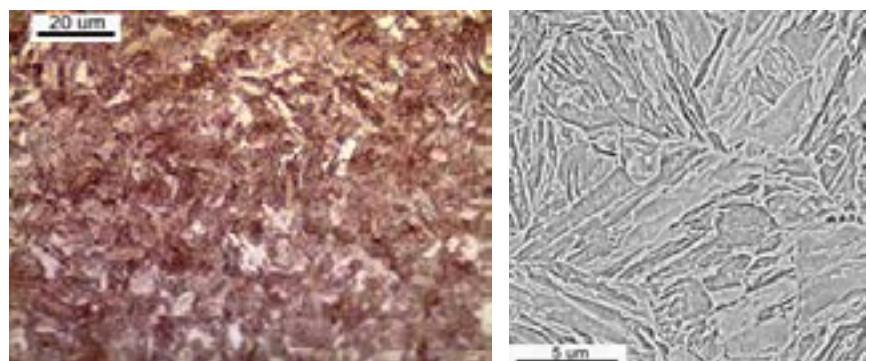


Fig. 1. Microstructure of the steel in the as-received state observed using: a) light microscopy at a magnification of 1000x, b) scanning electron microscopy at a magnification of 15000x, BSE

microstructure. Based on the foregoing it can be concluded that a short heating time used in the welding process and during accompanying procedures should not trigger significant changes in the structure of materials subjected to welding.

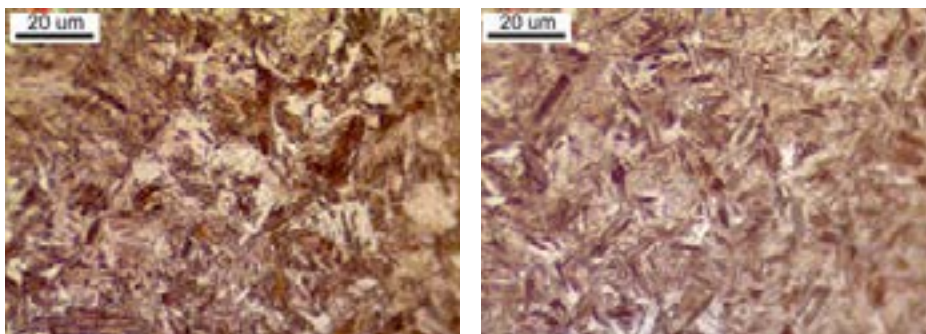


Fig. 2. Microstructure of the steel heated to a temperature of 150°C, subjected to holding for 30 minutes and cooled: a) in air, b) in water

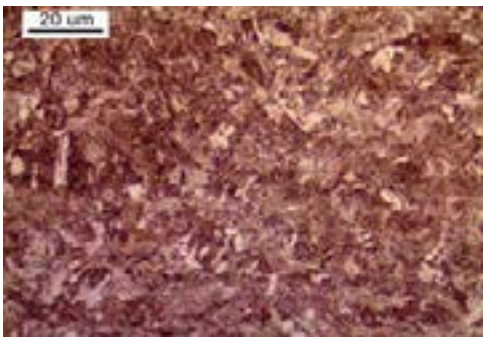
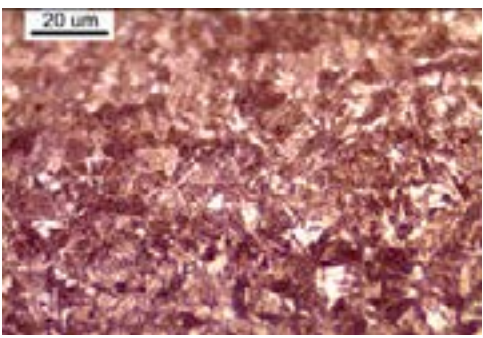
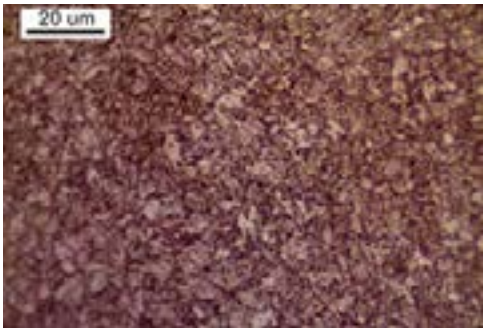
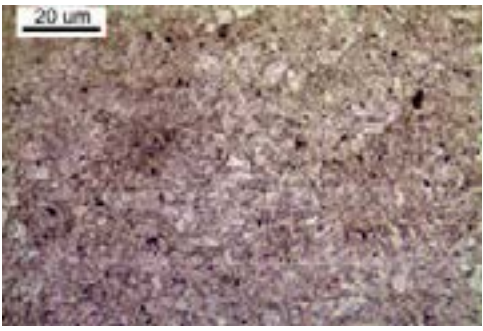
Temperature	Hold time: 30 min.	Hold time: 80 min.
250°C		
500°C		

Fig. 3. Microstructure of the steel heated to a temperature of 250 and 500°C, subjected to holding for 30 minutes and 80 minutes and cooled in air

### Hardness measurements

At stage 1 the Vickers hardness test involved the specimens annealed at a temperature restricted within the range of 100 °C to 250°C. The measurements were performed at the half of the thickness (approximately 2 mm from the surface) under an indenter load of 98.1 kG (HV<sub>10</sub>). At stage 2, i.e. in relation to a temperature of 250°C and that of 500°C as well as a hold time of 30 minutes and that of 80 minutes, the measurements were performed at the half of the thickness (approximately 1 mm from the surface) under an indenter load of 49.1 kG (HV<sub>5</sub>). Figure 5 presents the specimen after being heated to 500°C and subjected to holding at the aforesaid temperature for 80 minutes, with

visible hardness measurement points. The hardness test results are presented in Tables 3 and 4 as well as in Figures 5 and 6.

The analysis of the test results revealed their significant scatter restricted within the range of 15 HV to over 40 HV. The foregoing indicated the significant heterogeneity of the steel properties both along its length and across its thickness. After heating up to a temperature of 500°C and holding for 30 minutes and 80 minutes, the heterogeneous distribution of hardness remained; differences of measured values were slightly lower (below 20 HV).

An increase in a hold temperature was accompanied by a decrease in the mean hardness. Initially, within the temperature range of



Fig. 4. Vickers HV5 hardness test measurement points (specimen after annealing at 500°C)

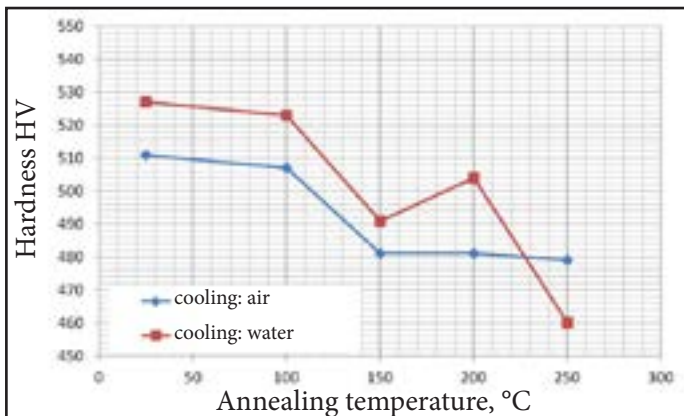


Fig. 5. Changes in hardness HV10 in relation to annealing within the temperature range of 100oC to 250oC (0.5 h) and cooling in water and air

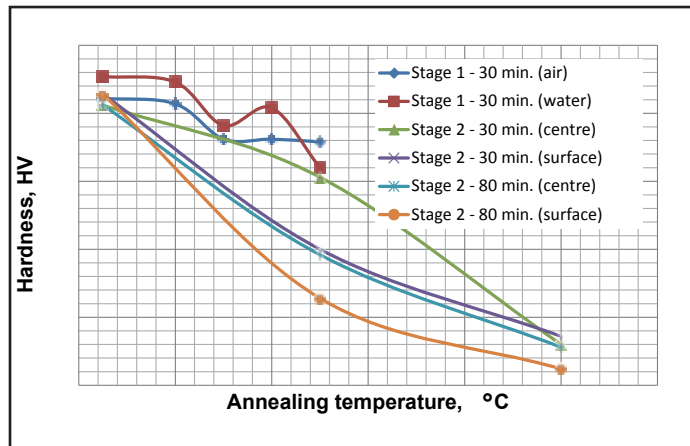


Fig. 6. Distribution of HV hardness in relation to an annealing temperature restricted within the range of 100°C to 250°C (stage 1 – HV10) as well as 250°C and 500°C (stage 2 – HV5) in relation to hold times of 30 minutes and 80 minutes and cooling in water and air

100°C to 250°C, a decrease was insignificant, i.e. from 515 HV<sub>10</sub> in the as-received state to 469 HV<sub>10</sub> at a temperature of 250°C (Table 3 and Fig. 5). In terms of a temperature of 500°C, the

Table 3. Hardness HV10 measurement results in relation to heating within the temperature range of 100°C to 250°C and free and quickened cooling

Specimen number	Measurement 1	Measurement 2	Measurement 3	Mean measurement value	Mean temperature value
01 (as-received state)	524	516	540	527	519
02 (as-received state)	494	504	536	511	
11 (100°C/30 min/W)	516	521	531	523	515
12 (100°C/30 min/A)	493	491	538	507	
21 (150°C/30 min/W)	459	486	528	491	486
22 (150°C/30 min/A)	482	485	476	481	
31 (200°C/30 min/W)	462	563	487	504	492.5
32 (200°C/30 min/A)	482	485	476	481	
41 (250°C/30 min/W)	455	469	457	460	469.5
42 (250°C/30 min/A)	467	471	499	479	

A – free cooling in air      W – quickened cooling in water

Table 4. Hardness HV5 of steel S1300QL in the as-received state and after holding in a furnace at a temperature of 250 °C and 500°C for 30 minutes and 80 minutes with cooling in air

Annealing conditions	At the half of the sheet thickness				On the sheet surface			
	measurement 1	measurement 2	measurement 3	mean value	measurement 1	measurement 2	measurement 3	mean value
As-received state	498	500	519	<b>506</b>	521	514	506	<b>514</b>
250°C/30'	450	462	447	<b>453</b>	416	377	408	<b>400</b>
500°C/30'	340	317	332	<b>330</b>	340	336	332	<b>336</b>
250°C/80'	385	401	402	<b>396</b>	380	373	340	<b>364</b>
500°C/80'	329	333	321	<b>328</b>	313	297	325	<b>312</b>

decrease of hardness was significant, i.e. to approximately 320 HV<sub>5</sub> (Table 4 and Fig. 6). In addition, the extension of a hold time resulted in a decrease in hardness restricted within the range of 40 HV to 50 HV. As regards a temperature of 500°C, the extension of hold time did not affect the hardness of the steel.

## Summary

The simulated preheating process revealed that temperatures not exceeding 250°C did not trigger any changes in the steel structure, composed of tempered martensite and bainite. The heating up to a temperature close to an average tempering point of 500°C triggered the intensified precipitation of carbides within martensite laths and boundaries of bainite grains. In addition, the increase in temperature was accompanied by a decrease in the steel hardness from an initial value restricted within the range of 515 - 520 HV to approximately 320 HV. The aforesaid decrease could significantly affect the functional properties of the steel by reducing its yield point and tensile strength. The tests also revealed that, below a temperature of 250°C, a decrease in hardness was affected by the duration of hold time. The extension of a hold time from 30 minutes to 80 minutes led to a decrease in hardness by approximately 40 HV. At temperatures exceeding 250°C, because of a heat input to the material, the process of carbide precipitation could be fast and result in the negligible effect of a hold time on hardness.

The above-named decrease in hardness at temperatures above 250°C and below A<sub>c1</sub> could also take place when making welded joints of high-strength toughened steels, where the heating of the base material by the heat discharged from the weld could trigger the presence of a softened zone.

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## Reference standards

- PN-EN 10025-6+A1:2009 - Wyroby walcowane na gorąco ze stali konstrukcyjnych - Część 6: Warunki techniczne dostawy wyrobów płaskich o podwyższonej granicy plastyczności w stanie ulepszonym cieplnie