# APPLICATION OF THE S690QL CLASS STEELS IN RESPONSIBLE WELDED STRUCTURES

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***Resume***

In this paper are considered the most important properties of a special class of high strength steels S690QL, which can be classified into the group of special low alloyed steels. The high strength steels belong into a group of high quality steels. They possess exceptional mechanical properties, especially tensile strength and toughness. Those favorable properties are being achieved by application of special procedures of thermo-mechanical processing and simultaneous alloying with adequate elements. The advantages that the S690QL steels have with respect to other steels are being presented here. However, possibilities for application of those steels in responsible welded structures are limited due to their only relatively good weldability. The special procedures for improving it are discussed here, primarily preheating, controlled heat input during welding and additional heat treatment of the welded joint. The aim of this paper is to point to the possibility of application of these steels for manufacturing of the responsible welded structures, and simultaneously to point to the fact that the properties of steels as declared by manufacturer (chemical composition, mechanical properties etc.) are not always reliable and that they can vary depending on the batch.

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## 1. Introduction

High strength steels of the S690QL class are being produced in Sweden and are known under the commercial mark WELDOX 700. The production procedure consists of the precisely defined phases and their chemical composition is strictly controlled. Such a procedure ensures acquiring of exceptionally high mechanical properties. The structure of those steels is interphase, what makes them easily weldable, but only for sheets of relatively small thickness. For production of the more massive welded structures exact instructions and recommendations must be followed, related to selection of the optimal welding technology.

Those steels are prone to appearance of phenomenon known as cold cracks. They appear due to a thermo-mechanical processing of the semi-finished pieces at elevated temperatures. The process consists of material heating up to the austenite region, when the recrystalization is complete, then follows rolling at that temperature and quenching (Q). After that, they are tempered (T) in order to obtain the interphase structures and to retain the high mechanical properties. Those steels are used in manufacturing of hoists and cranes, steel platforms, construction machines, transportation tanks, for parts and assemblies exposed to high dynamic loads, responsible welded structures and others.

Steels of the S690QL class belong to a group of special, low alloyed steels, where the chemical composition is defined by the delivery condition standard (EN 10025-6), and further prescribed by the manufacturer (Tab. 1). The carbon content is limited to 0.20% what improves the weldability. Addition of small quantities of other alloying elements causes improvement of those steels' properties, where the contents of niobium and boron should be especially emphasized since they deoxidize steel and significantly make steel grains smaller [1-3].

According to EN 10025-6, as well as the manufacturer, there exist three versions of the S690 steels: S690Q, S690QL and S690QL1, which differ from each other only by guaranteed impact toughness (S690Q-WELDOX D has guaranteed impact toughness of 27 J at 20°C, S690QL-WELDOX E has 27 J at – 40°C and S690QL1-WELDOX F has 27 J at – 60°C [2, 3].

## 2. Properties of S690QL steels

The main reasons for mass application of the high strength steels of this class are the exceptionally high mechanical properties, like tensile strength and yield stress, as well as the favorable impact toughness. The basic data provided by manufacturer for those steels are given in Table 2 [1, 3, 4, 8].

However, data about S690QL steel, supplied by the manufacturer, should be verified through tests, since the mechanical properties, as well as the chemical composition, can vary from batch to batch, what in some cases cannot be overlooked. This can be seen on the case of the differences in the chemical composition prescribed by standard EN 10025-6 (Tab. 1) and chemical composition obtained by the spectrographic analysis (Tab. 3) of the S690QL steel.

Thus, the analysed chemical composition shows smaller content of several elements, in several cases even absence of some of them. This is convenient form the aspect of steel's weldability, since the weldability esttimates are usually being done based on the chemical composition of steel as obtained from the steel mill, and thus they are estimated as less favourable.

What concerns the mechanical properties; there exist certain differences between the prescribed values and those obtained by experiments, depending on the plates' thickness. In Table 4 are presented experimental results for the plate of thickness 15 mm.

### *2.1. Weldability of high strength steels of S690QL class*

Weldability of high strength steel of the S690QL class is relatively good. However, some special additional measures are required for its improvement, primarily related to necessary preheating, controlled heat input during welding and subsequent heat treatment of the welded joint. Considering the properties of steels in question, namely that they are prone to form the cold cracks due to welding, the preheating is mandatory, especially when the pieces with large cross-sections are being welded. At the start of weldability estimates, one should first calculate the carbon equivalent (CE), which points to metallurgical weldability of those steels. In Table 5 are presented values of CE in terms of the cross-section thickness.

As it was already pointed out, these steels are prone to forming of cold cracks. That requires application of certain measures to ensure successful welding. The correct preheating and inter-pass temperature (interlayer temperature is the temperature, which the single-layer welding pass is being cooled to, i.e., the temperature at which the second pass deposition starts) are only two of measures aimed at preventing forming of cold (hydrogen) cracks. Some recommendations, that should be obeyed when welding of these steels, are listed here [1, 2, 8, 10]:

- Preheat the parts to temperature Tp = 150-200°C;

*Table 1*

*Prescribed chemical composition of S690QL steels.*

| Mark | Requirement | Maximum allowable content of alloying elements (%) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C | Mn | Si | P | S | Cr | Mo | Ni | V | Al | B | Cu | Ti | N | Nb |
| S690QL | Prescribed | 0.20 | 1.50 | 0.60 | 0.020 | 0.010 | 0.70 | 0.70 | 2.0 | 0.09 | 0.015 | 0.005 | 0.30 | 0.040 | 0.010 | 0.040 |

*Table 2*

*Prescribed mechanical characteristics of S690QL steels according to standard EN 10025-6.*

| Steel mark | Thickness (*mm*) | $R_m$ (*MPa*) | Min. $R_P$ (*MPa*) | Min. $A_5$ (%) | Microstructure |
|---|---|---|---|---|---|
| **S690QL Weldox 700 (D, E or F)** | 4.0-53.0 | 780-930 | 700 | 14 | Interphase structure, tempered |
| | 53.1-100 | 780-930 | 650 | 14 | |
| | 100.1-130 | 710-900 | 630 | 14 | |

*Table 3*

*Analyzed chemical composition of steel S690QL.*

| Mark | Requirement | Content of chemical elements (%) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C | Mn | Si | P | S | Cr | Mo | Ni | V | Al | B | Cu | Ti | N | Nb |
| S690QL | Prescribed max | 0.12 | 1.35 | 0.36 | 0.011 | 0.010 | 0.17 | 0.22 | 0.16 | 0.06 | 0.081 | 0.00147 | 0.04 | – | – | 0.0569 |

*Table 4*

*Experimental results of tensile test.*

| Sample No. | $L_0$ (*mm*) | $S_0$ (*mm²*) | $R_{p0.2}$ (*MPa*) | $R_m$ (*MPa*) | $A_{11.3}$ (%) | $A_g$ (%) |
|---|---|---|---|---|---|---|
| **1** | 89.28 | 50.27 | 781.94 | 797.81 | 14.19 | 1.73 |
| **2** | 89.28 | 50.27 | 809.40 | 839.92 | 11.30 | 5.79 |
| **3** | 88.42 | 50.01 | 800.41 | 835.52 | 9.98 | 4.86 |
| **4** | 88.29 | 50.27 | 811.95 | 842.45 | 10.92 | 5.48 |

- Lower hydrogen content in the weld (H < 5 ml/100 g of weld metal);
- Maintain the adequate preheating temperature (Tp) as well as inter-pass temperature - Tinterpass = 200-225°C;
- Apply low-hydrogen electrodes (mandatory keeping in dry place and drying according to manufacturer's recommendations);
- Never use filer metals of higher strength than the necessary and prescribed;
- Select the optimal order of welding, which would reduce the residual stresses and strains;
- Adopt correct clearance in the groove (maximum 3 mm for the butt and corner groove);
- The heating-through time should be 2 min/mm of thickness (even up to 5 min/mm according to this steel manufacturer); parts should be heated and cooled slowly;
- After depositing of each weld layer, the caterpillar surface should be thoroughly cleaned of slug;
- The attaching welds should be executed following the technological documentation (for the first weld), depending on the type of joint and the plate thickness, where the attaching weld length should be within range 40 – 50 mm; it is recommended that the filler metal for the attaching welds should be the same as for the root weld.

It should be emphasized that the root welds are usually done by the "soft" electrodes (austenite electrodes), while the cover welds should be done with the filler metals of higher strength, which would increase the welded joint's strength.

It should also be pointed that, related to thermo-mechanical procedure of manufacturing these steels, their application is limited to working temperatures which do not exceed 580°C, because, even when the tempering temperature is exceeded, the significant worsening of mechanical properties may occur [2, 3].

As already explained earlier, some of the most important welding parameters, which influence weldability, are: preheating temperature, heat input and additional heat treatment.

*Preheating temperature*

Preheating is a measure which was necessary for welding of the considered steel, since it removes the moisture from the welded joint and extends the cooling time of the heat affected zone (HAZ), what most frequently removes or significantly reduces danger of appearance of cold (hydrogen) cracks. Minimal preheating temperature, recommended by the manufacturer, is 140°C for equivalent thicknesses of the joints of 10.1 to 20 mm [4]. However, authors of this paper, based on their own experimental results [8, 10], recommend the preheating temperature in the range 150 to 200°C (150°C for thickness of 15 mm) in order for preheating to have positive effect on the welded joint properties. Temperature above 200°C is not recommended since it may cause deterioration of some of the mechanical properties obtained by the primary processing of steel or by microalloying.

*Heat input (ql)*

The heat input or linear welding energy has to be strictly controlled for the sake of preserving favorable, primarily mechanical, properties, microstructure and hardness of certain zones of the welded joint, above all the HAZ. The heat input is closely related to preheating temperature and thickness of the working pieces, what can be concluded from the diagram presented in Figure 1. For equivalent thickness of the but joint of 15 mm the quantity of the heat input should not be more than 20000 J/cm [4, 10].

*Additional heat treatment*

Taking into account the possibility of appearance of the cold cracks, when the preheating temperature falls below 100°C, sometimes it is necessary to apply additional heat treatment or slow cooling in order to

*Table 5*

*Values of the maximum carbon equivalent [2, 3].*

| Mark | Thickness *mm* | Chemical equivalent carbon (%) | |
|---|---|---|---|
| | | $CEV = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15}, \%$ | $CET = C + \frac{Mn+Mo}{10} + \frac{Cr+Cu}{20} + \frac{Ni}{40}, \%$ |
| **Weldox 700 (D, E or F)** | **8** | 0.43-0.55 | 0.29-0.36 |
| | **20** | 0.43-0.55 | 0.29-0.36 |
| | **30** | 0.46-0.55 | 0.31-0.36 |
| | **60** | 0.57-0.55 | 0.35-0.36 |

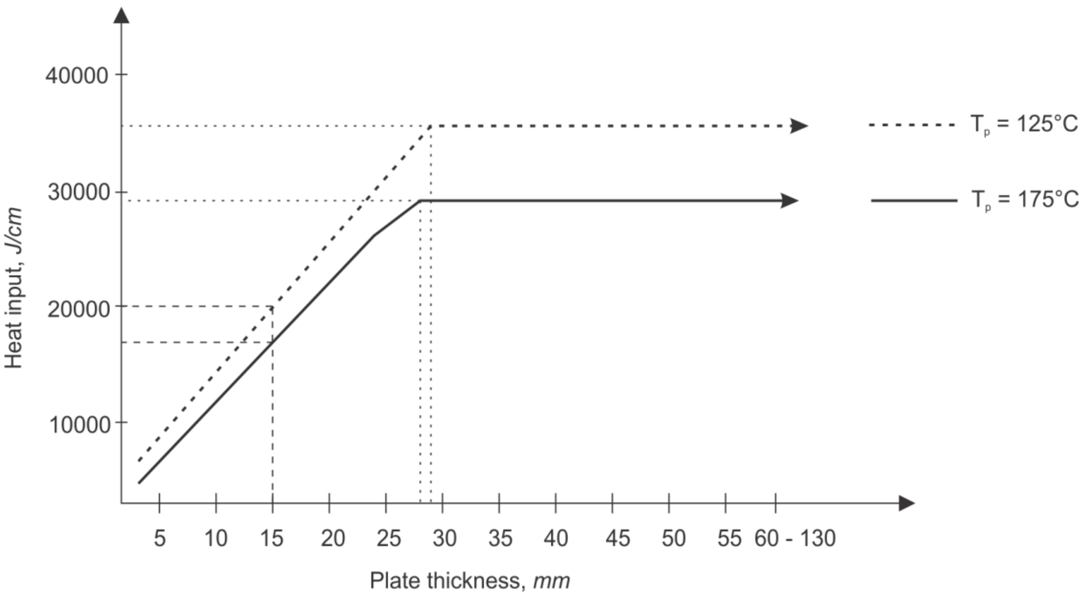



*Fig. 1. Recommended heat input for the preheating temperatures of 125 and 175°C.*

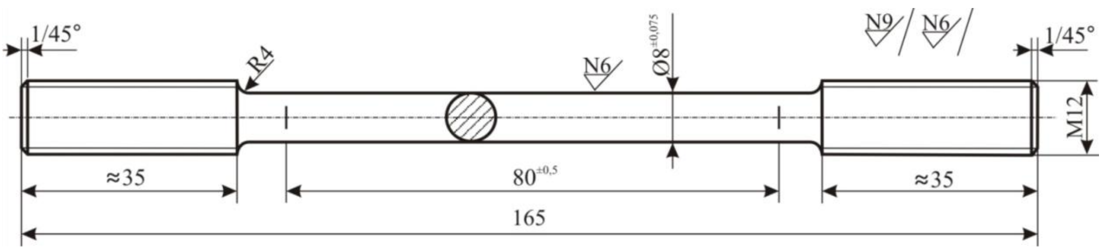



*Fig. 2. Appearance of a tensile test sample.*

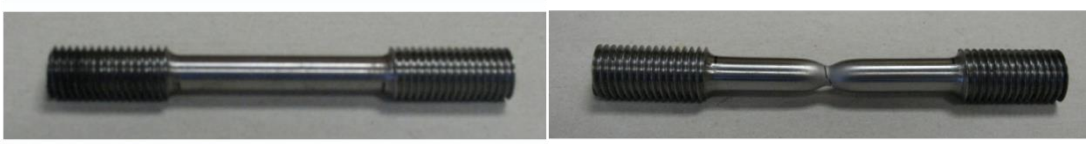


*Fig. 3. Sample appearance prior to (left) and after the test (right).*

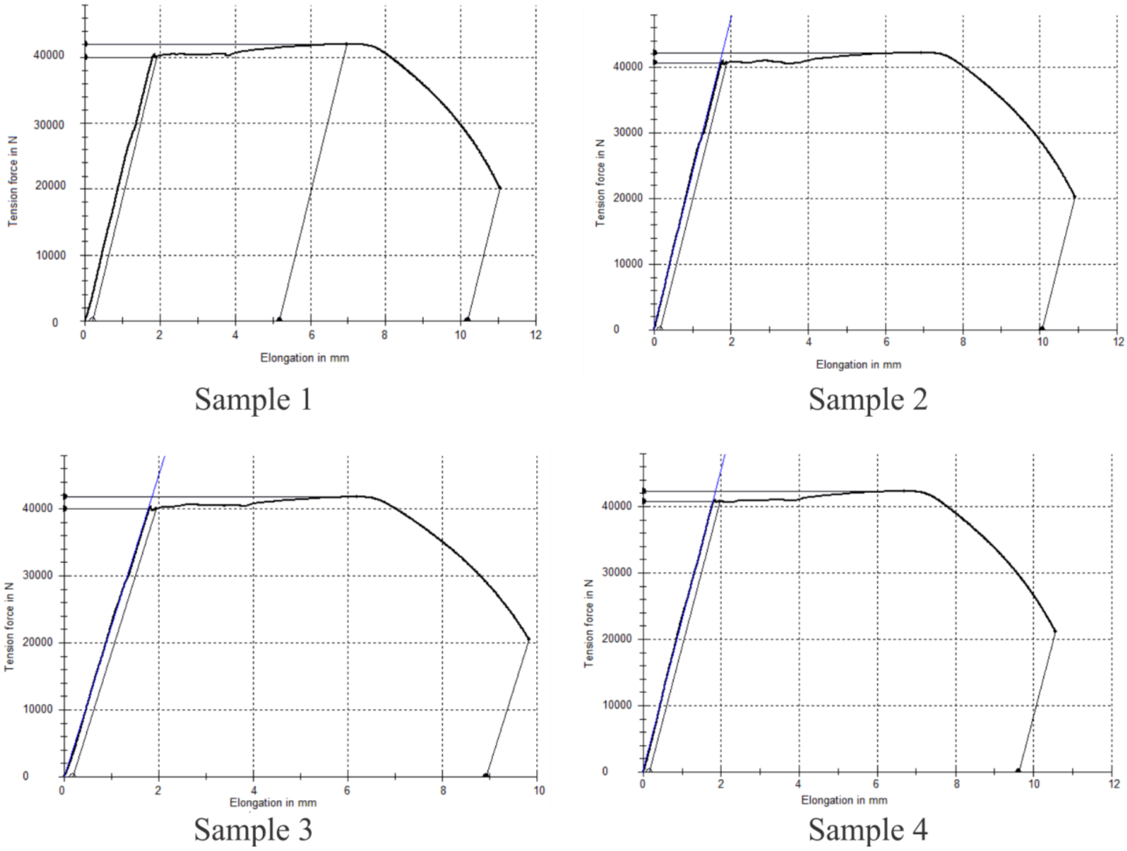



*Fig. 4. Tension test diagram for four samples.*

extend the cooling time from 800 down to 500°C (t8/5). By doing that, i.e., extending t8/5, one enables diffusion of hydrogen from the joint metal and HAZ. The additional heat treatment regime assumes keeping welded parts at 150°C for one hour for each 10 mm of thickness. After that time the welded parts should be slowly cooled [10]. Additional heat treatment leads to lowering the level of residual stresses in the welded joint and to obtaining more favorable structures in the HAZ [11].

## 3. Experimental investigations

Experimental testing of the S690QL steel included mechanical tensile test, impact toughness test and investigation of microstructure as well as hardness measurements.

*Tensile test.* Four specimens were prepared from the plate of thickness 15 mm, Fig. 2. The prepared samples were tested at the ZWICK/ROEL Z 100 testing machine, with the measurement range of 1 to 100 kN. The strain rate was 10 mm/min. Test results are presented in Table 4. Physical appearance of the tested sample is shown in Fig. 3. Based on sample fracture point appearance it can be concluded that this steel possess favorable ductility [2].

Characteristic force-displacement diagram in tension for four samples is shown in Fig. 4.

*Impact toughness test.* According to procedure, similar to that one for the tensile test, six samples, ISO-V (55×10×10 mm), were prepared (Figs. 5 and 6) for the toughness impact test according to standard EN 10045-1. Tests were performed on the instrumented Charpy pendulum in the accredited laboratory in Belgrade. Results of these tests of the base metal, at room and lowered temperatures, are presented in Table 6 [1, 5]. It should be emphasized that toughness drop can occur in certain zones of the welded joint due to unfavorable influence of temperature cycles to

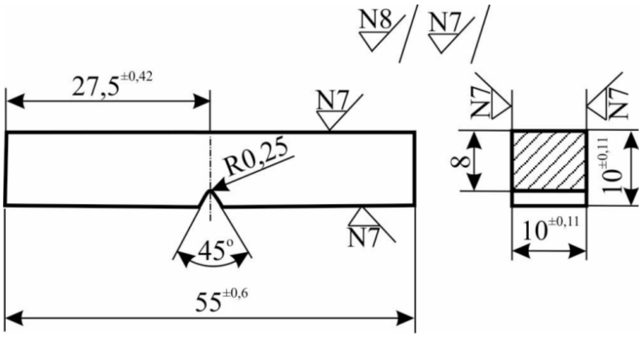



*Fig. 5. Appearance of the impact toughness test sample.*

*Fig. 6. Physical appearance of the impact toughness test samples.*

*Table 6*

*Values of impact toughness at room and lowered temperatures.*

| **Material type** | **Temperature testing (ºC)** | **Sample No.** | **Impact energy (*J*)** | | **Impact toughness (*J/cm²*)** | |
|---|---|---|---|---|---|---|
| | | | **Plate 1** | **Plate 2** | **Plate 1** | **Plate 2** |
| **S690QL (Weldox 700)** | **+ 20** | **1** | 235.17 | 242.02 | 293.96 | 302.52 |
| | | **2** | 222.44 | 226.19 | 278.05 | 282.74 |
| | | **3** | 234.68 | 250.89 | 293.34 | 313.61 |
| | **- 40** | **1** | 219.59 | 238.10 | 274.49 | 297.62 |
| | | **2** | 179.78 | 210.84 | 224.73 | 263.55 |
| | | **3** | 206.08 | 221.39 | 257.60 | 276.74 |

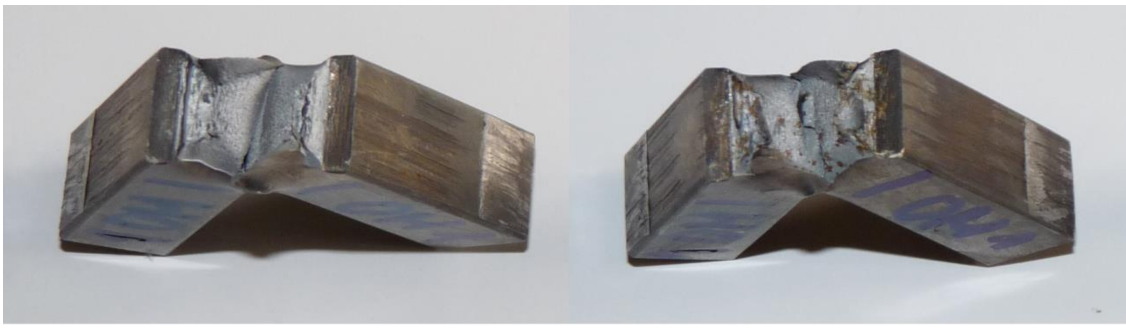


*Fig. 7. Appearance of the samples' fracture surfaces.*

*Table 7*

*Measured values of the S690QL steel's hardness.*

| **Sample No.** | **1** | | | **2** | | | **3** | | | **4** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **HV10** | 274 | 279 | 276 | 279 | 278 | 279 | 279 | 279 | 279 | 279 | 281 | 276 |

which those zones were exposed during the welding [12].

Share of the ductile fracture at room temperature was within range 89 – 96 %, while at the lowered temperatures it was 78 – 95 % (Fig. 7). Presented values of the impact toughness exhibit high level of impact toughness, which is maintained at the lowered temperatures, as well. Taking that into account, one can say that the S690QL steel is adequate for manufacturing very responsible constructions, since the tough material structure does not allow appearance of the initial cracks, thus preventing phenomenon of the brittle fracture.

In Figs. 8a and 8b are shown diagrams of force and fracture toughness variation with time, for the case of the cooled sample.

*Microstructure test.* This test referred primarily to determination of sizes and distribution of grains, where the structure of the considered steel was estimated as interphase tempered one, Fig. 9 [4]. Measured values of the base metal hardness (according to standard EN1321) were within limits 274 to 281 HV10 (Table. 7) [5]. Experimentally obtained results confirmed the fact that the S690QL class steels have exceptional mechanical properties, according to characteristic prescribed by standard EN 10025-6:2004. It should be mentioned that mechanical characteristics given in Table 4 were obtained during tests of proportionally long samples (for example A113). During the repeated tests, when the proportionally short samples were used, the average value of extension A5.65 = 14.78 5 was obtained. This conclusion enables and justifies application of those steels for very responsible structures.

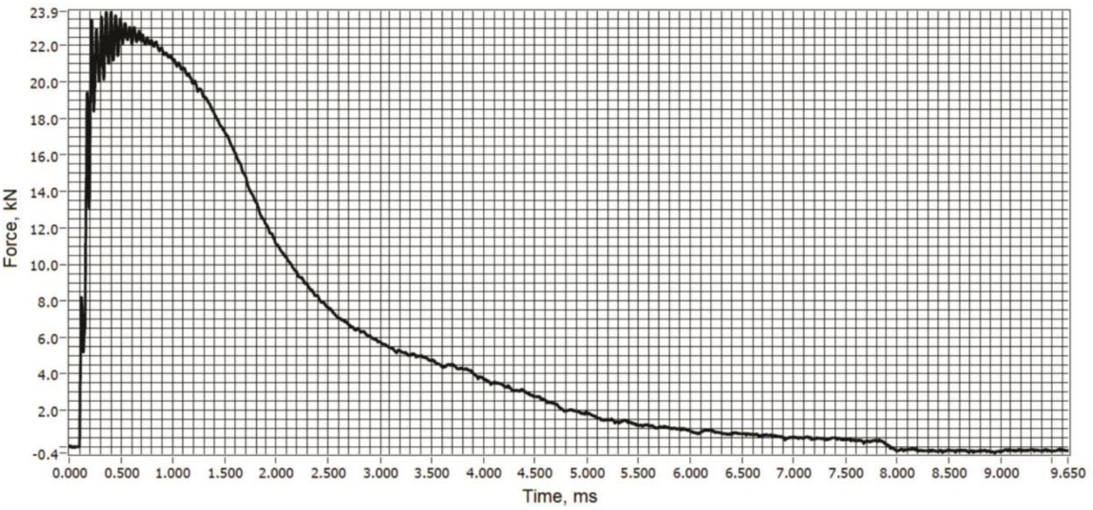
*Hardness.* Hardness of the S690QL steel was measured on four samples and in several points. The obtained results are presented in Table 7.

From table 7 one can notice that the hardness values are grouped around 280 HV10, but it should be pointed that due to welding that value changes, and in some zones it can drastically increase (in the merging zone it can even reach 390 HV10), what should also be kept in mind.

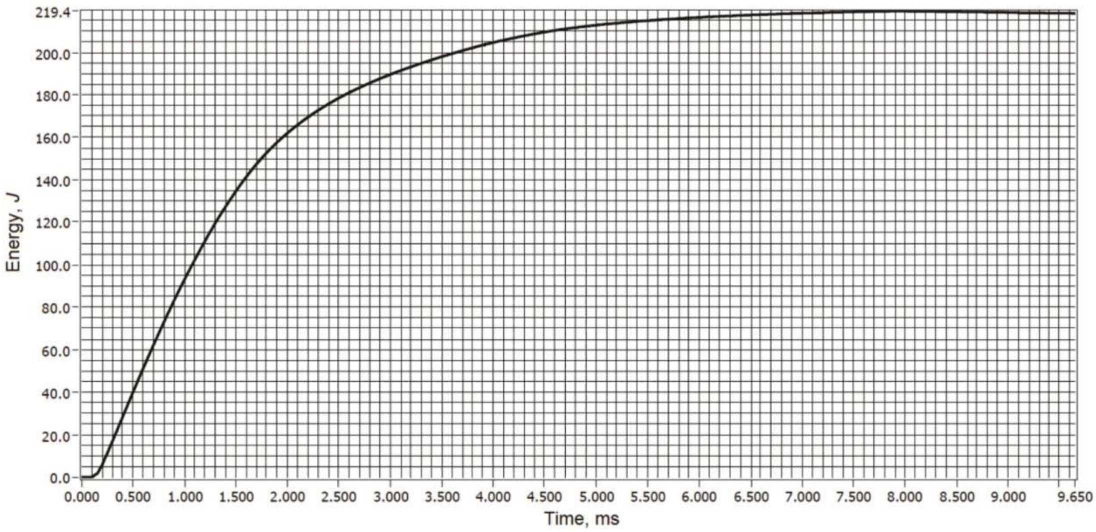
## 4. Importance and application of S690QL steels

Application of the S690QL steels is primarily related to very responsible structures made by welding. Related to that, it should be emphasized that in selecting the welding technology, it is necessary to grasp all the influential factors and to select the adequate welding technology, since the uncontrolled heat input can result in worsening of properties acquired through the complex thermo-mechanical processing. This paper is an attempt only to point to some of the possibilities of application of those steels, which primarily refer to manufacturing of the responsible welded structures exposed to external static and dynamic loads. It should also be emphasized that high strength properties of these steels enable application of significantly smaller cross sections of structural elements, what significantly decreses the weight of the structure, as well as the quantity of the filler metal needed for welding.

It was also proved that data obtained from the manufacturer, related to steel's properties and even chemical content can not be treated as completely reliable, but that they differ from batch to batch. In order to show those differences additional experimental investigations were conducted, which were concerned with determining the exact chemical composition, the most significant mechanical properties, toughness, hardness and micro structure. Authors have presented those experimental results also, thus giving a contribution to better understanding problems related to those steels' applications, where the main conclusion was that the considered steels can fulfil the high requirements related to durability of the welded structure.




**a)**




**b)**

*Fig. 8. Variation of force (a) and fracture toughness (b) with time – sample 1 (– 40ºC).*

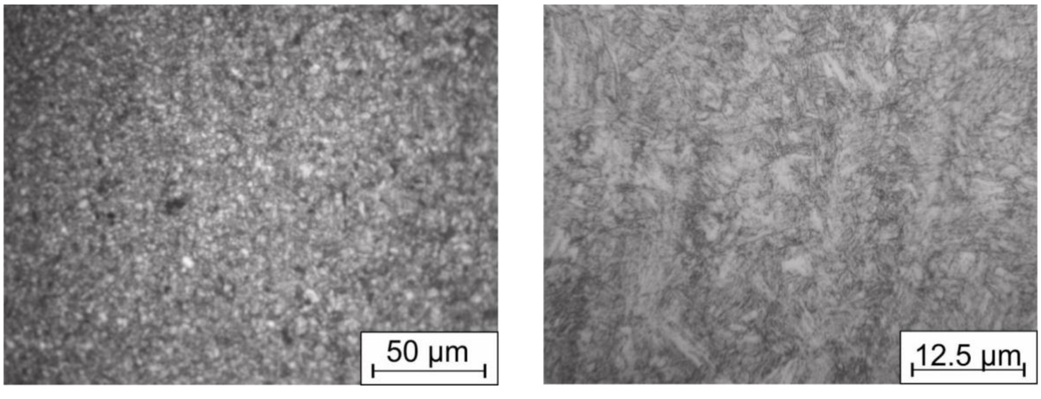



*Fig. 9. Microstructure of the base metal.*

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***Note***

*The shorter version of this work was presented at "SEMDOK 2013" Conference in Terchova, Slovakia, January 30 – February 1, 2013. – reference [6].*

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