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INFLUENCE OF DIMENSIONAL SIZE OF ROLLED PRODUCT MADE OF S690QL STEEL ON IMPACT TOUGHNESS AND GRAIN SIZE

Aida Imamović[1a], Mirsada Oruč[1b], Milenko Rimac[1c], Gorazd Kosec[2], Safet Hamedović[1d]

[1]Fakultet inženjerstva i prirodnih nauka, Univerzitet u Zenici, B&H
[2]SIJ Acroni d.o.o. Jesenice, Slovenia
[1a] aida.imamovic@unze.ba, 0009-0000-5902-9906
[1b] mirsada.oruc@unze.ba, 0000-0002-9980-7650
[1c] milenko.rimac@gmail.com, 0009-0007-1045-0346
[2] gorazd.kosec@acroni.si, 0009-0002-6930-964X
[1d] safet.hamedovic@unze.ba, 0009-0000-3443-9546

Abstract

Fine-grained structural steel of the S690QL designation is widely used due to its very good mechanical properties and good weldability and bending, resistance to abrasion and corrosion. It is most often made in the form of plates of different thicknesses. S690QL steel plate has excellent performance characteristics and is used when low temperature resistance and important strength components are required. It is used in addition to applications for construction machines and structures, mining machines and in the energy sector, highways, railway bridges, etc.

Since this steel is used in very demanding conditions such as low temperature, it is very important to test the mechanical properties of the impact toughness at these temperatures. Toughness is an important property that can indicate a material's tendency towards brittle fracture. In this work, a large number of samples were tested for this property, i.e. impact toughness at a temperature of -40°C taken from plates of different thicknesses made of S690QL steel. In addition to this property, the grain size of this steel after heat treatment is also taken into account. These characteristics and their mutual dependence provide directions for correcting the production of semi-finished products or finished products

Key words: *steel S690QL, dimensions of rolled plates, impact toughness, grain size*

1. INTRODUCTION

S690 QL steel is a high-strength, fine-grained structural steel that, in quenched and tempered condition, has a minimum yield strength R_{eH} of 690 MPa with guaranteed toughness (Charpy impact toughness) of 30 J at a temperature of -40°C, for rolled plates with thicknesses ranging from 3 to 50 mm.

Since S690 QL is a high-strength structural steel produced in accordance with the EN 10025-6 standard, it is thermally treated by quenching and tempering and possesses good bending and welding properties. According to EN 10025-6:2004+A1:2009 and the DIN EN 10025-1 standard, which is harmonized with the former, impact toughness tests are conducted on both longitudinal and transverse sections of the samples at a temperature of -40°C.

Testing and evaluation of results were carried out in accordance with the EN 10025-6 and DIN EN 10025-1 standards, using standard procedures applied in the accredited Mechanical and Metallographic Testing Laboratory of the “Kemal Kapetanović” Institute at the University of Zenica. It is important to note that the delivery standard EN 10025-6 prescribes testing of tensile properties and impact toughness only on the longitudinal section at a temperature of -40°C [1].

In this study, in addition to impact toughness testing on the longitudinal direction of the rolled plate samples, tests were also conducted on samples taken in the transverse direction, as well as grain size analysis. The aim was to determine the correlation between these parameters and to identify potential directions for further improvement of mechanical properties.

2. CHARACTERISTICS OF S690QL STEEL PLATES

Structural steel S690QL belongs to the group of high-quality high-strength steels, which are fully killed during production. The chemical composition of this steel is shown in Table 1, and its mechanical properties are shown in Table 2.

Table 1. Chemical composition of S690QL steel products in quenched and tempered condition according to EN 10025-6:2004+A1:2009 (max. %)

Steel	C	Si	Mn	P	S	N	B	Cr	Cu	Mo	Nb	Ni	Ti	V	Zr
S690QL	0.22	0.86	1.80	0.025	0.012	0.016	0.006	1.6	0.55	0.74	0.07	2.1	0.07	0.14	0.17

Depending on the product thickness and production conditions, the manufacturer may add one or more alloying elements to the steel up to the maximum values in order to achieve the desired properties. At least 0.010% of grain-refining elements must be present. Aluminum is also one of these elements. The minimum content of 0.010% refers to soluble aluminum, and this value is considered achieved if the total aluminum content is at least 0.013% [2].

Table 2. Mechanical properties of S690QL steel products according to EN 10025-6 for plate thicknesses less than 50 mm and greater than 3 mm

Steel	R_{eH}, MPa	Rm, MPa	A, %	KV at -40°C, J, longitudinal	KV at -40°C, J, transverse
S690QL (1.8928)	Min.690	770-940	Min.14	30	27

The standard EN 10025-6:2004+A1:2009 has also been adopted as a Bosnian-Herzegovinian standard, with the latest edition published as BAS EN 10025-6+A1:2024 (Hot-rolled products of structural steels – Part 6: Technical delivery conditions for flat products of high yield strength structural steels in the quenched and tempered condition).

This steel is designed to provide an excellent combination of high strength, toughness, abrasion resistance, and weldability. The main reasons for the widespread use of high-strength steels of this class are their exceptionally high mechanical properties, such as tensile strength and yield strength, as well as favorable impact toughness and fracture energy [3].

3. IMPACT TOUGHNESS

Impact toughness testing is performed according to the customer's requirements, and in this study, the results are presented for unfavorable service conditions, i.e., tests conducted at a temperature of -40°C. The tests were carried out on a large number of samples taken from test plates in both the longitudinal and transverse directions, using the Charpy V-notch method, in the accredited Mechanical Laboratory of the "Kemal Kapetanović" Institute at the University of Zenica, in accordance with the BAS EN ISO 148-1:2017 standard.

After quenching and tempering, the plates exhibit an improved structure typical of hot-rolled plates that have undergone subsequent heat treatment.

It should be noted that toughness is influenced by the average grain size, not by isolated clusters of larger grains, as long as the majority of grains are small on average. It can be assumed that such larger grains are mainly associated with non-uniform distribution of certain elements, i.e., their uneven concentration (especially those that, through precipitation of their compounds, influence grain size).

A variety of factors affect the toughness of a material during testing, such as:

- testing temperature,
- microstructure (especially grain size),
- shape and dimensions of the notch,
- specimen dimensions,
- impact velocity, etc.

Testing temperature has the greatest influence on toughness, i.e., on the material's impact toughness. In general, material toughness decreases as the testing temperature decreases. This is because a lower temperature reduces the plasticity or deformability of the material [4].

Microstructure also has a significant impact on the toughness of the material. The smaller the crystalline grain size, the higher the toughness. In steels, reducing the grain size by one unit on the ASTM E112 scale lowers the transition temperature by approximately 15°C. Deformed materials also exhibit greater toughness, i.e., a lower transition temperature, due to their anisotropic structure, especially in the longitudinal direction [4].

In plate materials (e.g., sheet metal), the highest impact energy is observed in the rolling direction (1), slightly lower in the transverse direction (2), and the lowest in the through-thickness direction (3) (see Fig. 1).

Alloying elements (C, Ni, Al, Mo...) and elements generally classified as impurities (P, S, O, N...) in steels can be divided into two groups based on their effect on impact toughness:
– elements that reduce impact toughness, and
– elements that increase impact toughness.

The first group, which reduces impact energy, includes carbon (C) and phosphorus (P). Carbon increases the content of cementite and pearlite, thereby raising the ductile-to-brittle transition temperature. Phosphorus reduces the plasticity and toughness of steel. During cold working, phosphorus causes brittle fracture due to the formation of a brittle solid solution (iron phosphide) that segregates along grain boundaries and in interdendritic regions.

The second group, which increases impact energy, includes nickel (Ni), molybdenum (Mo), and aluminum (Al). Nickel expands the γ-phase region and significantly improves the toughness of the material. Molybdenum promotes carbide formation, which contributes to improved toughness by producing a fine-grained, evenly distributed structure. Aluminum, as a deoxidizing element, helps develop a fine-grained microstructure, thereby increasing the steel's toughness. Additionally, through the formation of aluminum nitride (AlN), it reduces the nitrogen (N) content in the solid solution, which further enhances material toughness [5].

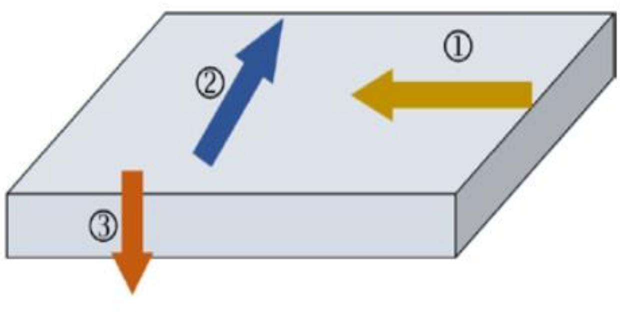

Figure 1. Impact fracture work of the material depends on the sampling direction [5]

3. EXPERIMENTAL PART

In the experimental part of this study, 60 samples of rolled test plates of different thicknesses were examined, ranging from 7.96 mm to 40.72 mm. Test specimens for impact fracture work were made from these plates, with smaller specimens being prepared from plates thinner than 10 mm. The dimensions of the specimens affect the material's toughness in different ways. The specimen length has the least effect, while width and thickness similarly contribute to the reduction of toughness. The most important factor is the ratio between notch depth and specimen thickness. Therefore, the standards for the acceptance and delivery of general structural steels (DIN 17100) prescribe lower values of impact toughness (KV) for narrower specimens [4].

It should be noted that there is no clear correlation between toughness or impact fracture work and other mechanical properties of the material. However, it is generally true that materials with high toughness or impact toughness usually have lower strength values and higher values for elongation and reduction of area.

3.1. Impact Fracture Work Testing

Standard EN 10025-6 for hot-rolled plates in quenched and tempered condition, made of S690 QL steel, prescribes for impact toughness testing at a temperature of -40°C a minimum average value of 30 J from three tests on longitudinal specimens, and 27 J on transverse specimens of the plate.

The appearance of the test plates from which the samples were taken for testing is shown in Figure 2.

Figure 2. Test plates from which specimens for impact toughness and grain size testing were taken

The obtained values from the impact toughness tests at a temperature of -40°C, as well as the grain sizes for the samples taken from plates of different thicknesses (ranging from 7.96 mm to 40.72 mm), were thoroughly analyzed and presented in the form of a diagram.

4. ANALYSIS OF TEST RESULTS

This study analyzed the influence of product dimensions on impact toughness and grain size, as well as their mutual relationship. The results obtained from 60 tested plate samples with thicknesses ranging from 7.96 mm to 40.72 mm are presented in a diagram, Figure 3.

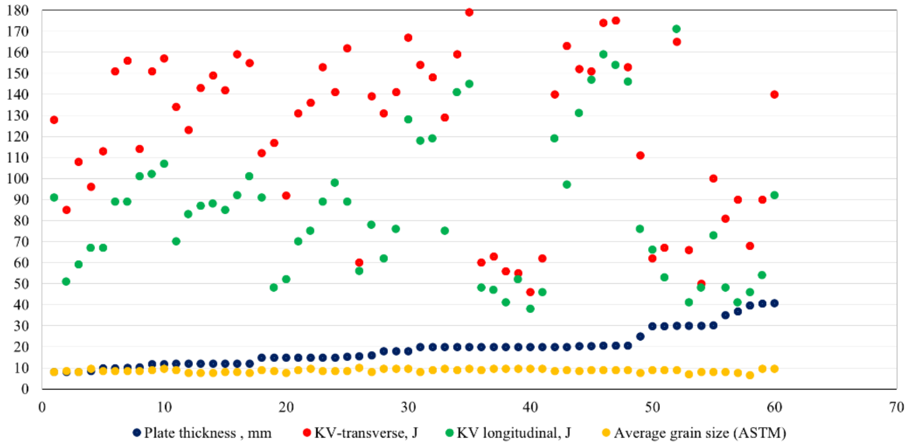

Figure 3. Presentation of test parameter results for 60 tested plate samples with thicknesses ranging from 7.96 mm to 40.72 mm

From Figure 3, it can be seen that the impact toughness results are inconsistent, but fall within the acceptable values required by the standard. As the plate thickness increases, the impact toughness decreases in both the longitudinal and transverse directions, while the grain size remains fairly uniform in both directions. It can also be observed that, for some samples (mostly those of smaller dimensions), the impact toughness values in the transverse direction are somewhat higher than in the longitudinal direction. This should be the subject of future analysis, as it is possibly influenced by the sampling location, the marking of the rolling direction, or internal irregularities (such as segregation, inclusions, etc.).

For a more detailed analysis, correlations of the mentioned values were performed. Thus, Figure 4 shows the relationship between the impact toughness in the longitudinal and transverse directions, and a strong correlation between these parameters is evident, as indicated by the high correlation coefficient.

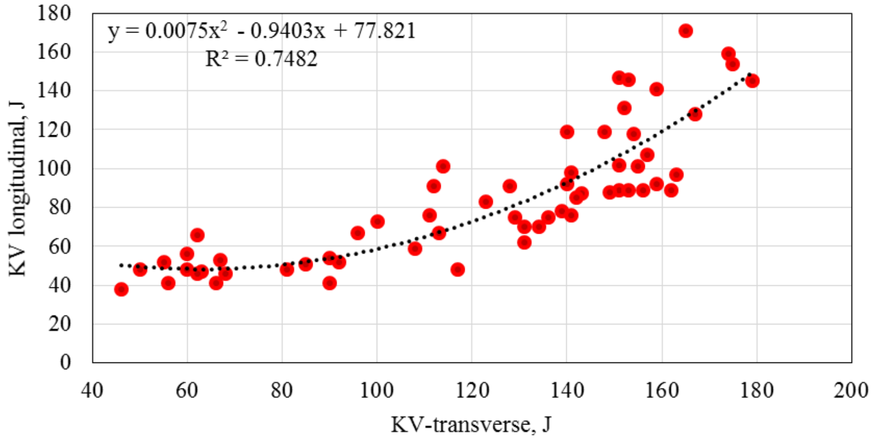

Figure 4. Dependence of impact toughness in the transverse direction on the impact fracture work in the longitudinal direction

In Figures 5, 6, 7, and 8, attempts were made to establish correlations between product dimensions and the impact toughness of samples in both the transverse and longitudinal directions, as well as between impact toughness and the average grain size. Since the results are quite scattered, the presented correlations have low correlation coefficients. However, they may indicate certain trends for further analysis and possible adjustments in the production technology.

As shown in Figures 5 and 6, the values of impact toughness in both transverse and longitudinal directions decrease with increasing dimensions (which was expected) and are mostly grouped around the lower dimension range (from 7.96 mm to approximately 20 mm).

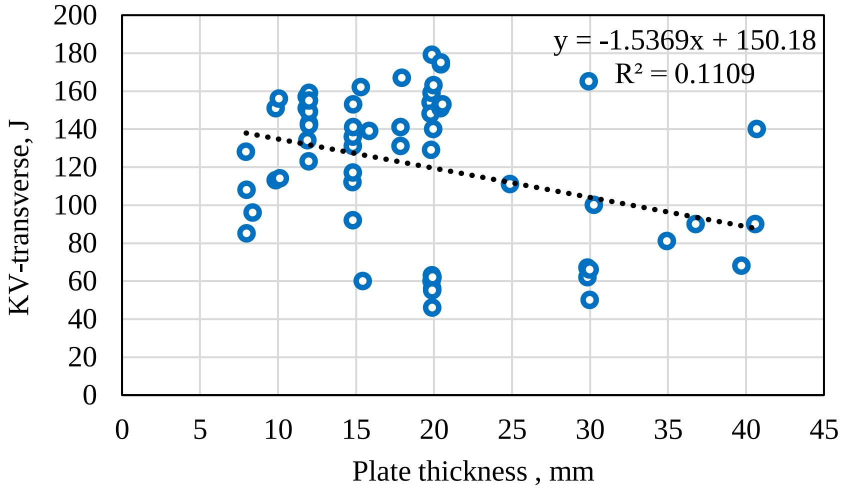

Figure 5. Dependence of plate thickness and impact i toughness n the transverse direction

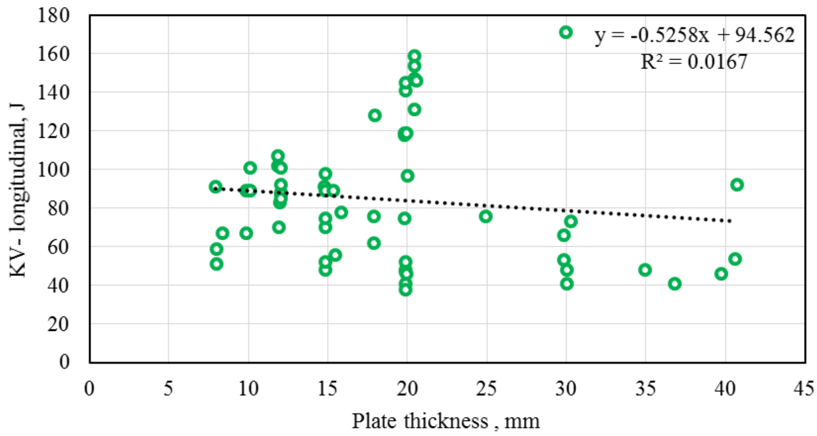

Figure 6. Dependence of plate thickness and impact toughness in the longitudinal direction

Figures 7 and 8 show the dependence of impact toughness on the average grain size. The correlation of impact toughness for samples taken in the transverse and longitudinal directions relative to grain size is not reliable due to the scatter of values (the correlation coefficient is low). However, it is still noticeable that the impact toughness is lower for larger grain sizes, which is expected, and vice versa-especially in the testing of samples in the longitudinal direction.

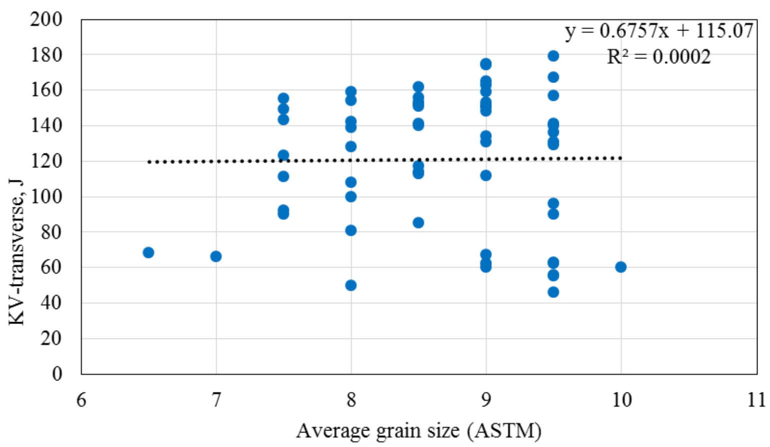

Figure 7. Dependence of impact toughness (transverse) on average grain size

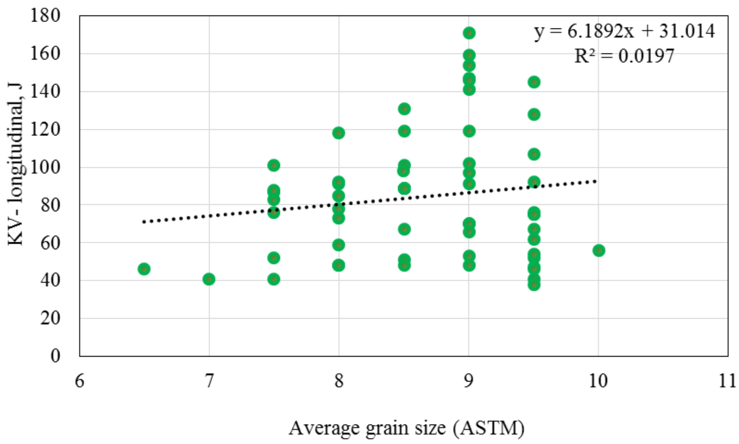

Figure 8. Dependence of impact toughness (longitudinal) on average grain size

5. CONCLUSION

Steel S690QL is designed to provide an excellent combination of high strength, toughness, abrasion resistance, and good weldability. The main reasons for the widespread use of high-strength steels of this grade are their exceptionally high mechanical properties, such as tensile strength and yield stress, as well as favourable impact toughness, i.e., impact fracture work.

Impact toughness tests were conducted at low temperatures on samples taken from different lengths of rolled plates to determine their mutual dependence and provide guidelines for further production technology. Additionally, the average grain size was determined for all samples except for the microstructure. The grain size obtained for all samples is quite uniform, with no significant deviations, apart from occasional clusters of somewhat larger grains, which did not show any significant impact on the required properties.

The anisotropy of microstructure and grain size is not pronounced to a great extent in the longitudinal and transverse test samples, which also influenced the impact toughness results.

Testing of toughness, i.e., impact fracture work at a temperature of -40°C, showed that all average and individual values are significantly above the required standards.

It was also observed that some samples (mostly those with smaller dimensions) had somewhat higher impact toughness values in the transverse direction than in the longitudinal direction. This should be the subject of future analysis, as the influence of sampling location, rolling direction marking, or internal irregularities (segregation, inclusions, etc.) on these values is possible.

All conducted tests provide directions for improving production technology and the stability of the production process.

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