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# FATIGUE LIFE OF BUTT WELDMENTS MADE OF S1100QL STEEL



**Key words**: welding, UHSS, fatigue, welding parameters.

**Abstract:** Fields of application for quenched and tempered advanced high-strength steels are mainly ground-moving, mining equipment, commercial vehicles, and truck cranes. One of the main aspects determining range of applicability for the high strength steels is the possibility to obtain welded joints with the given fatigue strength. Information about fatigue behaviour of the weld joints strongly increases the operational safety of the structures. Factors influencing mechanical properties of the joints can be related to the welding parameters, i.e. welding current, voltage, and interpass and preheat temperatures. Thermo-mechanical process (fusion welding) also causes the diversification of the microstructure in the weld and heat affected zones. Microstructure changes induce residual stress, influencing the fatigue behaviour of the weld joint. The main topic of the paper are results of the experimental fatigue tests performed for S1100QL butt welds produced with two different technological parameter setups. Technological parameters configurations were selected on the basis of experimental tests carried out for sheets with a thickness of 12 mm. The low and high welding parameters differed due to energy introduced into the system. The energy was controlled by current parameters and the preheating of joined elements. In both configurations, it was possible to make welded joints that meet regulatory requirements but differ in the level of introduced internal stresses and microstructural properties in heat affected zone sizes. The joints were additionally subjected to standard strength and microstructural tests.

### Trwałość zmęczeniowa doczołowych złączy spawanych wykonanych ze stali S1100ql

**Słowa kluczowe:** spawanie, UHSS, zmęczenie, parametry spawania.

**Streszczenie:** Obszar zastosowania stali ulepszanych cieplnie to głównie maszyny służące do robót ziemnych, urządzenia górnicze, pojazdy użytkowe oraz żurawie samochodowe. Jednym z głównych aspektów określających zakres stosowalności stali wysoko wytrzymałych jest możliwość uzyskania połączeń spawanych o zadanej minimalnej wytrzymałości zmęczeniowej. Informacje na temat zjawisk zmęczeniowych zachodzących w złączach spawanych znacznie zwiększają bezpieczeństwo eksploatacyjne konstrukcji. Czynniki wpływające na właściwości mechaniczne złączy mogą być związane z parametrami spawania, tj. prądem spawania, napięciem, temperaturą międzyściegową i temperaturą wstępnego podgrzewania. Proces termomechaniczny, jakim jest spawanie łukiem elektrycznym, powoduje również zróżnicowanie mikrostruktury w samych spoinach i strefach wpływu ciepła. Zmiany mikrostruktury wywołują między innymi naprężenia szczątkowe wpływające na trwałość zmęczeniową złącza spawanego. Głównym tematem artykułu są wyniki eksperymentalnych testów zmęczeniowych wykonanych dla spoin doczołowych S1100QL wytworzonych przy użyciu dwóch różnych konfiguracji parametrów technologicznych. Połączenia zostały dodatkowo poddane standardowym testom wytrzymałościowym i mikrostrukturalnym. W artykule zaprezentowano również symulację propagacji wzrostu pęknięć zmęczeniowych.

## Introduction

The development of the new mechanical engineering constructions requires specified criterions described by industrial and environmental standards. The combination of operational safety and mass reduction is one of the main trends in the optimization of mechanical structures [1, 2]. In the case of mechanical design, those aims can be obtained by the application of ultra-high-strength steels. From the environmental point of view, carbon dioxide emissions generated by the metal industry are increasing year by year. There is a possibility for reducing air pollution and the use of natural resources by increasing material efficiency.

The higher strength of UHSS steel has an important influence on the mass of the automotive structures. Less material is required to sustain similar performance, which can affect the reduction of CO2 emissions directly related to energy consumption and lower fuel economy. The use of ultra-high-strength steel (UHSS) rather than conventional structural steel can probably influence and reduce emissions (Fig. 2).

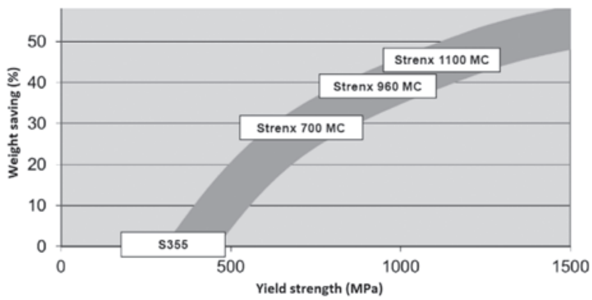


**Fig. 1. Potential weight saving as a percentage when using UHSS structural steels compared to regular structural steel [3]**

According to the definitions available in literature, steels with yield strength higher than 550MPa are described as UHSS, which is inconsistent with the definition of HSS steel (yield strength higher than 355 MPa and lower than 700 MPa).

Highly strength steels are a group of materials that have gained greater use in recent years. The number of papers published in journals is increasing in the past years. Hence, the most typical applications for UHSSs are booms, lifters, and vehicles of all kind.

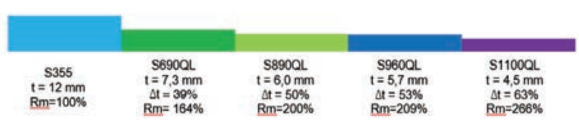


**Fig. 2. Comparison of cross-sections for standard steel and UHSS**

The main difficulties resulting from UHSS use in structural and mechanical constructions are related to the description of the standards. Eurocode 3 standards (EC3) does not include information about designing structures using over 700 MPa yield strength steels. Other challenges are linked with the use of cold forming and welding technologies. The manufacturing process becomes more difficult when yield strength becomes higher. A higher overall strength of the material causes higher residual stress and a higher spring-back effect. Moreover, a larger possible bending radius is need compared to the standard construction steel. Bending machines with a higher power have to be used [4]. Fusion welding technology of the UHSS also causes additional strength and technological problems. During cooling, quenched and tempered UHSSs have a tendency to cold- and hydrogen cracking. Welding itself also causes thermomechanical changes in the microstructure, which result in a softening phenomenon registered in the heat-affected zone (HAZ). Lower strength zones influence weld strength performance and reduce the advantage of the UHSS. However, there are also steels that do not suffer from the softening of the HAZ as transformation induced plasticity and complex phase steels [5] and such steels have been adopted in the automotive industry and for mobile heavy equipment. Welding of UHSS is, however, not without its complications and welding processes for these steels need careful attention. For instance, their high susceptibility to cracking and Heat Affected Zone (HAZ. Research on mechanical properties is required to expand the scope of the application of UHSS. Factors influencing joint strength are directly related to the technical parameters of the welding process. The energy put into the weldments and preheating temperature can affect the overall strength and fatigue properties of the joints. The paper presents the results of the experimental fatigue tests performed for S1100 specimens subjected to cyclic tension-compression loading. Fatigue testing was performed for two groups of specimens described by welding parameters. Finite element stress analysis in the weldments is also presented.

## 1. Fatigue tests of the UHSS – recent research

SSAB's Weldox S1100 E steel transverse butt weldments were subjected to fatigue loading [6]. The results of experimental tests exhibited a decrease in mechanical properties related to the cutting technology (laser cutting compared to water cutting). Yield strength and ultimate tensile strength were lowered at the edge cuts by 12% and 25%, respectively, than manufacturer technical data descriptions. In the base material fatigue tests, S690 steel had higher fatigue strength compared to the S1100. This result was explained with the different surface roughness properties. In the fatigue tests of butt-welded joint, S1100 specimens obtained higher fatigue life compared to the S690 steel (Fig. 1). Cracks initiated in the area of the weld toe [6].

Studies on the low cycle fatigue (LCF) UHSS butt welds were presented in the paper [7]. Specimens of three steel grades S960QL, S960M, and S1100QL were subjected to constant and variable amplitude loadings. Variable loading was generated on the base of the crane truck data logging system. Specimens were welded with the MAG welding process and filler material with 890MPa yield strength. According to the research conclusions, welding quality had a meaningful influence on fatigue life. Moreover, differences in the fatigue life were exhibited in comparison to manual automatic welding.

The low cycle fatigue range of the UHSS welds was also described in [8]. Specimens made of S960QL steel were TIG welded. X96-IG filler material was used in the specimen preparation. Monotonic tensile tests were conducted to identify mechanical properties. Residual stress was measured using X-ray diffraction. The fatigue lives of the welds were significantly lower than the base material (around 90%). The decrease was observed in high and low cycle fatigue regimes. Stress concentration factors were also determined via the Lawrence's method, Jawdokimov's method, and FEA.

Other works related to fatigue phenomena of UHSS welds can also be indicated in [9–11].

## 2. Material properties

Specimens were cut from 12 mm thick plates. Mechanical properties of the material were identified with standard testing methods: tension and Charpy tests. Mechanical properties and the chemical composition of the S1100 steel are presented in Tables 1 and 2.

**Table 1. Mechanical properties of the s1100ql steel**

| Mechanical properties | | | | | | |
|---|---|---|---|---|---|---|
| $R_e$, MPa | $R_m$, MPa | A, % | $K_v$, J (-40°C) | $K_v$, J (-60°C) | E, GPa | u,- |
| 1157 | 1384 | 10 | 46 | 33 | 200 | 0,3 |

where: $R_e$ – yield strength, $R_m$ – ultimate strength, $A$ – elongation, $K_v$ – impact resistance, $E$ – Young modulus, u – Poisson's ratio.

**Table 2. Chemical composition of the s1100ql**

| Chemical composition of the S1100 steel | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C | Si | Mn | P | S | N | B | Cr | Cu | Mo | Nb | Ni | Ti |
| 0.17 | 0.25 | 1.12 | 0.011 | 0.001 | 0.003 | 0.002 | 0.67 | 0.05 | 0.62 | 0.03 | 0.06 | 0.005 |

The microstructure of the S1110 alloy is characterized by a typical martensitic structure due to the change in the chemical composition and the production process. Inclusions of high-temperature carbides are visible. An example of the microstructure is presented in Figure 3.

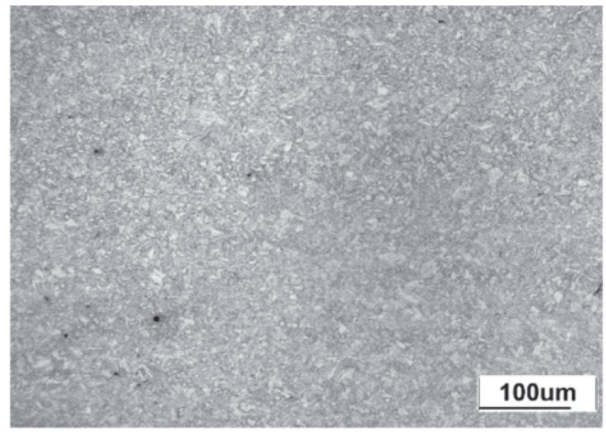


**Fig. 3. Martensitic microstructure of the S1100 steel**

Method 111 (MMA) was used in the welding of the specimens, and it is the most commonly used method for assembly work. It consists of striking the arc and melting the material with a hot-melted electrode. During the melting of the electrode, the cover is mixed with the connected material and provides a gas shield for the liquid weld pool and is the source of elements that enrich the composition of the weld. Weldments were made according to specifications of the technological parameters.

**Table 3. Welding parameters**

| Parameter Description | Welding Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Welding position | Layers | Pre-heat, °C | Filler Size, mm | Current, A | Voltage, V | Current type | Travel speed [cm/min] | Heat input [kJ/mm] |
| High | PA | A | 120-150 | 2.5 | 100-120 | 24-26 | DC/(+) | 10-20 | 0.58-1.48 |
| | | B,C,D | | 3.2 | 150-170 | 27-28 | | 15-20 | 0.97-1.52 |
| Low | PA | A | 120-150 | 2.5 | 60-80 | 22-23 | DC/(+) | 15-30 | 0.21-0.59 |
| | | B,C,D | | 3.2 | 80-100 | 23-24 | | 30-50 | 0.18-0.38 |

Parameter settings were based on the experience and the limits of achieving joints meeting the requirements of technical supervision. Edges of the plates were prepared before welding. Parameters of the joint preparation design are presented in Figure 4.

The obtained joints were subjected to strength and metallographic tests to confirm the correctness of weldments mechanical properties. An exemplary microstructure of the joint is presented in Figure 5.

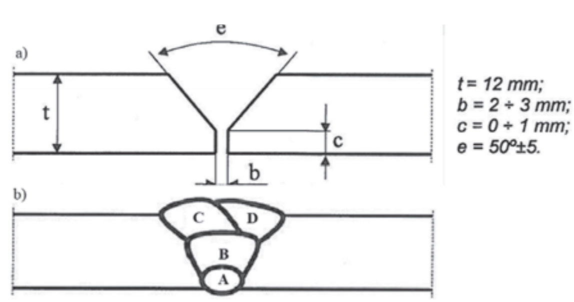


**Fig. 4. Joint design: a – plate preparation, b – layers layout**

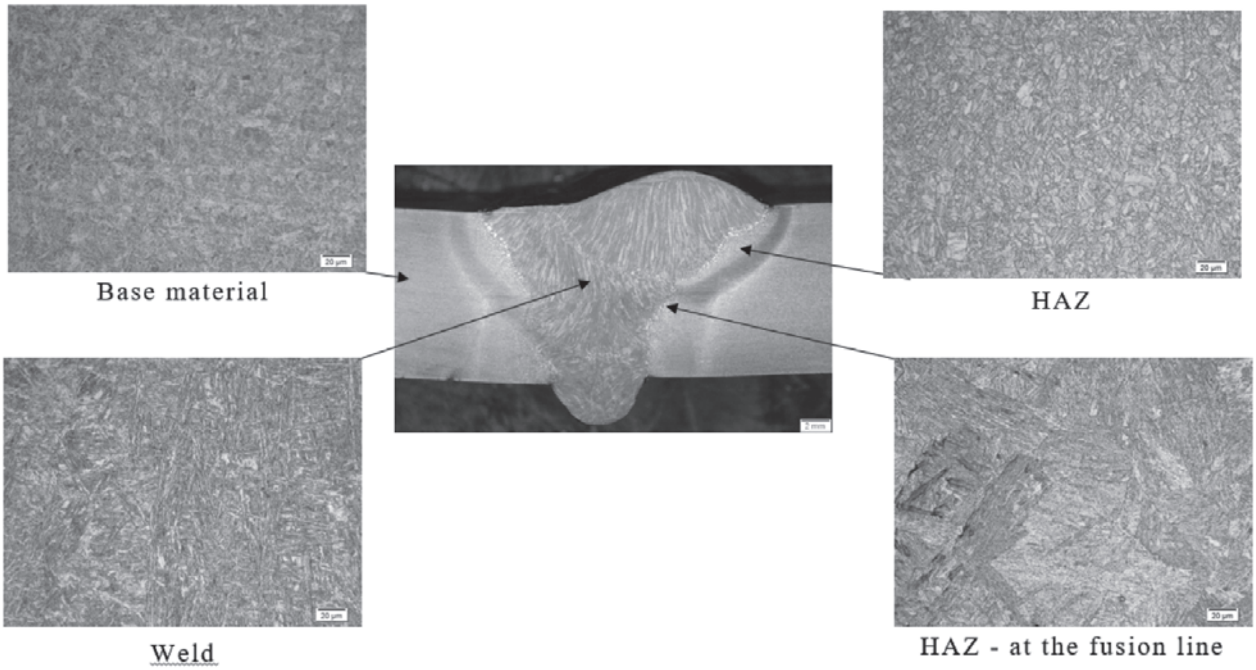


**Fig. 5. Weld zones microstructure**

The microstructure of the S1100QL base material consists of tempered martensite. The welds are dominated by fine-grained martensite, and the areas of the bainitic structure are also visible. Martensite fragmentation is higher closer to the weld face and in the areas of overlapping welds.

In the heat affected zone (HAZ), the area of grain growth near the martensite-bainitic fusion line can be distinguished. In the place of the influence of heat cycles of overlapping welds, the HAZ has a coarser character and the zone is wider. In this case, there is also a tendency to form structures with martensitic islands at the transition from the heat affected zone to the base material. Observed weld asymmetry results from welding technology (sequence of runs).

## 3. Fatigue tests

Fatigue tests were performed using a hydraulic testing machine equipped with force and displacements measurement systems. Specimens were subjected to the cyclic loading. The asymmetry coefficient for all of the performed tests was R = -1. Fatigue properties were obtained for welds and the base material. The shape and dimensions of the specimens are presented in Figure 6. In the case of the base material, the dimensions of the specimens were identical and did not contain weld geometry.

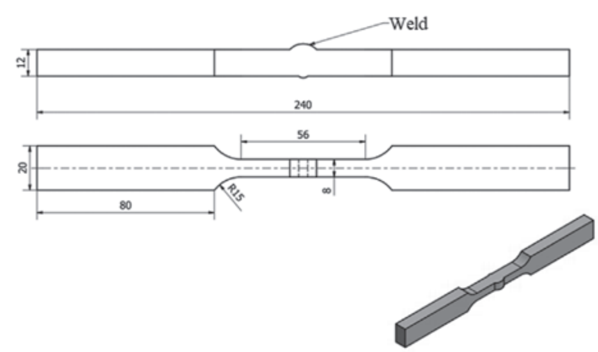


**Fig. 6. Specimen shape and dimensions**

Results of the fatigue tests were presented in the form of S-N Wöhler characteristics [12].

$$\sigma_a = A + m \log N_f \qquad (1)$$

where: $N_f$ – number of cycles, $\sigma_a$ – nominal stress amplitude, $A$, $m$ – coefficients of regression model.

Base material results are presented in Figure 7. Results of the fatigue testing preformed for weldments are presented in Figure 8. Fatigue life obtained by the specimens is much lower compared to the base material. The influence of welding parameters on fatigue life of the samples is relatively small, and, at this step of the research, the phenomena require more testing. Due to the number of tested samples in combination with the relative repeatability of results falling within the standard spreading band equal to three for fatigue tests, fatigue characteristics presented in Figures 7 and 8 were extended beyond the regions of the stress state, which were included in the research.

Initiation of the fatigue cracks was observed in the root side of the weldments. Example cracks are presented in Figure 9.

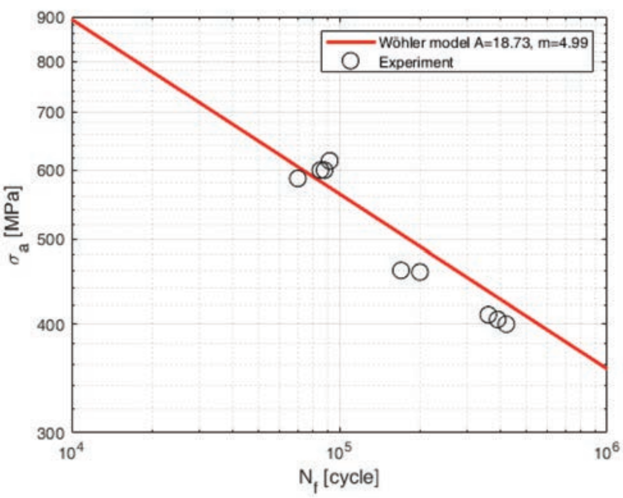


**Fig. 7. Results of the fatigue testes of the base material**

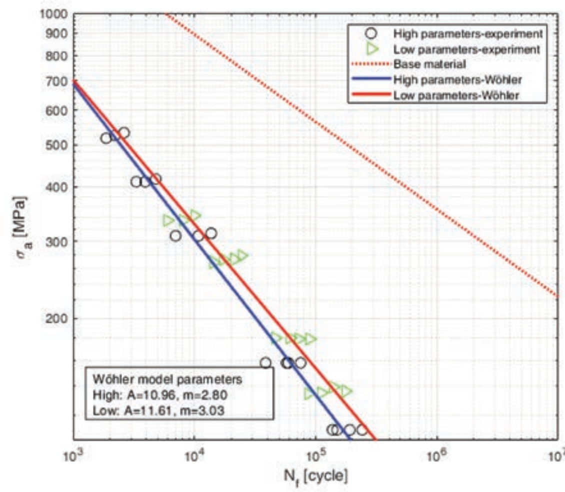


**Fig. 8. Results of the fatigue testes of the welded specimens**

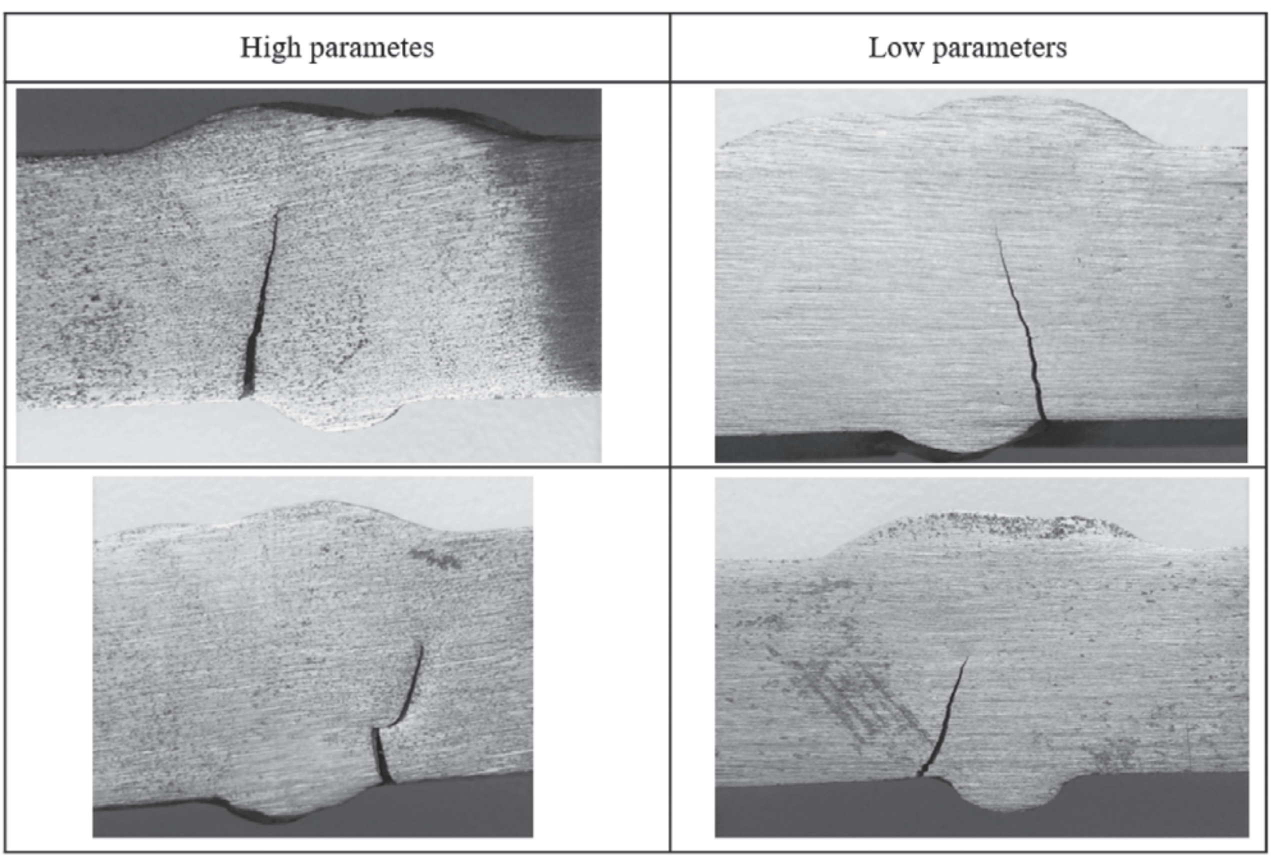


**Fig. 9. Fatigue cracks in the specimens**

## 4. Effective notch stress method

In the fatigue strength assessment by the effective notch stress (ENS), the stress value in the local profile of the weld is taken into calculations. In this method, the shape of the weld is replaced by the effective notch root radius (1 mm for structural steels with plate thickness higher than 5 mm) [13]. In the presented research, the weld profile was created on the base of the microstructure observations. Maximum local stress values in the notch were obtained by FEA. The weld geometry model, mesh, and results are presented in Figures 10–11. The linear elastic material behaviour model was used in the analysis. Strength properties were defined in accordance with Table 1.

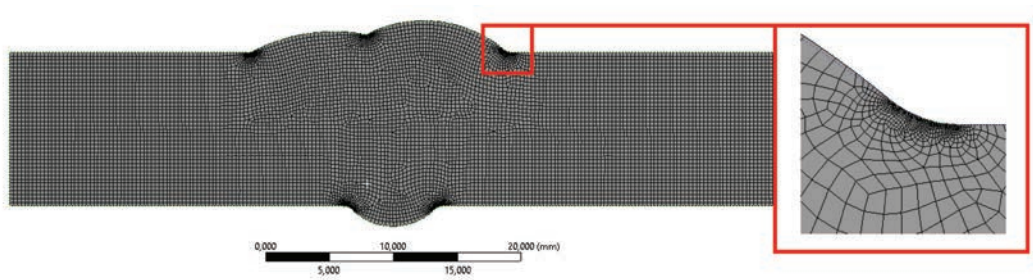


**Fig. 10. FEM model of the weldment**

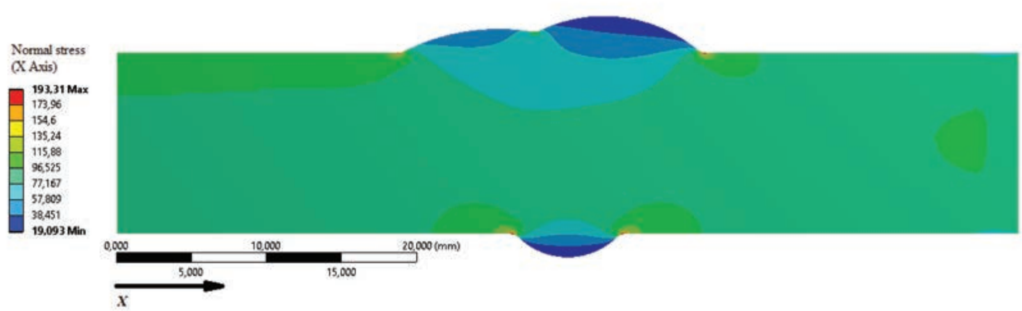


**Fig. 11. Results of the calculations, normal stress distribution**

The result from the calculations can be used to evaluate the fatigue life of weldments. Comparisons between fatigue lives calculated on the base ENS method and base material fatigue data are presented in Figure 12. The results of the calculations do not fit experimental data and cannot be used in design calculations.

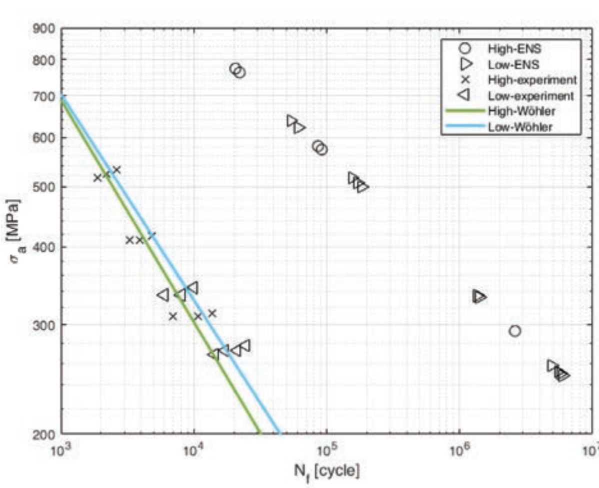


**Fig. 12. Results of the ENS calculations and experimental data**

## Conclusions

The following conclusions and observations were made on the basis of the conducted research:

- Fatigue tests performed on two groups of specimens made of S1100QL steel showed relatively small differences in the obtained results for low and high welding parameters. The phenomena require further tests and investigations.
- Fatigue cracks propagated in all samples from the root of the weld (D weld run side – Figure 4), which may result from the asymmetrical weld.
- The fusion welding process decreases the fatigue life of the S1100 steel.
- Fatigue life obtained by means of ENS calculations does not correspond to the experimental characteristics of joints. In the case of the used joint configuration and load, the method cannot be used to assess fatigue life.
- The phenomenon of fatigue in welded joints from UHSS requires further research. From the perspective of the application of this type of materials in engineering constructions, it is reasonable to look for a computational algorithm that allows one to design the durability of connections in various load conditions.

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