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Fatigue resistance of welded joints of S690QL high strength steels

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Abstract—In our days the high strength steels are used increasingly greater fields, especially in welded structures. Because of this, it is important to deal with the features of the welded joints. The design of a structure is frequently done on static loading, but the welded structures often exposed with cyclic loading. From that viewpoint the welded joints have significance. In this study the low cycle and high cycle fatigue features of the welded joints of S690QL high strength steels are presented.

I. INTRODUCTION

Nowadays, because of the different claims against the base materials, multiple expectations evolve [1], the development of the steels must follow that (for example, the preservation of the ductility, beside the increased strength). Beside of this, the structures are often exposed with cyclic loading, so fatigue may be occur, this means a more complex expectation against the base material.

At the same time, because of the application, the weldability is also a main feature of these steels. The welding procedure – because of the heat input – modifies the original microstructure of the base material. So we get entirely different mechanical characteristics, which are not allowable in many cases in terms of the structure.

The phenomena of the fatigue can be occurred in the welded structures, where the local stress places are playing significant role. Besides the shape of the welded structure, the form of the welded joints and the differences in the bond are included in these stress concentration places, since real perfect joints cannot be prepared. Considering that, the characteristics of the welded joints are different from the base materials, therefore it is important to examine the low cycle fatigue behavior of these joints.

Especially because of the quality of the welded joints and the fatigue resistance depend on several welding parameters. Such as the applied welding process, current, voltage, welding speed and the joint shape, or a more general index-number, the linear energy (E,) too. For that reason, on the judgment of the capacity of the construction, the knowledge of the dominant material index-numbers (yield strength, fatigue limit, low cycle fatigue resistance, etc.) of the base material and the welded joints are very important.

It is important to examine steels and welded joints with increased strength (for example S690, S960, S1100), because their fatigue behavior do not know entirely. The Eurocode 3 [2], which is dealing with the production of the welded steel structures, currently include steels with guaranteed yield strength up to 460 MPa, and with additional limitations up to 700 MPa. Another recommendation [3], released by the International Institute of Welding (IIW), include fatigue properties and weldability of steels with yield strength up to 960 MPa. Above these values, they do not deal with fatigue properties of the structures or welded joints, although both the low cycle and high cycle fatigue phenomenon may appear with certain structures.

In favor of this welding experiments were made on S690QL fine-grained, quenched and tempered, high strength steel. Also low cycle fatigue (LCF) and high cycle fatigue (HCF) experiments were made on the base material and the welded joints. On behalf of comparison the received results were compared with the data from different literatures.

II. QUENCHED AND TEMPERED HIGH STRENGTH STEELS

A. Development of the high strength steels

The steel manufacturer continuously develops newer and newer quality steels. Besides the importance of weldability, one of the largest aims was the increases of the strength of the steels. Besides the increases of the bearing capacity, the reduction of the quantity of the used steels became determining in the latter decades.

In case of the higher strength steels the area of the section, and the weight of the structure can be decreasing, the own mass of the construction are reducible, together and with this, the weight of the joints. Besides of the economic benefits, this is also beneficial to the mechanical characteristics. In general, with the increases of the yield strength, the area of the section can be decreasing, and with this the weight as well, this can be seen in Fig. 1 [4].

The high strength steels are mostly use in cases where the static strength is determinative. The smaller use of these steels, in the case of structures with alternating loading, is due to the fatigue strength of the welded joints. Because these properties after welding, according to the present design regulations (for example Eurocode 3),

![Figure 1. Relation between the weight and the steel grade](image)
are independent from the tensile strength of the base material. This means the fatigue properties are mainly affected by the applied parameters during welding. During the lifetime of a structure, not only static loading evolve, so knowing these features is necessary.

The main applications of the high strength steels, for example mobile cranes or earthmoving equipment, which can be tolerate extreme environmental effects (operating on negative temperature) and extreme loading conditions.

**B. Production of S690QL steels**

There are several possible ways to increase the strength of metallic materials. But in many cases these can be used only with slight plane thickness \((s \leq 3 \text{ mm})\). These for example, the formation of a complex phase, like the duplex, triplex or twip steels. But in the case of the examined heavy plate thickness region \((15-30 \text{ mm})\) with grain refinement and with the change of the second phase quality, size and distribution can be reached effectively the higher strength.

The base of the strength enlargement is that the reduction of the grain size of a given volume increases the surface of the grain boundaries and the phase boundaries, which at the same time increases the crystallographic defects, and due to this the energy of the material increases too. It follows from this, that the reduction of the grain size increases the strength features, especially the yield strength. The reduction of the grain size also effects favorable on the impact test, besides that increases the Charpy impact energy, reducing the transition temperature as well [5].

During our experiments, the examined S690QL steel group belongs to the upper category of the high strength steels, their minimum yield strength is 690 MPa, but even 800 MPa can be reached. In the marking of the steel, the “L” means that this group can be used at negative temperatures, like mobile cranes.

The carbon content of the quenched and tempered high strength steels is small, averagely 0.15 wt%, and the main alloying elements are the manganese, the molybdenum, the chromium, the nickel, and microalloying element is the boron. These are effects on the quenched thickness too; accordingly we achieve full martensitic microstructure in the case of heavy plate thickness. However, because of the small carbon content, the distortion effect of the evolved martensite is slight, we get blind quenching. Namely, the outstanding strength of these steels can be achieved not only with heat treatment, but with alloying and with using of special production technology, which cause the desired complex microstructure: ferrite matrix with tempered bainit and martensite. Such a microstructure can be seen in Fig. 2. part b). In favor of comparison in the figure also can be seen S355 base material (a), S960QL high strength steel base material (c) and S690QL welded microstructure.

**C. Weldability of S690QL steels**

The production of the high strength steels result in non-equilibrium microstructure, which alters the welding process irreversible, hence the original microstructure can be not repositioned after the welding.

The heat affected zone can be easily hardened, furthermore in case of too large heat input the heat affected zone can be softened comparing to the base material, which can be caused strength and hardness decreasing. Of course, both cases are non-tolerable, because of these to moderate these effects additional microalloys used on these steels, like aluminium, niobium, vanadium and titanium. Of course these feature changes also affects the fatigue properties, the different quality zones in the welded joint largely changes the fatigue resistance.

![Figure 2.](image-url)

**Figure 2.** Different yield strength steels microstructures: a) S355 base material, b) S690QL base material, c) S960QL base material, d) S690QL welded joint
Besides all these, further undesirable phenomena can be appearing: different types of cracks. Primarily the cold cracking, on behalf of avoidance the workpiece must be preheated before the welding, and it is necessary to limit the linear energy too. At the same time it is necessary to attend to the risk of the appearance of the hot cracking. The complex tasks of the weldability of the high strength steels summarize the Graville diagram (Fig. 3.). It can be clearly see, that the higher strength steels, such as the examined base material, list in the hardly welded category (III.), based on the carbon content and carbon equivalence.

In the case of these steels, one of the most important features of the successfulness of the weldability is the heat input which we describe with the linear energy. If the value of this is too low, the cooling rate of the welded joint may be too fast, and then cold cracks can be developed. In the opposite case, strong coarse grain microstructure can be evolved in the heat affected zone, which can be caused the decreasing of the strength and toughness features. This effect can be demonstrated best with the hardness distribution along the welded joint. The comparison of literature [10] and own experiments data can be seen in Fig. 7.

Therefore, we received a narrow welding lobe, inside this the quality of the joint may be suitable. Of course, besides the previously mentioned characteristics, the material quality, the chemical composition and the applied thickness are important too.

We use the $t_{8.5/5}$ cooling time for the common description of the welding conditions and parameters. This means the welded joint cooling time from 850 °C to 500 °C. Because of the previously mentioned reasons, the cooling time is a narrow range, which values are very dissimilar in the different literatures. Based on our own experiments and different sources the cooling time range is between 6 s and 15 s in the case of S690QL steels [7, 8].

Since this parameter demonstrate the cooling time of the welded joint, and by this the cooling rate, so this parameter closely relate with the evolved microstructure, and this the evolved properties. Accordingly to this, with hardness tests, the kept of the welding parameters can be easily overseen. The relation between the hardness and the cooling time can be seen in Fig. 4.

It is necessary to note that a relatively smaller linear energy is more beneficial based on the experiments, in the case of the welded joint strength, toughness and residual stresses. On the other hand, in the case of the production and the productivity the higher linear energy is the beneficial.

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**D. Selection of filler materials**

The selection of the filler materials in the case of the high strength steels is also a very important task. It is necessary to take into consideration that in the case of the examined steels – based on the ratio of the base material and the filler material mechanical properties – matching, overmatching and undermatching filler materials can be used.

In case of matching condition, the evolved mechanical properties of the joint are equal or nearly the same as the base material. In undermatching case the mechanical properties of the joint are lower than the base material properties, while in case of overmatching condition the joint properties higher than the base material features.

It is important to note, that the matching of the filler material can be done not only by the mechanical properties, but with other features as well, such as the transition temperature or the cracking sensitivity. Furthermore, we may not speak absolute matching in the case of high strength steels. For example, an undermatching coupling with the same rate in a case of a higher strength steel means a higher difference in the properties. According to this, the authors of the article [9] introduced the relative undermatching concept. This means the value of the matching expressed with the percentage of the guaranteed yield strength of the base material ($r_{\text{un}}$).

The comparison can be done by the mechanical properties, for example the minimal yield strength or the minimal tensile strength. It is important to note, that in the case of matching condition, it is very hard to equal all of the mechanical properties. This is due to the fact, that the ratio between the yield and tensile strengths in the case of the base material is usually smaller, than in the case of the filler material. At the case of the high strength steels this ratio similar, both in the base material and the filler material.

General principle, that in the case of the hot rolled steels, equal or slightly higher strength matching filler materials are used. In case of higher strength
overmatching filler materials, it is necessary to count on high residual stress, which can be unfavorable. In case of high strength steels, with yield strength over 600 MPa, it is more beneficial to use undermatching filler materials. Of course in that case lower strength welded joint was gained.

Despite the smaller strength, these filler materials have many advantages, which can be used effectively on high strength steels. Such positive attribute are the higher toughness of the weld metal, the higher resistance against the hydrogen cracking or the smaller residual stress in the welded joint. It is necessary to note, that the mechanical properties of the welded joint exceed the minimal requirements of the base material in the case of undermatching filler material.

Besides the mentioned benefits, it is important to note that the location of the welded joint in the structure is very important too. On those places, where the joint is load-bearing, essential that the strength of the joint is equal the base material strength. But, on the places where the loading is lower (not load-bearing joints), may be enough using smaller strength joints.

In the other hand, because of the higher strength weld metal, overmatching filler materials are used as well in many cases. In that case the higher yield strength of the welded joint is more beneficial, despite the slightly higher residual stress or the higher toughness. An industrial example for the overmatching filler materials is FORTACO Zrt. (Jászberény), where the major part of the used filler materials is overmatched.

So it is stable, that the selection of the filler material is a very complex task. The examined steel (S690) is in the range, where matching, undermatching or overmatching filler materials can be used as well.

In favor of comparison of the different strength filler materials, we collect data from three different manufacturers. We choose the filler materials correlate to the S690 steel group, in the case of GMAW welding. The selected manufacturers are the INEFIL, the BÖHLER and the THYSSEN companies. The selected filler materials and their main mechanical properties can be seen in Table 1, while the chemical composition can be seen in Table 2.

### III. WELDING EXPERIMENTS

Based on the previous statements, welding experiments on S690QL (RUUKKI OPTIM 700 and SSAB WELDOX 700) quenched and tempered base material with 15 mm (RUUKKI, R_p0,2 = 809 MPa, R_m = 850 MPa, A = 17%) and 30 mm (SSAB, R_p0,2 = 791 MPa, R_m = 836 MPa, A = 17%) thickness was made.

For the welding experiments the gas metal arc welding (GMAW, ISO code: 135) was chosen, because these steels are welded mostly with this procedure. It is important to note, that because of the heavy plate thickness in these products, in the case of productivity submerged arc welding (SAW, ISO code: 121) can also be used, but because of the complicated products and the controlled linear energy problem this procedure is used only limited cases. Also based on industrial experiences, M21 mixed gas with 18% CO2 and 82% Ar as shielding gas was chosen. As filler material, INEFIL NiMoCr wire with 1.0 mm diameter (R_p0,2 = 750 MPa, R_m = 820 MPa, A = 19%) was chosen. In the case of the filler material choosing, this means a matching coupling, in other words the mechanical properties of the filler material and the base material are nearly equal. For the experiments REHM MEGAPULS 500 welding equipment was chosen. The dimensions of the used plates were 300 mm x 125 mm. The experimental composition is shown in Fig. 5.

<table>
<thead>
<tr>
<th>Matching condition</th>
<th>Filler material</th>
<th>INEFIL 80 Ni1</th>
<th>NiMo 1-IG</th>
<th>Union MoNi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undermatching</td>
<td>Grade</td>
<td>530/600</td>
<td>620/700</td>
<td>620/700</td>
</tr>
<tr>
<td></td>
<td>Elongation, %</td>
<td>26</td>
<td>23</td>
<td>18</td>
</tr>
<tr>
<td>Matching</td>
<td>Grade</td>
<td>INEFIL NiMoCr</td>
<td>X 70-IG</td>
<td>Union X85</td>
</tr>
<tr>
<td></td>
<td>R_m/R_p0,2, MPa</td>
<td>750/820</td>
<td>800/900</td>
<td>770/880</td>
</tr>
<tr>
<td></td>
<td>Elongation, %</td>
<td>19</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>Overmatching</td>
<td>Grade</td>
<td>INEFIL 120 S1</td>
<td>X 90-IG</td>
<td>Union X90</td>
</tr>
<tr>
<td></td>
<td>R_m/R_p0,2, MPa</td>
<td>790/840</td>
<td>890/940</td>
<td>890/950</td>
</tr>
<tr>
<td></td>
<td>Elongation, %</td>
<td>16</td>
<td>20</td>
<td>15</td>
</tr>
</tbody>
</table>

### TABLE I

<table>
<thead>
<tr>
<th>Matching condition</th>
<th>Filler material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undermatching</td>
<td>INEFIL</td>
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<td>0.6</td>
<td>1.1</td>
<td>-</td>
<td>1.0</td>
<td>0.1</td>
<td>0.12</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>BÖHLER</td>
<td>0.08</td>
<td>0.6</td>
<td>1.8</td>
<td>-</td>
<td>0.9</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>THYSSEN</td>
<td>0.1</td>
<td>0.65</td>
<td>1.55</td>
<td>-</td>
<td>1.1</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Matching</td>
<td>INEFIL</td>
<td>0.08</td>
<td>0.5</td>
<td>1.6</td>
<td>0.3</td>
<td>1.5</td>
<td>0.25</td>
<td>0.12</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>BÖHLER</td>
<td>0.1</td>
<td>0.6</td>
<td>1.6</td>
<td>0.25</td>
<td>1.3</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>THYSSEN</td>
<td>0.09</td>
<td>0.7</td>
<td>1.7</td>
<td>0.3</td>
<td>1.85</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Overmatching</td>
<td>INEFIL</td>
<td>0.07</td>
<td>0.5</td>
<td>1.7</td>
<td>0.1</td>
<td>2.3</td>
<td>0.5</td>
<td>0.08</td>
<td>0.007</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>BÖHLER</td>
<td>0.1</td>
<td>0.8</td>
<td>1.8</td>
<td>0.35</td>
<td>2.25</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>THYSSEN</td>
<td>0.1</td>
<td>0.8</td>
<td>1.8</td>
<td>0.35</td>
<td>2.3</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### TABLE II

The guaranteed chemical composition of the welded joint material (weight%)

The table lists the chemical composition of the welded joint material for different filler materials and matching conditions.
During the selection of the welding parameters, we seek after that the cooling time ($t_{8.5/5}$) is going to be between 6 s and 15 s, we observed this. To the determination of the welding parameters WeldCalc software by SSAB was used. With this, consider the cooling times: the optimal parameters can be easily determined. The used welding parameters of the two plate thickness region can be seen in Table 3.

For the minimum preheating temperature 150 °C was chosen, and for the maximum interpass temperature 180 °C. For the determination of these parameters previously experiments and literature data were used [4, 7, 8]. The welding parameters (voltage, current, wire speed, amount of shielding gas) were recorded continuously during the experiments with the help of WeldQAS (HKS) process monitoring device. This sensor not only shows the parameters in real time, but recorded them as well. Besides all these regulations, the linear energy was between 700 J/mm and 1200 J/mm in both thickness regions. The root layers were made by a qualified welder; while the other layers were made by welding automate. The done welded joints can be seen in Fig. 6.

On the complete joints welding procedure tests were made too, the worked out technic proved to be suitable based on these results. For the control of the welding parameters and the cooling time, thus the evolved microstructure, macroscopic test with hardness test was made. The result can be seen in Fig. 7, where we compare the result with literature data as well [10].

Based on the figure, it can be seen that the examined steel (colored), compared to the literature data (gray), in the case of the crown side, behavior like the steels with higher strength; while in the case of the root, minimal hardness decreasing can be seen.

So it can be state, that during the welding of the critical root layer, the suitable cooling time was kept, quenched microstructure did not evolved.

IV. LOW CYCLE FATIGUE (LCF) EXPERIMENTS

The complete welded joints were examined both with low cycle fatigue and with high cycle fatigue test, in favor of the knowing of the fatigue properties. Firstly, low cycle fatigue experiments were done on the base material and the welded joints.

Test specimens with long cylindrical section were used for the experiments both in the case of the base material and the welded joints. In this case of the joints, it is important to note, that the 15 mm thickness plate was used and from the joint the test specimens were worked out in a way that the weld should be in the middle section of the test specimen. The shape and the dimensions of the test specimens can be seen in Fig. 8. During the low cycle fatigue experiments $R = -1$ stress ratio was used, with triangular loading wave form and with total strain amplitude control, at room temperature, using MTS 312 electro-hydraulic universal materials testing device.

<table>
<thead>
<tr>
<th>Plate thickness [mm]</th>
<th>Layer</th>
<th>Current [A]</th>
<th>Voltage [V]</th>
<th>Welding speed [cm/min]</th>
<th>Wire speed [m/min]</th>
<th>$E_v$ [J/mm]</th>
<th>Cooling time $t_{8.5}$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1-2.</td>
<td>145</td>
<td>19.7</td>
<td>20</td>
<td>6</td>
<td>750</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>3-4.</td>
<td>260</td>
<td>29</td>
<td>40</td>
<td>13.0</td>
<td>1050</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>5-8.</td>
<td>265-270</td>
<td>30</td>
<td>45</td>
<td>13.2</td>
<td>1000</td>
<td>8.5</td>
</tr>
<tr>
<td>30</td>
<td>1-2.</td>
<td>130</td>
<td>19.0</td>
<td>20</td>
<td>6</td>
<td>750</td>
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<tr>
<td></td>
<td>3-6.</td>
<td>260</td>
<td>29</td>
<td>40</td>
<td>13.0</td>
<td>1050</td>
<td>9</td>
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<td></td>
<td>7-12.</td>
<td>265-270</td>
<td>30-31</td>
<td>45</td>
<td>13.2</td>
<td>1000</td>
<td>8.5</td>
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</tbody>
</table>
The representative hysteresis curves were registered continuously during the experiments, and we used them to determine the necessary attributes and relationships. In the knowledge of these data we calculated the relation between the cycles to failure \( (N_t) \) and the total \( (\varepsilon_a) \), the elastic \( (\varepsilon_{ar}) \) and the plastic \( (\varepsilon_{ap}) \) strain amplitudes, which can be describe with the following equation:

\[
\varepsilon_a = \varepsilon_{ar} + \varepsilon_{ap} = \frac{\sigma_f}{E} \cdot N_t^b + \varepsilon_f \cdot N_t^c.
\]  

In the equation (1) the \( \sigma_f \), \( \varepsilon_f \), \( b \) and \( c \) are parameters, and were determined from the examination results.

It is important to note, that the describe plastic strain amplitude, which can be express with the Manson-Coffin empirical equation used only with notch free, cylindrical test specimen, with constant amplitude and frequency loading [11].

The fatigue experiments were made firstly on the examined base material, than the specimen from the welded joints were tested, in favor of comparison the results shown in a common diagram with literature data [12, 13] (Fig. 9). In the figure, in favor of simplicity, only the plastic strain amplitudes were shown, function in cycles to failure. Approximate curves were fitted to the measured values, and the equations of these with the square of the correlation index (\( R^2 \) - expresses the goodness of fit) were shown in the figure. The fatigue experiments parameters can be seen in Table 4.

The comparative materials from literature [12] are the S355 base material \( (C = 0.1 \text{ w\%}, \ Si = 0.15 \text{ w\%}, \ Mn = 0.64 \text{ w\%}, \ Cr = 0.076 \text{ w\%}, \ Cu = 0.38 \text{ w\%}, \ Mo = 0.014 \text{ w\%}, \ Ni = 0.095 \text{ w\%}, \ V = 0.003 \text{ w\%}, \ P = 0.022 \text{ w\%}, \ S = 0.041 \text{ w\%}) \), and the S690 base material \( (C = 0.077 \text{ w\%}, \ Si = 0.048 \text{ w\%}, \ Mn = 1.35 \text{ w\%}, \ Cr = 0.025 \text{ w\%}, \ Ni = 0.0365 \text{ w\%}, \ Nb = 0.042 \text{ w\%}, \ Ti = 0.086 \text{ w\%}, \ Al = 0.036 \text{ w\%}, \ P = 0.009 \text{ w\%}, \ S = 0.005 \text{ w\%}) \); and from other literature [13] is the S1100 base material \( (R_e = 1148 \text{ MPa}, \ R_m = 1450 \text{ MPa}, \ C = 0.18 \text{ w\%}, \ Si = 0.2 \text{ w\%}, \ Mn = 0.835 \text{ w\%}, \ Cr = 0.56 \text{ w\%}, \ Ni = 1.88 \text{ w\%}, \ Mo = 0.564 \text{ w\%}, \ V = 0.057 \text{ w\%}, \ Cu = 0.01 \text{ w\%}, \ Nb = 0.017 \text{ w\%}, \ Ti = 0.086 \text{ w\%}, \ Al = 0.61 \text{ w\%}, \ P = 0.007 \text{ w\%}, \ S = 0.003 \text{ w\%}) \).

Besides of the previously given results, the plastic strain amplitude - stress amplitude relationship, in other word the cyclic yield curves were determined too. In the case of test specimen with constant, total strain amplitude loading, the stress amplitude continuously changes, so the cyclic yield curves determined from the stress amplitudes at the 50% of the lifetime. The cyclic yield curves of the examined base materials and welded joints can be seen in Fig. 10, and their parameters were summarized in Table 5.

Regression function to the experimental data was fitted in the form of a power function, approached to the data lines with the following equation:

\[
\sigma_{a50} = K \cdot \varepsilon_{ap}^n,
\]  

where \( \sigma_{a50} \) is the stress amplitude belongs to the 50% of the cycles to failure, \( K \) and \( n \) parameters calculated from the experimental results.
Figure 9. Comparison of the plastic strain amplitudes

**TABLE IV.**

The parameters of the Manson-Coffin equation

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Coefficient ($\varepsilon_f'$)</th>
<th>Exponent (c)</th>
<th>Correlation index (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355 [12]</td>
<td>0.4659</td>
<td>-0.664</td>
<td>0.899</td>
</tr>
<tr>
<td>S690 [12]</td>
<td>0.4402</td>
<td>-0.809</td>
<td>0.994</td>
</tr>
<tr>
<td>S1100 [13]</td>
<td>9.930</td>
<td>-0.978</td>
<td>-</td>
</tr>
<tr>
<td>S690QL base material</td>
<td>0.2648</td>
<td>-0.589</td>
<td>0.987</td>
</tr>
<tr>
<td>S690QL welded joint</td>
<td>0.0231</td>
<td>-0.314</td>
<td>0.796</td>
</tr>
</tbody>
</table>

Figure 10. Cyclic yield curves
TABLE V.
THE PARAMETERS OF THE CYCLIC YIELD CURVES

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Coefficient (K)</th>
<th>Exponent (n)</th>
<th>Correlation index (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355 [12]</td>
<td>595.85</td>
<td>0.0757</td>
<td>0.699</td>
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<tr>
<td>S690 [12]</td>
<td>1282.6</td>
<td>0.09211</td>
<td>0.994</td>
</tr>
<tr>
<td>S1100 [13]</td>
<td>1280</td>
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<td>-</td>
</tr>
<tr>
<td>S690QL base material</td>
<td>822.85</td>
<td>0.0703</td>
<td>0.9726</td>
</tr>
<tr>
<td>S690QL welded joint</td>
<td>1107.2</td>
<td>0.1308</td>
<td>0.9183</td>
</tr>
</tbody>
</table>

V. HIGH CYCLE FATIGUE (HCF) EXPERIMENTS

Besides of the low cycle fatigue experiments, the examined base material and welded joint were tested by high cycle fatigue examination.

For the experiments MTS 810 electro-hydraulic, universal material testing device was used. Flat test specimens with radius were used, at room temperature, in all cases. In the case of the base material the test specimen width was 24 mm, the radius was 92.5 mm, the thickness was 6 mm and the nominal cross-section was 6 mm x 8 mm (Fig. 11, part a). In the case of the welded joints, the test specimen dimensions are 18 mm, 60 mm, 6 mm and 6 mm x 8 mm, respectively (Fig. 11, part b).

Constant load amplitude, with $R = 0.1$ stress ratio, $f = 30 \text{ Hz}$ loading frequency and sinusoidal loading wave form were applied during the experiments. The geometry of the test specimen are shown in Fig. 11.

High cycle fatigue experiments were performed on the plates with 30 mm thickness. In the case of the welded joints, test specimens in two directions were worked out. In the case of the first joint transversal and perpendicular to the surface test specimen were made (Fig. 12. {m}). In that case from the joint, the test specimen were cut out in a way that the weld should be in the middle section of the test specimen, so because of the $X$ weld shape, the critical root section get into the examination range. From the second welded joint also transversal, but parallel to the surface test specimen were made (Fig. 12. {p}), so we examined the upper side of the joint. The position of the test specimens can be seen in Fig. 12.

In favor of comparison the gathered results were completed with literature data [14] and present in a common diagram (Fig. 13.). In the case of literature [14] the $S690QL$ material has the following parameters, $R_y \geq 690 \text{ MPa}$, $R_m = 770-940 \text{ MPa}$, $A \geq 14\%$.

In the case of the perpendicular test specimen, data with continuity flaws welded joint also shown (Fig. 13. {h}). So the difference between a suitable and a flowed welded joint is clearly visible.

Figure 11. High cycle fatigue test specimens

Figure 12. Position of the test specimens in case of $s = 30 \text{ mm}$
VI. SUMMARY

According to the performed welding experiments and the low cycle fatigue and high cycle fatigue experiments the following conclusions can be drawn.

- According to the completed welding joints, the developed welding technology and the determined welding parameters are suitable for making welding joints with an adequate quality.
- From the comparison of the low cycle fatigue data of the base material and the welded joint statable, that in the case of identical total and plastic strain amplitudes, the welded joint can be tolerate smaller number of cycles until the failure, then the base material. The ratio between the cycle to failure of base material and the welded joints is decreasing with the increasing of the total and plastic strain amplitudes (Fig. 9).
- The cyclic yield curve measured on the $S_{690QL}$ base material continuously advance over the welded joint curve, what may be related to the applied filler metal somewhat smaller yield strength. To the welding experiments matching filler metal was used, but the mechanical properties cannot be fitted perfectly either in this case (Chapter 3.).
- Analyzing the measured results and the literature data, it is statable, that the cyclic yield curves of higher strength steels and welded joints continuously advance over the curves of the smaller strength steels (Fig. 10). At the same time between the cycles to failure and the yield strength, in the case of equal plastic strain amplitudes, definite tendency cannot be established (Fig. 9).
- For the more accurate judgment of the received results, further examinations require both on the base material and on the welded joints.
- Based on the high cycle fatigue tests, the fatigue limit of the base material is relatively high, and confirms the assumption, that the higher strength steels have higher resistance against the high cycle fatigue.
- Additionally statable, that the given results are in harmony with the literature data.
- Based on Fig. 13. it is statable, that the high cycle fatigue resistance of the welded joints are lower, than the base material.
- Compare to the parallel and the perpendicular test specimen results, probably the latter case means worst circumstances. The reason for this probably, that the perpendicular test specimen are include a larger part of the welded joint.
- The results came from the flawed welded joint confirm the continuity flaws unbenefficial effect to the fatigue resistance.

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