Welding properties and fatigue resistance of S690QL high strength steels

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Abstract. The objective of this article is to present the first results of our research work. In order to determination and comparison of the fatigue resistance, high cycle fatigue tests (HCF) were performed on RUUKKI OPTIM S690QL quenched and tempered high strength steel. In parallel these; welded joints were made on the same steel using gas metal arc welding (GMAW, MIG/MAG) to preparation of the cyclic investigations of the welded joints. In the article, the performance of the welding experiments will be presented; along with the results of the HCF tests executed on the base material and its welded joints. Furthermore, our results will be compared with different literary data.

Introduction

In our days, the high strength steels play an important role in the welded structures. Under the different claims of applications (e.g. frames, cranes, bridges), complex expectations are evolved with the materials, and the material innovation must follow these tendencies; for example beside the increased strength, preservation of the more deformability. These constructions are often loaded under cyclic stress, so their typical damage form is the fatigue, which means even more complex expectation with the base material.

At the same time, the typical production technology is the welding, which – because of the heat input – modifies the original microstructure of the material. In this way, we achieve totally different mechanical characteristics, which is not allowable in many cases in terms of the construction. Accordingly, there is great significance of testing the welded joints of these steels, and the development of the suitable production technology. On the basis of the complexity of the problems, this article mainly focuses on the fatigue behavior of these steels. We summarized the high cycle fatigue (HCF) examinations, executed both on S690QL quenched and tempered high strength steel base material and its welded joints, and the results of these experiments.

During our experiments, 30 mm thickness base material was used. The main reason for this is, that these steels frequently use in mobile cranes, scrapers, bulldozers structural elements, where the typical thickness is between 60 and 80 mm. The direct examination of this thickness is not practical, but in the terms of the weldability and fatigue features the chosen thickness is just significant.

It is important to note, that the use of the "high strength" attribute, which is featured in the title too, is not unified in the literature, the valid standards do not state the word. At the same time the examined steel group (quenched and tempered steels) is named high strength steels (between 460 and 960 MPa yield strength) by the EN 10025-6 prescription, which is use in Hungary too. But many manufacturers do not use in this way the title.

The authors of the article [1] suggested a possible way to grouping these steels. Accordingly to that steels can be titled as high strength steels (HSS) between 600 and 1200 MPa minimal tensile strength, therefore the S690QL steel group examined by us, too. This grouping can be seen in Fig. 1.

As we can see, the examined steel group belongs to the middle section of the high strength steels, their minimum tensile strength is 770 MPa (\(R_{\text{eff}} \geq 690\) MPa), but even 850 MPa can be reached. In the marking of the steel, the „L” means that this group can be used at negative temperatures, for
example mobile cranes [2]. 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. The result is a complex phase: ferrite with tempered martensite and bainite.

As we can see, the production of the high strength steels results in nonequilibrium 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 effected zone can be softened comparing to the base material, which can be caused strength and hardness decreasing. Further undesirable phenomena can be appear: 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.

**Welding experiments**

In the case of the S690QL high strength steels, one of the most important features of the successfullness of the weldability is 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 grained microstructure can be evolved in the heat affected zone, which can be caused the decreasing of the strength and toughness features. Therefore, a narrow welding lobe was received; inside this the quality of the joint may be suitable. It is necessary to note that the smaller linear energy is more beneficial based on the experiences, in the case of the welded joint strength, toughness and residual stresses [3]. Beside the linear energy, the preheating and the interpass temperatures are significant too, that the quality of the joint is defined collectively. In the practice, the cooling time \( t_{8,5/5} \) can be used to manage these features, which has a narrow range too, in the case of S690QL steels it is generally 6 – 15 s.

Based on the previous statements, we made welding experiments on S690QL quenched and tempered base metal with 30 mm thickness \( (R_{p0.2} = 809 \text{ MPa}, R_m = 850 \text{ MPa}, A = 17 \%) \). The aim of the welding experiments was to qualify our welding technology, and make usable welded joints for different kind of examinations, mainly for high cycle fatigue tests.

For the welding experiments we chose the gas metal arc welding (GMAW), because these steels are welded mostly with this procedure. Based on industrial experiences too, we chose M21 mixed gas with 18 % \( \text{CO}_2 \) + 82 % \( \text{Ar} \) as shielding gas. As filler material, we chose Inefil NiMoCr wire with 1,0 mm diameter, which is a matching filler material in the case of the base material. In the interest of the uniform stress distribution, we designed X joint preparation, and during the welding we rotated the test specimen regularly.
In order to reaching the cooling time between 6 s and 15 s we used the following welding parameters shown in Tab 1.

Table 1. Welding parameters.

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<tbody>
<tr>
<td>1.</td>
<td>DCEP</td>
<td>130</td>
<td>19</td>
<td>20</td>
<td>5.5</td>
<td>800</td>
</tr>
<tr>
<td>2.</td>
<td>DCEP</td>
<td>145</td>
<td>20</td>
<td>20</td>
<td>6</td>
<td>800</td>
</tr>
<tr>
<td>3-8.</td>
<td>DCEP</td>
<td>260</td>
<td>29</td>
<td>40</td>
<td>13</td>
<td>1000</td>
</tr>
<tr>
<td>9-20.</td>
<td>DCEP</td>
<td>250-260</td>
<td>28-29</td>
<td>35-45</td>
<td>13</td>
<td>1000-1200</td>
</tr>
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For preheating temperature 150 °C, and for interpass temperature 180 °C were prescribed. Welding parameters were recorded continuously during the experiments with the help of WeldQAS process monitoring device. Besides all these regulations, the linear energy was between 800 J/mm and 1200 J/mm. The experimental composition is shown in Fig. 2.

![Fig. 2. The composition of the welding experiments.](image)

**High cycle fatigue tests on base materials**

In the interest of the welded joints of the S690QL steels resistance against the cyclic loading, we made experiments on the base material and there welded joints. We performed high cycle fatigue (HCF) experiments on the base material with MTS 810 electro-hydraulic materials testing equipment, at room temperature and on laboratory environment. We used flat test specimens weakened with 92,5 mm radius, the specimen thickness was 6 mm and their width was 24 mm. We applied constant load amplitude during the experiments, with R = 0,1 stress ratio, f = 30 Hz loading frequency, and sinusoidal loading wave form. The test equipment and the geometry of the test specimens are shown in Fig. 3.

The results of our experiments we compared with some data can be found in the literature [[4][6]] and we present these in a common diagram (Fig. 4.). In the case of the steel D38MSV5S (0,384 wt% C, 5,67 wt% Si, 1,23 Mn wt% etc.) the R_{p0,2} = 608 MPa, R_{m} = 878 MPa, A = 20 % [[4], in the case of the S690 steel the R_{eff} = 733 MPa, R_{m} = 787 MPa, A = 17 % [[5], while in the case of S690QL steel the R_y ≥ 690 MPa, R_{m} = 770-940 MPa, A ≥ 14 % [6].
Based on Fig. 4, we can state that the high cycle fatigue resistance of the examined base material (black squares) is considerable and is in accordance with the data can be found in the literature [4]. The difference compared with the other results probably caused by the different parameters of the experiments, such as the different stress ratio (R) or the different testing frequency (f).

High cycle fatigue tests on welded joints

After that we finished and evaluated the high cycle fatigue experiments on the base material, we made test specimens from the welded joints, present in the previous point and shown in the Fig. 5. We also made high cycle fatigue experiments on these specimens.
On behalf of comparison we changed nothing on the experiment conditions, only slightly changed the test specimens shape. So, we also used MTS 810 electro-hydraulic materials testing equipment, at room temperature and on laboratory environment. On the test specimens we take into consideration that the welded joint must locate in the center line of the specimens, so the specimens itself must take out from the center of the welded plate, shear to the surface. Since we used X shape joints the weakest part of the welded joint locate this region. The flat test specimens weakened with 60 mm radius, the specimen thickness was 6 mm and their width was 30 mm, therefore the critical section was a 6x8 mm rectangle section. We also applied constant load amplitude during the experiments, with R = 0,1 stress ratio, f = 30 Hz loading frequency, and sinusoidal loading wave form.

Just like previously we compared the results of our experiments with some data can be found in the literature [6] and we present these in a common diagram (Fig. 6). In this figure we present our results both on the base material and their welded joints, too. At the same time we had shown the literature [6] results on behalf of comparison; these data also refer to base material and welded joints.

![Figure 6](image-url)

**Fig. 6.** Results of high cycle fatigue (HCF) tests on base material and welded joints.
It is important to note, that in this article [6] the applied welding process was also gas metal arc welding, but they examined full butt weld joints and we examined test specimens take out from butt weld joints. Even so it is state, that the results of the welded joints are similar, even though the stress ratio is also different. Furthermore it is clearly shown, that the fatigue resistance of the welded joint is less than the base material resistance.

Therefore, the microstructural changes during the welding process affect negatively not only the strength properties, which was examined previously [7], but also the fatigue features as well. But for correct assessment we need more experiments, which we will realize in the future.

Summary

Based on our first investigations and their results 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.
- Based on the high cycle fatigue (HCF) tests on the base material and their welded joints, the fatigue limit of the base material is relatively high (approximately 70% of the $R_{m}$ value), at the same time the fatigue limit of the welded joints is lower.
- The welding cycle effect negatively both on the mechanical properties (see our previous experiments [7]) and the fatigue resistance.
- Our results are in harmony with the results can be found in the literature.

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References
