Comparing the Reliability of Structural Steel Welds using Ultrasonic Fatigue Testing

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Abstract. There is a limited data on VHCF for structural steels welds for over 10 million cycles. The purpose of this research is a fatigue performance comparison of the welds made of steels S355JR and S275JR. The goal of reaching gigacycle fatigue domain is achieved using the ultrasonic fatigue testing at 20kHz. Fatigue samples are prepared to investigate the influence of two surface conditions – polished and pre-corroded. Fatigue failures are driven primarily by the welding porosity with the fatigue life duration dependent on the size and location of pores. Visual comparison of fatigue data for steels poses a challenge, because of the massive scatter of experimental data points. Therefore, a statistical approach is used with a Fatigue Performance Parameter applied to the fatigue data for welded samples to quantify the quality of the material.

Introduction

Unalloyed low-carbon steel grades S235, S275 and S355 (EN 10025) are common structural materials for the heavy machinery in minerals, sand & aggregate applications. Currently, these components are designed with high safety factors against SN curves with an assumed asymptotic fatigue limit above >10^7 load cycles. Nevertheless, fatigue cracks are seen even at the high number of cycles (>10^8), producing a big data scatter (over an order of magnitude) as the stress reduces. While high-cycle fatigue failure occurs at the surface, fatigue cracks at the very high number of cycles (>10^8) may initiate at oxides or intermetallic inclusions below the surface (or slag and flux inclusions for welds) typical for Very High-Cycle Fatigue (VHCF) regime. Recently, ultrasonic fatigue (USF) testing results have been published for S275JR+AR [1] and Q355B [2] grades that demonstrated a pronounced frequency effect and several technical challenges associated with accelerated fatigue testing. However, there is almost no VHCF data (>10^8 cycles) for the welds made of low-carbon steel grades from EN 10025 and their equivalents with just a few publications, e.g. results for the bridge steel Q345 [3]. So this research is focused on USF testing of two specific subgrades S275JR+AR and S355JR+AR with a goal of fatigue performance comparison for different surface conditions.

Scope of the work

The main purpose of this research is a fatigue performance comparison of the welds made of currently preferred steel S355JR and the candidate steel S275JR. Welded machinery assemblies are designed to work for several years at typically 16-20 Hz frequencies of loading under low stress amplitudes. In order to reach a few billion cycles within a practically sustainable testing time, an accelerated fatigue testing is required. The goal of reaching gigacycle fatigue domain is achieved using the ultrasonic fatigue testing approach with Shimadzu USF-2000A system.

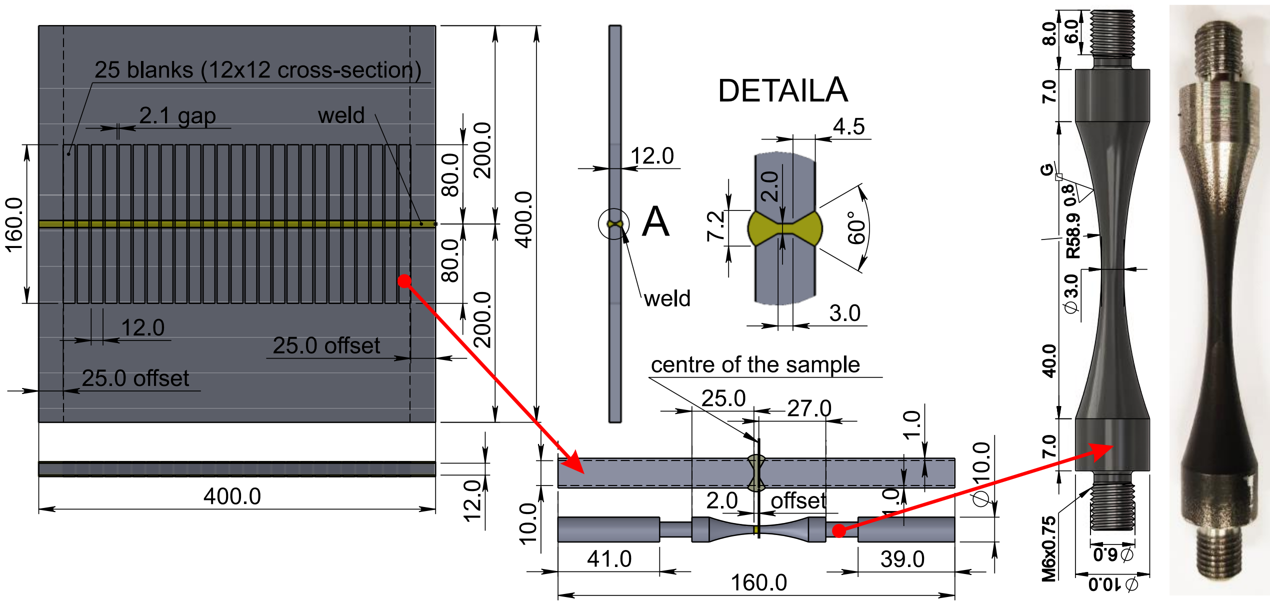

Figure 1: Manufacturing of USF testing samples from the plates welded with a double-V butt joint.

The fatigue samples have a standard tapered shape are cut out of the welded plates to have a HAZ in the middle as shown in Fig. 1. The fatigue samples are prepared to investigate the influence of two surface conditions – polished and pre-corroded. In the polished samples, fatigue failures are driven primarily by the welding porosity with the fatigue life duration dependent on the size and location of pores. In the pre-corroded samples, fatigue failures are driven primarily by the corrosion pitting with the fatigue life duration dependent on the amount of corrosion damage to the surface. Visual comparison of fatigue data for S275JR and S355JR steels poses a challenge, because of the massive scatter of experimental data points making the determination of SN curves impossible. Therefore, statistical approach is used.

Fatigue Performance Parameter

There is a significant variation in both the size and location of pores which has a massive effect on the fatigue life of each welded sample. The size of pores that initiated the crack growth and resulted in failure varies from 50μm to almost 1mm, with a distance to the surface varying from the centre of the sample cross-section to a few micrometres or partly open pore. At the same nominal stress amplitude level, the fatigue life can vary from 1 million cycles for a small sub-surface pore (like shown in Fig. 2 with Ø = 75μm) to 100 million cycles for a relatively big pore sitting 5 pore diameters away from the surface. To address this issue in the analysis of experimental results, a Fatigue Performance Parameter (P_{fp}) is applied to the fatigue data for welded samples to quantify the quality of the material:

$$P_{\mathrm{fp}} = \ln N \cdot \sigma_{\mathrm{a}} \,,$$

where N is a number of cycles to failure and σ_{a} is a stress amplitude.

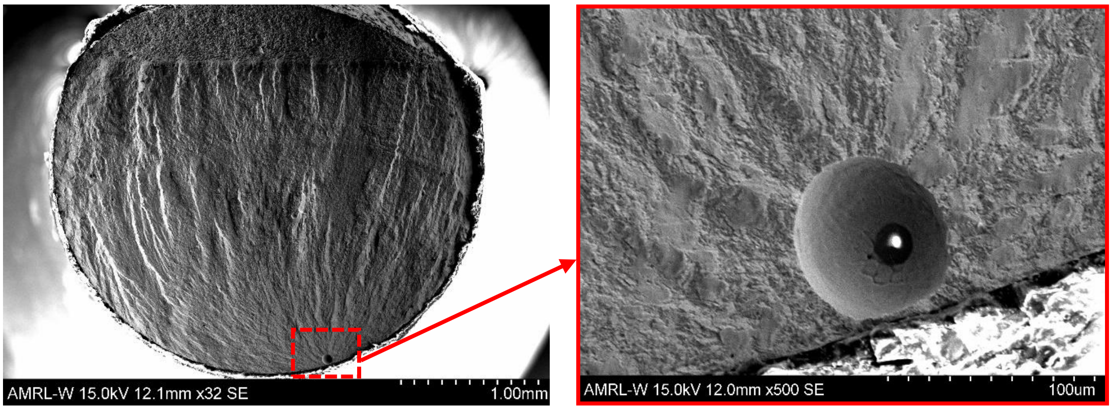

Figure 2: Typical welding pore found on fracture surfaces of USF testing specimens cut from weldments.

Conclusion

Welds made of currently preferred steel S355JR and the candidate steel S275JR were tested at ultrasonic frequency of 20kHz in two conditions – polished surface and pre-corroded. The obtained experimental data was aggregated and processed using a Fatigue Performance Parameter (P_{fp}) to identify a better performing grade. Comparison of P_{fp} for parent materials with polished surface demonstrated a significant advantage of S355JR grade which is attributed to a higher yield strength resulting a longer time to crack initiation. However, this advantage reduces to just a few % difference in P_{fp} for welded samples with polished surface, where the cracks mostly initiate from the welding pores. This observation proves that internal welding defects eliminate any benefits of higher yield strength by a sharp reduction of the time to crack initiation. But the most important finding is that the comparison of welded samples in the pre-corroded condition shows a slight benefit for the candidate grade S275JR. It should be noted that in pre-corroded samples the cracks mostly initiate from the corrosion pits on the surface, that proves a higher damaging effect of corrosion on the fatigue performance compared to the negative influence of porosity. The advantage of S275JR pre-corroded welds can be associated with a higher ductility of this grade, which results in a better tolerance to both internal (corrosion pitting) and external (welding porosity) defects.

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