Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 38 (2022) 490–496

Structural Integrity Procedia

www.elsevier.com/locate/procedia

FATIGUE DESIGN 2021, 9th Edition of the International Conference on Fatigue Design

Investigation of S275JR+AR structural steel fatigue performance in very high cycle domain

Yevgen Gorash[a,*], Tugrul Comlekci[a], Gary Styger[b], James Kelly[c], Frazer Brownlie[a]

[a] *Weir Advanced Research Centre, University of Strathclyde, Glasgow, Scotland, UK*
[b] *Weir Minerals South Africa, 31 Isando Road, Isando, Johannesburg, South Africa*
[c] *Advanced Materials Research Laboratory, University of Strathclyde, Glasgow, Scotland, UK*

Abstract

There is a limited data on VHCF for structural steels and their weldments for > 10^7 cycles. Unalloyed low-carbon steel S275JR+AR (EN 10025) is a common structural material for the components made for the minerals and mining applications. The purpose of this research is an investigation of the gigacycle domain for S275JR+AR grade that is intended to work for years at normal frequencies (10-20 Hz) of loading with low stress amplitudes. The work focuses on ultrasonic fatigue testing of the steel in both as-manufactured and pre-corroded conditions. As the heating is a massive challenge for ultrasonic fatigue testing especially in the case of structural steels attributed with a pronounced frequency effect, temperature control arrangement is crucial for proper implementation of testing. The frequency effect is assessed by comparing the fatigue test data at 20kHz and conventional frequency of 15Hz. Its contribution is found to be significant because there is no overlap between the stress ranges of interest. The ultrasonic fatigue data is intended to be applied to the fatigue assessments of the equipment operating at normal frequency for 10^{10} cycles. Thus, the effect of frequency sensitivity is quantified by calculating the difference in terms of stress amplitude between corresponding SN curves.

Keywords:
Crack arrest, Structural steel, Very High Cycle Fatigue, Ultrasonic, Corrosion, Frequency effect

1. Introduction and motivation

Unalloyed low carbon steels or standard, according to EN 10025-2 (2019) in Europe, structural steels are dominant materials for components and equipment used in the minerals and mining industry. Despite good static strength, manufacturability and fatigue resistance, this group of steels has a pronounced strain rate effect. This is a big challenge for the determination of SN curves with accelerated fatigue testing and especially the fatigue limit that strongly depends on the frequency of testing. The purpose of this research work is an investigation of the fatigue performance of S275JR+AR steel grade in the gigacycle domain (10^9 – 10^{10} cycles) that is intended to work for several years at a

* Corresponding author. Mob.: +44-790-9780901; Tel.: +44-141-4447969.
E-mail address: yevgen.gorash@strath.ac.uk

10.1016/j.prostr.2022.03.049

normal frequency of 15-16 Hz of loading with low-stress amplitude. However, accelerated fatigue testing (typically at 20 kHz) using ultrasonic machines significantly exaggerates fatigue strength compared to normal loading conditions. This issue needs to be addressed in the first instance in this research.

Currently, components for the minerals and mining industry 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 usually 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 in case of welds). The existence of this transition in the failure mechanisms in the Very High-Cycle Fatigue (VHCF) regime has to be proved for the class of structural steels including S275JR+AR grade, which is in the focus of this work.

2. Available fatigue data

Available fatigue standards, e.g. BS 7608 (2014), do not contain reliable experimental data up to 10^9 cycles and hence the "fatigue design" of the responsible components is completed with stress amplitudes as low as 2% of the yield strength according to recommendations by Hobbacher (2016). The available design SN curves (Haibach, 2003; ANSYS Inc., 2020) for structural steel grades (EN 10025-2, 2019) are limited by 10^6 considering a fatigue limit above this threshold. Thus, currently, machines for minerals and mining are most likely "over-designed" and hence not cost-effective.

The main problem is that there is limited data on VHCF for low-carbon structural steels, so it is difficult to make practical engineering predictions for the gigacycle domain (10^9 – 10^{10} cycles). The existence of the plateau that characterizes a transition from HCF to VHCF is an open question. Even a bigger challenge is the interpretation and utilization of the obtained ultrasonic data, which proves a considerable frequency sensitivity. This can be seen comparing the experimental SN diagrams with fatigue tests conducted at 110 Hz and 20 kHz for structural steels including C15E, C45E, C60E by Bach et al. (2018) and fatigue tests at 10 Hz and 20 kHz for structural steel JIS S38C by Nonaka et al. (2014). The fatigue limits identified at 20 kHz at around 10^8 cycles to failure for S355J0 and S355J2 subgrades by Klusák and Seitl (2019) are significantly higher than the recommended design values reported by Haibach (2003) and ANSYS Inc. (2020) for 10^6 cycles at low frequency.

3. Experimental procedure

3.1. Ultrasonic machine

The number of cycles beyond 10^7 can be attained in a viable period using the recently developed high-frequency testing techniques running usually at 20 kHz. VHCF becomes increasingly important for the equipment that is required to operate without failure into the gigacycle domain ($> 10^9$ cycles) for years and even decades of continuous service, which is typical for minerals separation and transportation applications. To assess fatigue for 10^9 cycles requires 1.6 years of normal testing at 20 Hz, which is not feasible. In contrast to that, when doing ultrasonic testing at 20 kHz, it would take only 0.6 days, if intensive cooling is not required. Therefore, the central piece of the experimental setup is the ultrasonic fatigue testing system with an average stress loading mechanism, that consists of a standard Shimadzu USF-2000A machine and Shimadzu AG-X series (AG-X5kN) table-top autograph by Shimadzu Corp. (2020) with a maximum of 5kN tensile load. Mean stress loading mechanism based on AG-X5kN exerts constant mean stress in the test sample by pulling it from both ends with the recommended force of $\leq$ 1.5 kN. Figure 1a shows the USF-2000A machine attached to the moving crosshead on one side and the frame base on the other side with a test sample in the middle. The standard air-cooling nozzles are pointed at the sample to suppress intensive heating.

3.2. Tensile testing

Ultrasonic fatigue testing is based on the loading by resonance when longitudinal elastic waves are induced in the specimen with a peak in its central gauge location. Therefore, the proper setup of the ultrasonic test requires accurate elastic properties of the tested material as directly define the stress amplitude and mean stress values applied to the

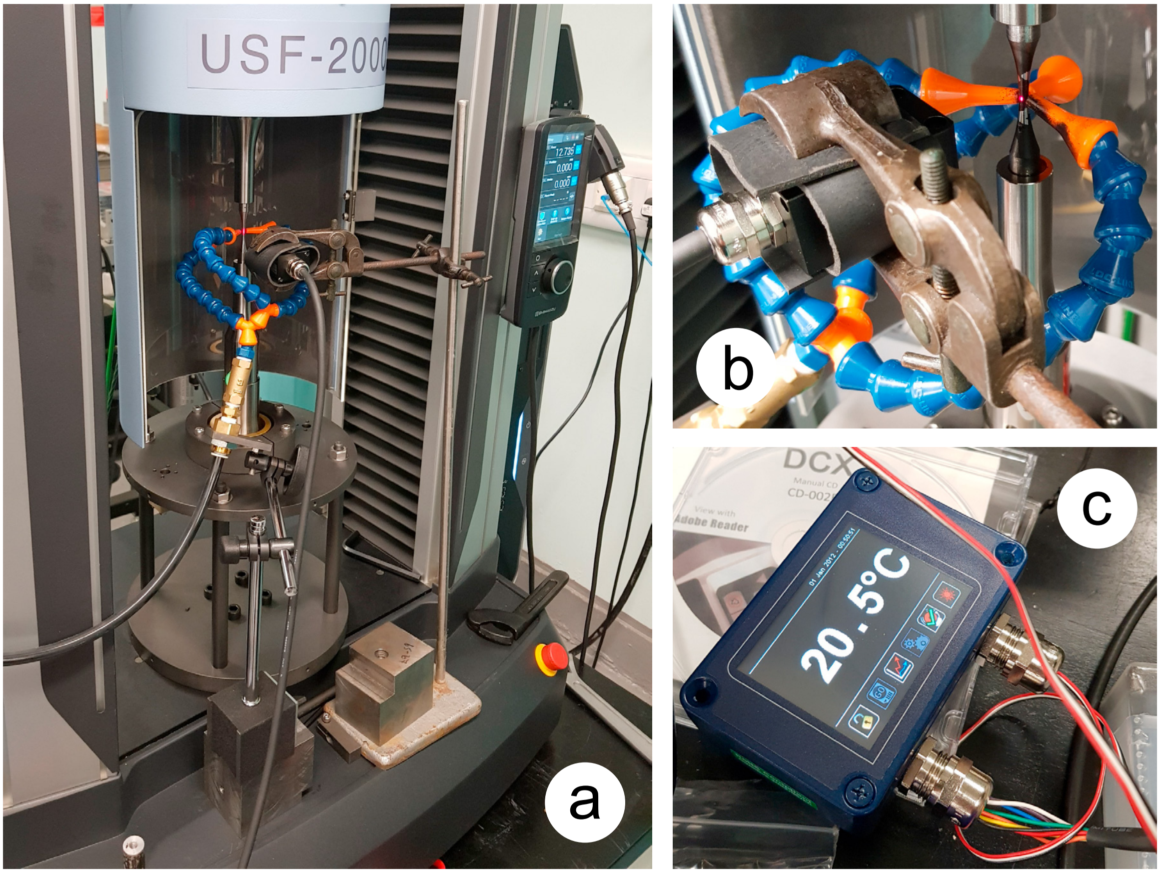

Fig. 1. Arrangement for temperature control of the ultrasonic test: a) USF-2000A with average stress loading mechanism; b) Pyrocube IR temperature sensor; c) touch screen display for PyroCube.

Table 1. Mechanical properties of 12mm thick hot-rolled plate made of S275JR+AR structural steel.

Young's modulus [GPa]	0.2% proof stress [MPa]	Tensile strength [MPa]	Elongation at break [%]
211.1 (210‡)	314 (338* / 275†)	468.9 (469* / 410†)	31.8 (30.5* / 23†)

‡ values according to the standard EN 1993-1-1 (2005)
* values from the material quality certificate provided by the manufacturer
† values according to the standard EN 10025-2 (2019)

sample. The tensile testing was done using Instron 8802 servo-hydraulic fatigue testing system with actuator force capacity up to ±250 kN. Round tensile samples 150 mm long were cut from the hot-rolled plate with a thickness of 12 mm. The grip length sides are both 50 mm long, and gauge length is 50 mm with fillets of 25 mm in diameter. The obtained experimental values for S275JR+AR grade are reported in Table 1 and compared to the values from the material quality certificate provided by the manufacturer and values from standards EN 10025-2 (2019) and EN 1993-1-1 (2005). The comparison indicates insignificant deviation for all properties with Young's modulus very close to the standard value from EN 1993-1-1 (2005), slightly better value of yield strength in certificate compared to the experiment, and the tensile strength and elongation at break values being very similar for experiment and certificate. However, both yield / tensile strength and elongation at break in actual material are superior to those prescribed by the standard EN 10025-2 (2019).

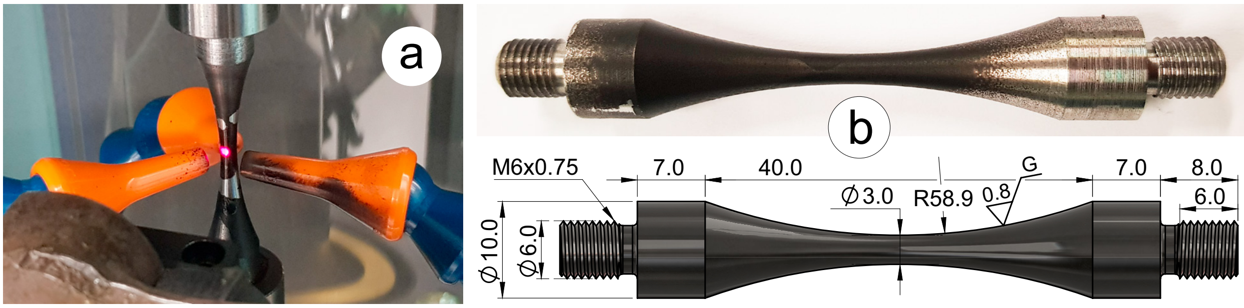

Fig. 2. Specimen for ultrasonic test: a) inserted in UFS-2000A with temperature measurement spot; b) solid model with dimensions and manufactured and painted.

3.3. Heat generation

As the heating is a massive challenge for ultrasonic fatigue testing (Bathias, 2014) especially in the case of structural steels attributed with a pronounced frequency effect including S275JR+AR grade, temperature control arrangement is crucial for proper implementation of testing. The use of intermittent driving with load blocks and cooling pauses was inevitable to address the intensive heating. The temperature monitoring is done using PyroCube thermometer from CALEX Electronics that includes infrared temperature sensor (PCU-S1.6-2M-1V) shown in Fig. 1b and configurable touch screen display for PyroCube (PM030) shown in Fig. 1c. The sampling interval of 1 s is used for temperature data logging. The duration of the cooling pause is selected manually in the test setup by the measured temperature from the touch screen display with the condition to keep it below 25°C. The cooling pause varied from 0.5 s to 5 s depending on the stress level with extended pauses needed for high-stress amplitudes. The duration of the full-amplitude load block was 0.1 s for all implemented tests.

3.4. Specimens manufacturing

The ultrasonic samples geometry has been manufactured following the standard WES 1112 (2017) with a minimum recommended diameter of 3 mm in the gauge location. It is designed to resonate at 20 kHz and provide efficient air cooling within the allowable range of horn end displacements. Figure 2a shows the sample during the testing with the cooling nozzles and infrared sensor pointing at the middle of the specimen gauge. To improve the accuracy of non-contact temperature monitoring, the samples have been painted in black matt color using Rust-Oleum Stove & BBQ spray paint as shown in Fig. 2b. It has been practically identified that this coating provides a reliable adhesion to the metal surface and resistance to elevated temperatures. As manufactured the surface of gauge location has a shiny mirror finish with emissivity close to 0. The applied coating massively improves the emissivity bringing it close to 1 and making the infrared temperature monitoring efficient. Finally, the dimensions of the ultrasonic samples are shown in Fig. 2c.

3.5. Corrosion effect

To study the effect of corrosion on the fatigue resistance of S275JR+AR grade, a batch of pre-corroded samples have been prepared. They have the same dimensions (see Fig. 2c), but they were subject to 3.5% NaCl solution as the corrosion medium in 0.5L beakers as shown in Fig. 3a. Figures 3b-3d show the effect of corrosion on the surface of the sample after 17 days of “still seawater” treatment. The threads on the ends of the samples were protected from corrosion using RS PRO White PTFE thread seal tape 12 mm wide. Threads and adjacent areas were wrapped up in multiple layers of tape with different degrees of orientation, as shown in Figs. 3b & 3c. This sort of waterproof isolation appeared to be quite reliable, as after removing the tape the surface under it showed very minor signs of corrosion, as can be seen in Fig. 3d. When taken out of the water, samples have a thick rust layer as shown in Fig. 3b, but this layer is not mechanically stable and can be easily washed and wiped out. Under a greasy layer of rust pre-corroded sample reveals a nice grey matt surface with an emissivity of 0.3-0.5, which is still good for infrared temperature monitoring.

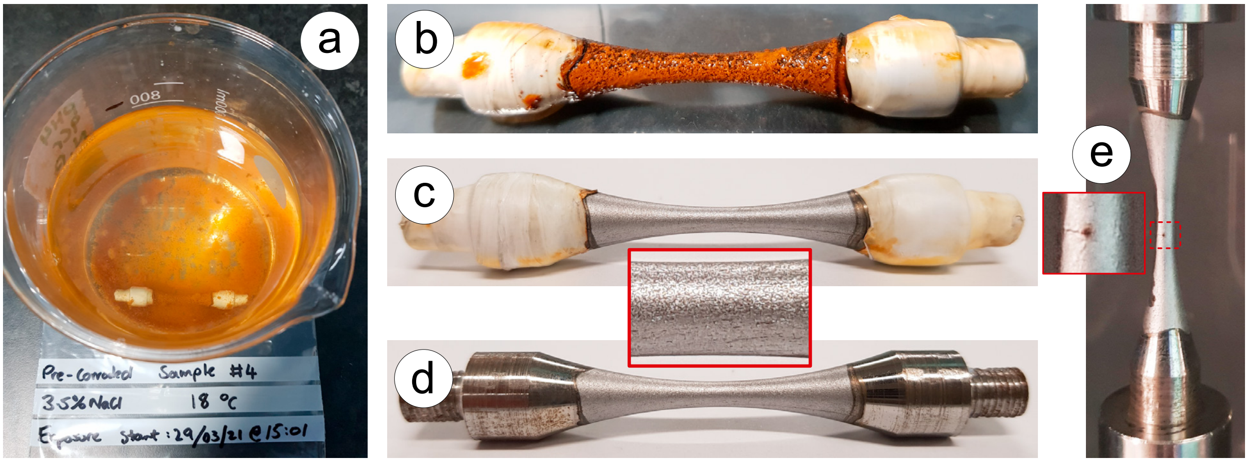

Fig. 3. Pre-corroded specimen for ultrasonic test: a) 3.5% NaCl solution with the submerged specimen; b) rust layer on the specimen; c) washed specimen with thread seal tape; d) specimen ready for testing; e) specimen at the end of the test with a crack in the middle.

The pre-corroded surface is evenly covered with pits, as a result of material loss, that can be seen without additional magnification, as shown in Fig. 3c & 3d. The surface roughness of all pre-corroded batch was measured using the surface roughness machine Mitutoyo SV 600 and appeared to be Ra=12.5 μm on average with a variation of ±0.5 μm. The benefit of result analysis provided by a pre-corroded surface was that the crack in the gauge area (see Fig. 3e) was visible compared to painted samples.

4. Results and discussion

The summary of the obtained fatigue testing results for S275JR+AR grade is shown in Fig. 4 in the form of data points and trendlines. Testing was done at a conventional frequency of 15 Hz and ultrasonic frequency of 20 kHz to study the strain-rate effect on the fatigue resistance. Its contribution is found to be significant because there is no overlap between the stress ranges of interest. Low-frequency testing is done in the range of 175-275 MPa while ultrasonic testing in the range of 300-400 MPa. Data points at 15 Hz were obtained with Instron 8802 servo-hydraulic fatigue testing system using the same specimens as used for tensile testing, but with a better surface finish. The obtained SN curve using power-law trendline shows little scatter with $R^2 = 0.92$ and looks quite consistent when compared with the available SN curves from material databases (Haibach, 2003; ANSYS Inc., 2020). The SN curve for S275JR+AR grade looks better than the lower bound of averaged fatigue data for JR, J0, J2 subgrades of S275 from the Granta database (ANSYS Inc., 2020), but worse than the 50% probability SN curve averaged for all subgrades from FKM database (Haibach, 2003). The conventional fatigue limit for S275JR+AR is expected to be around 215 MPa, which is higher than 179 MPa from ANSYS Inc. (2020) and 195 MPa from Haibach (2003).

Ultrasonic testing results can fall into three groups:

1. data points with crack originating on the surface;
2. data points with a crack starting from subsurface;
3. data points for pre-corroded samples.

All groups of datapoints at 20 kHz demonstrate a relatively small scatter when fitted with power-law trendlines as shown in Fig. 4. The major challenge is intensive heat generation, especially when running tests at high-stress levels 375-400 MPa. Figure 5 shows the temperature history in the sample tested at 400 MPa that lasted over 8000 seconds and accumulated over 4 million cycles before failure. It was possible to keep the temperature with the "room temperature" range of 15-30°C for about half of the testing time using a maximum cooling pause of 5 s. However, in the second part of the specimen life, the exponential growth of temperature is seen with temperatures up to 200°C just before failure. When approaching the stress levels close to the fatigue limit the cooling pause has been reduced to 0.5 seconds.

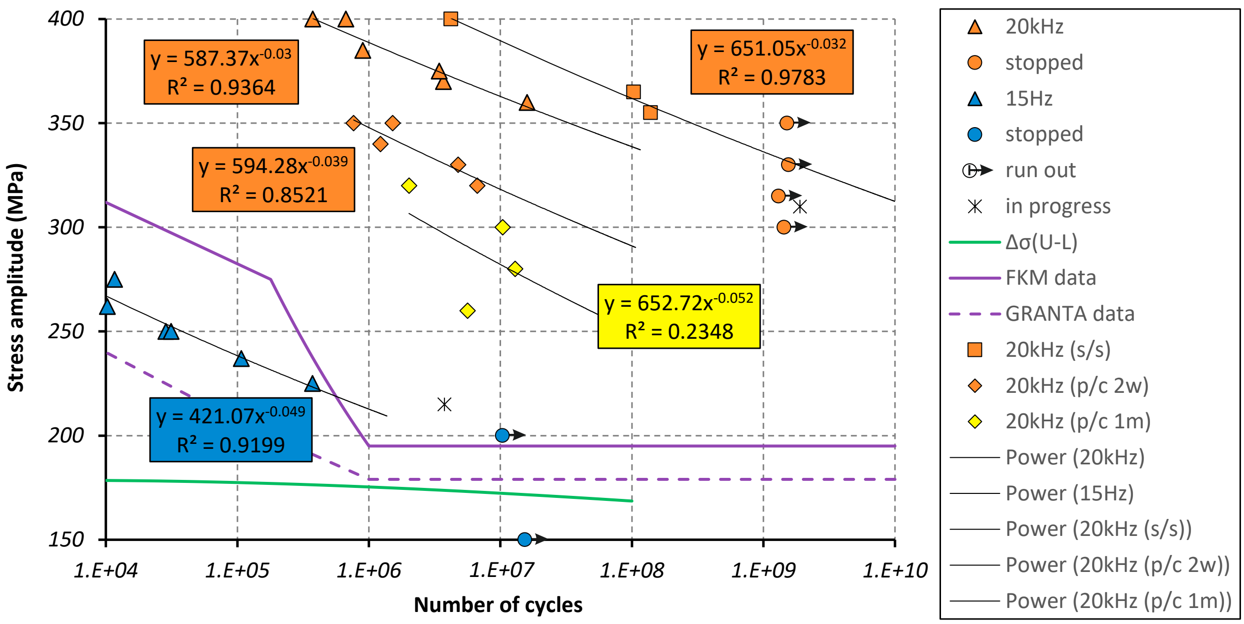

Fig. 4. Summary of fatigue testing for S275JR+AS including base dry and pre-corroded samples.

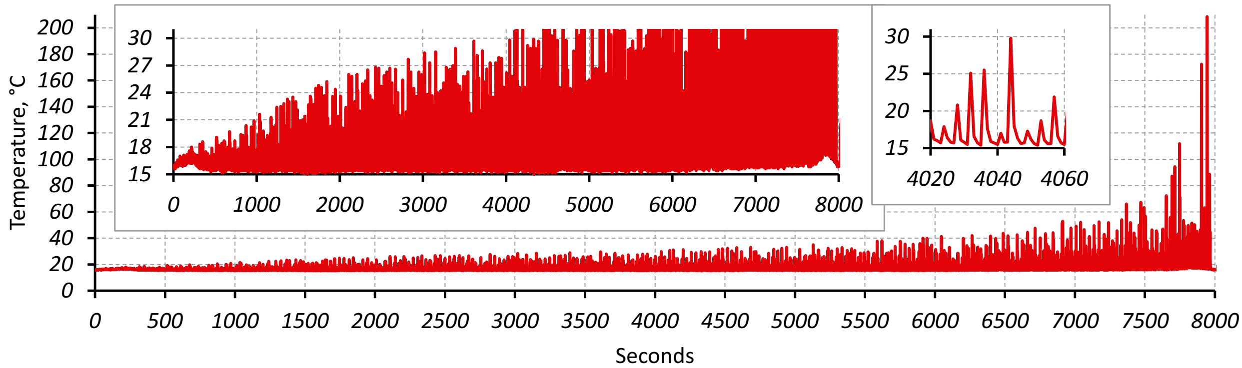

Fig. 5. Temperature history of the ultrasonic fatigue test lasted 4m cycles at 400 MPa stress amplitude.

The ultrasonic fatigue limit for S275JR+AS grade with mirror surface finish is found to be 350 MPa as confirmed by four samples in the range of 300-350 MPa that run out after 1.2 billion cycles. Three samples have demonstrated an order of magnitude longer fatigue life (see Fig. 4), and, for this reason, have been grouped and used to generate a sub-surface SN curve. The assumption of sub-surface crack origin has been investigated using optical and SEM microscopy, as shown in Fig. 6. The pre-corroded samples demonstrated significantly lower fatigue resistance with finite fatigue life of about 1 million cycles at the stress level corresponding to the fatigue limit for the ideal surface. As seen in Fig. 4, the drop of fatigue performance by 1.5 orders of magnitude in terms of cycles to failure and by over 50 MPa in terms of stress amplitude. This can be explained by the absence of the crack initiation phase in pre-corroded samples, as the crack grows directly from pits, as stress concentrators.

The difference between 15 Hz and 20 kHz SN curves was measured in terms of stress amplitude as 170 MPa on average and used as a basic tool for frequency correction. Scaling down the fatigue limit from 350 MPa at 20kHz using 170 MPa correction gives 180 MPa as a conservative prediction of the conventional fatigue limit at 15Hz for S275JR+AS, which is close to values from the literature (Haibach, 2003; ANSYS Inc., 2020).

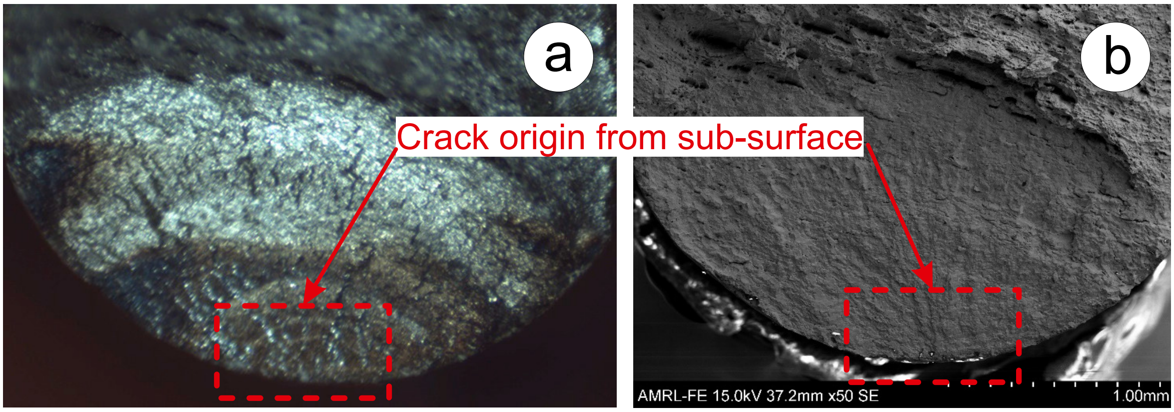

Fig. 6. Investigation of the fracture surface of the sample run at 400 MPa stress amplitude with a sub-surface crack origin for over 4 million cycles using: a) optical microscopy; b) SEM microscopy.

5. Conclusions

Parent / dry and parent / pre-corroded condition of S275JR+AR steel grade has been investigated. Confidence and competence in running ultrasonic fatigue tests with Shimadzu USF-2000A has been obtained. The duration of fatigue tests has been limited so far by 1 billion cycles, but there is a potential to achieve 10 billion cycles. Heat generation remains the most significant technical challenge, but further investigation into more efficient air coolers and water cooling is in progress. Basic quantification of the frequency effect contribution has been done using the difference in stress amplitude between SN curves. Basic extrapolation of the ultrasonic fatigue testing results into low frequency domain can be applied to the data from pre-corroded samples. Fracture surfaces of failed specimens can be examined using both optical and SEM microscopy. The work to test grade S275JR+AR for fatigue performance in welded condition considering mean stress and corrosion effects is under preparation.

Acknowledgements

The authors greatly appreciate Weir Minerals South Africa for the motivation and practical guidance and Shimadzu Europe & UK for the technical support over the course of this work.

References

ANSYS Inc., 2020. GRANTA EduPack. Material properties database v. 20.1.0. Granta Design Ltd.. Cambridge, UK.

Bach, J., Göken, M., Höppel, H.W., 2018. Fatigue of low alloyed carbon steels in the HCF/VHCF-regimes, in: Christ, H.J. (Ed.), Fatigue of Materials at Very High Numbers of Loading Cycles. Springer Fachmedien, Wiesbaden, pp. 1–23.

Bathias, C., 2014. Coupling effect of plasticity, thermal dissipation and metallurgical stability in ultrasonic fatigue. Int. J. of Fatigue 60, 18–22.

BS 7608, 2014. Guide to fatigue design and assessment of steel products. The British Standards Institution, London, UK.

EN 10025-2, 2019. Hot rolled products of structural steels - Part 2: Technical delivery conditions for non-alloy structural steels. European Committee for Standardization, Brussels, Belgium.

EN 1993-1-1, 2005. Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings. European Committee for Standardization, Brussels, Belgium.

Haibach, E., 2003. FKM-Guideline: Analytical Strength Assessment of Components in Mechanical Engineering. 5th ed., VDMA Verlag, FKM, Frankfurt am Main, Germany.

Hobbacher, A.F., 2016. Recommendations for Fatigue Design of Welded Joints and Components. 2nd ed., Springer International Publishing, Cham, Switzerland.

Klusák, J., Seitl, S., 2019. Very high cycle fatigue tests of high strength steels S355 J0 and S355 J2. Procedia Structural Integrity 17, 576–581.

Nonaka, I., Setowaki, S., Ichikawa, Y., 2014. Effect of load frequency on high cycle fatigue strength of bullet train axle steel. Int. J. of Fatigue 60, 43–47.

Shimadzu Corp., 2020. USF-2000/USF-2000A Instruction Manual: Hardware. Manual v. 349-04408E. Shimadzu Corp.. Kyoto, Japan.

WES 1112, 2017. Standard test method for ultrasonic fatigue testing of metallic materials. The Japan Welding Engineering Society, Tokyo, Japan.