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

Yevgen Gorash[1]*, Tugrul Comlekci[1], Gary Styger[2], James Kelly[3] and Frazer Brownlie[1]

[1] *Weir Advanced Research Centre, University of Strathclyde, Scotland, UK*
[2] *Weir Minerals South Africa, 31 Isando Road, Isando, Johannesburg, South Africa*
[3] *Advanced Materials Research Laboratory, University of Strathclyde, Scotland, UK*

* Corresponding author: yevgen.gorash@strath.ac.uk

INTRODUCTION AND MOTIVATION

Unalloyed low carbon steels or standard, according to EN 10025 [1] 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 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.

AVAILABLE FATIGUE DATA

Available fatigue standards, e.g. [2] do not have 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 [3]. The available design SN curves [4,5] for structural steel grades [1] 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 [6] and fatigue tests at 10 Hz and 20 kHz for structural steel JIS S38C [7]. The fatigue limits identified at 20 kHz at around 10^8 cycles to failure for S355J0 and S355J2 subgrades [8] are significantly higher than the recommended design values reported in [4,5] for 10^6 at low frequency.

EXPERIMENTAL PROCEDURE

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 [9] 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 ≤1.5kN. 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.

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 sample. The tensile testing was done using Instron 8802 servo-hydraulic fatigue testing system with actuator force capacity up to ±250kN. Round tensile samples 150mm long were cut from the hot-rolled plate with a thickness of 12mm. The grip length sides are both 50mm long, and gauge length is 50mm with fillets of 25mm 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 – BS EN 10025-2: 2019 [1] and EN 1993-1-1: 2005 [10]. The comparison indicates insignificant deviation for all properties with Young's modulus very close to the standard value, 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 [1].

As the heating is a massive challenge for ultrasonic fatigue testing [11] 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) in Fig.1b and configurable touch screen display for PyroCube (PM030) shown in Fig.1c. The sampling interval of 1s 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 0.5s to 5s depending on the stress level with extended pauses needed for high-stress amplitudes. The duration of the full-amplitude load block was 0.1s for all implemented tests.

The ultrasonic samples geometry has been manufactured following the standard WES 1112: 2017 [12] with a minimum recommended diameter of 3mm 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.

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 12mm 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. 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=12.5μm on average with a variation of ±0.5μm. 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.

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 15Hz and ultrasonic frequency of 20kHz 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 15Hz 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 [4,5]. 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 [5], but worse than the 50% probability SN curve averaged for all subgrades from FKM database [4]. The conventional fatigue limit for S275JR+AR is expected to be around 215 MPa, which is higher than 179 MPa from [5] and 195 MPa from [4].

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 datasets demonstrate a relatively small scatter when fitted with power-law trendlines, see 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 5s. 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.

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.

CONCLUSIONS

The difference between 15Hz and 20kHz 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 the values from the literature [4,5].

ACKNOWLEDGEMENTS

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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 [10]

* values from the material quality certificate provided by the manufacturer

† values according to the standard BS EN 10025-2: 2019 [1]

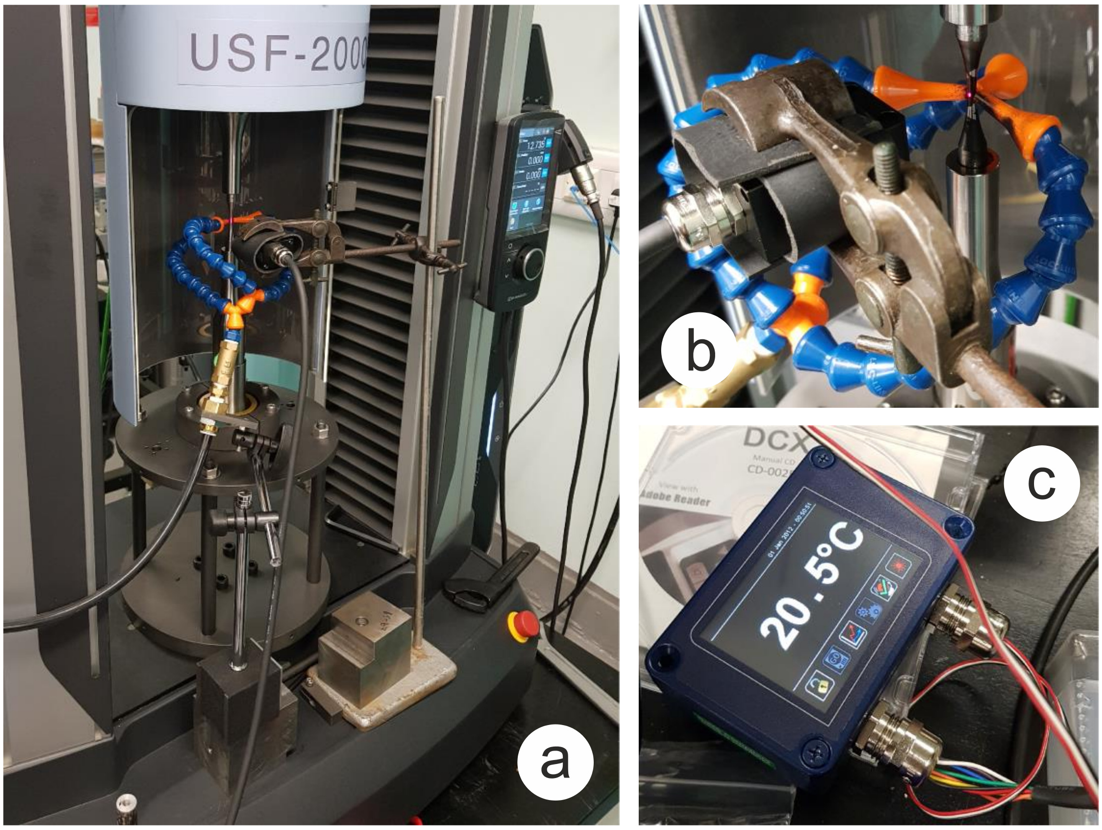

Fig. 1 Arrangement for temperature control of the ultrasonic test: a) USF-2000A with average stress loading mechanism; b) Pyrocube IR temperature sensor; c) touch screen display for PyroCube.

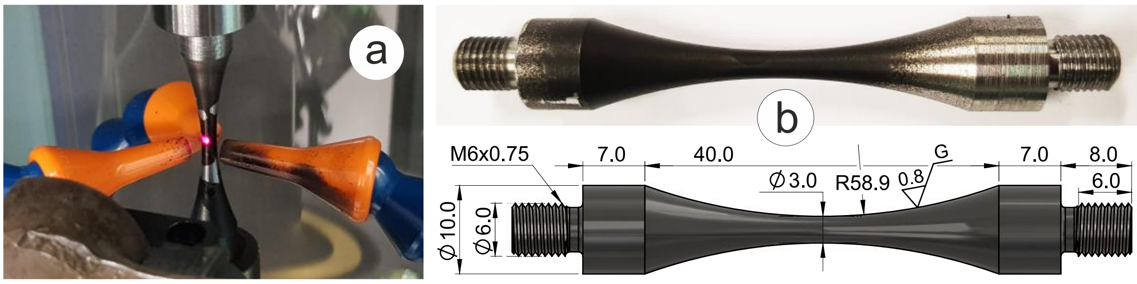

Fig. 2 Specimen for ultrasonic test: a) inserted in UFS-2000A with temperature measurement spot; b) solid model with dimensions and manufactured and painted.

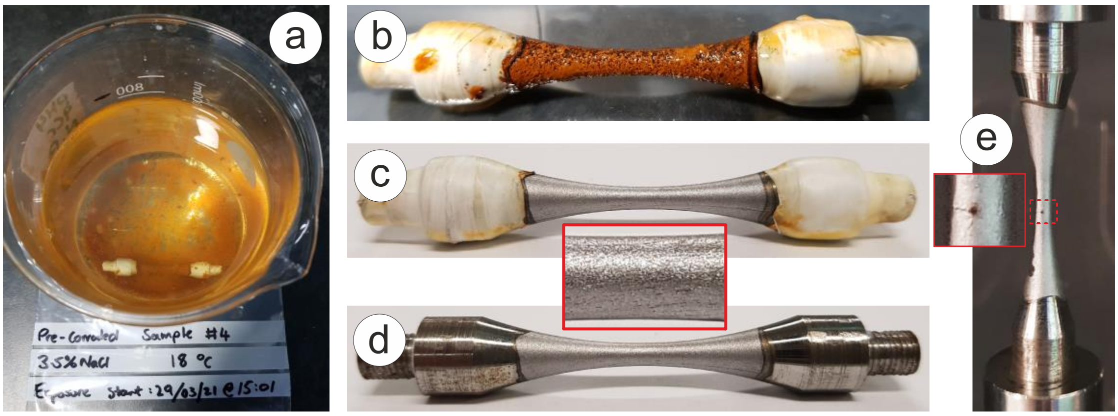

Fig. 3 Pre-corroded specimen for ultrasonic test: a) 3.5% NaCl solution with the submerged specimen; b) rust layer on the specimen; c) washed specimen with thread seal tape; d) specimen ready for testing; e) specimen at the end of the test with a crack in the middle.

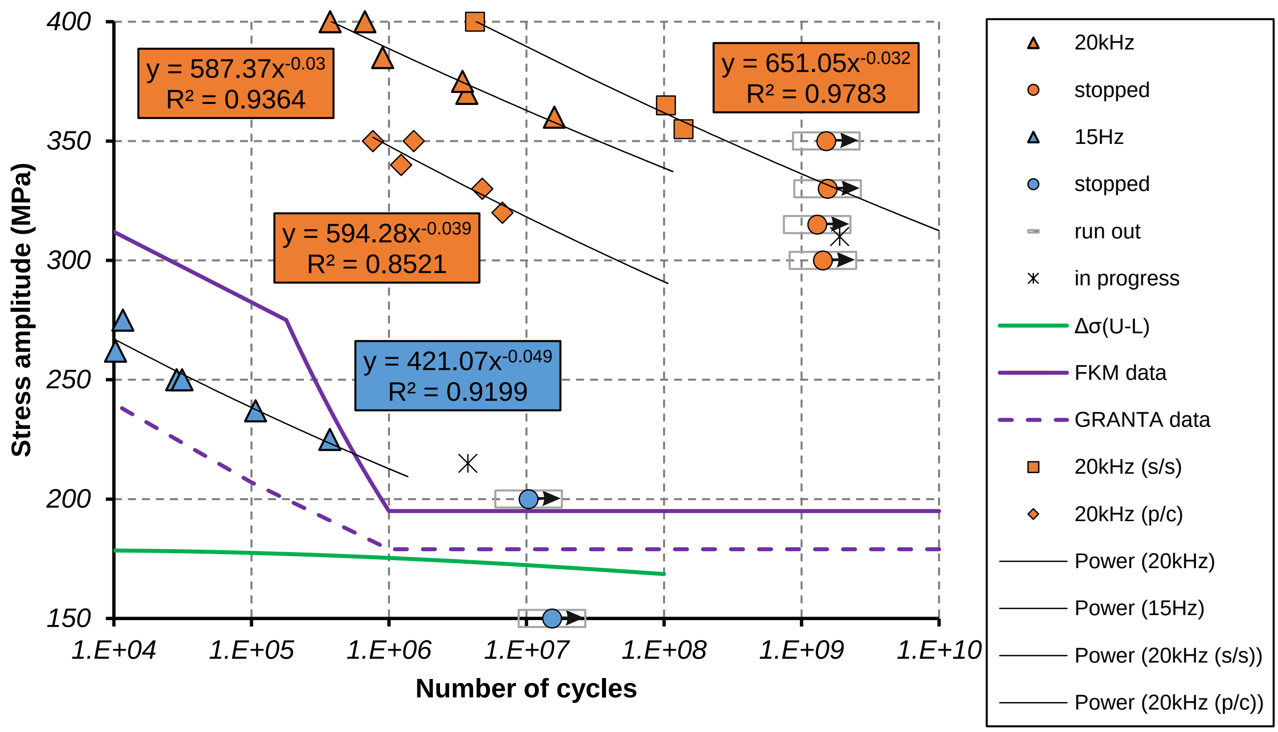

Fig. 4 Summary of fatigue testing for S275JR+AS including base dry and pre-corroded samples.

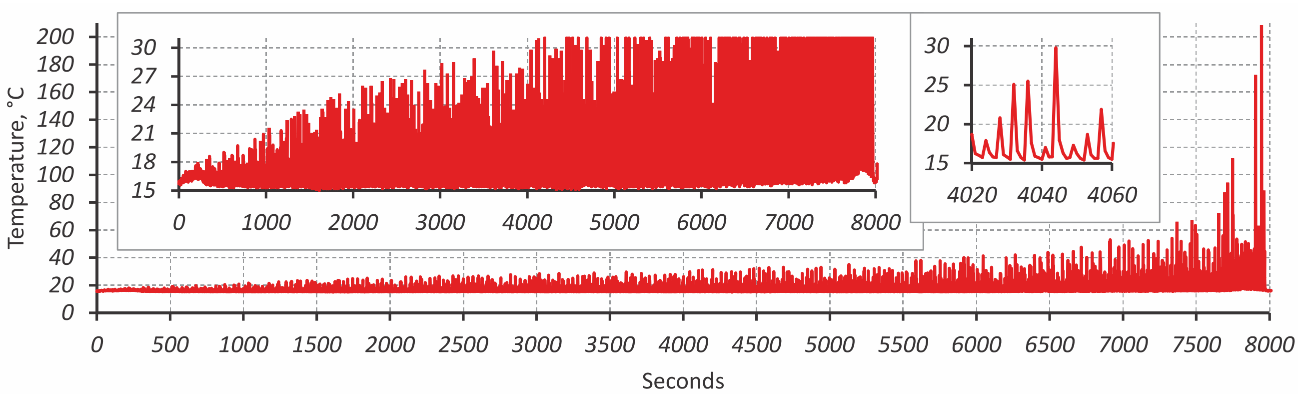

Fig. 5 Temperature history of the ultrasonic fatigue test lasted 4m cycles at 400 MPa stress amplitude.

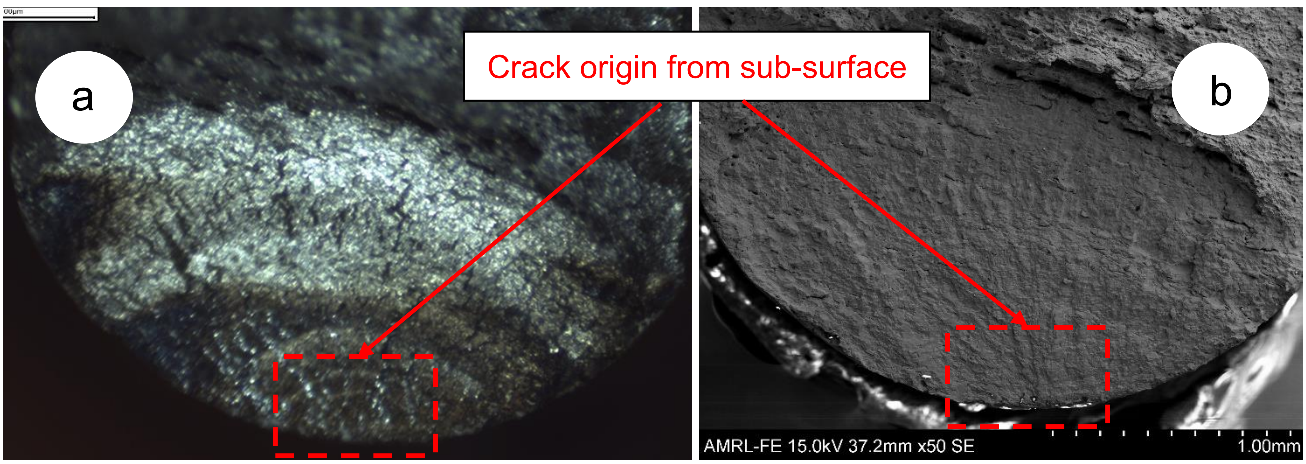

Fig. 6 Investigation of the fracture surface of the sample run at 400 MPa stress amplitude with a sub-surface crack origin for over 4 million cycles using: a) optical microscopy; b) SEM microscopy.