Virtual Seminar Series – Tuesday 2, 9, 16 November

Challenges of Very High Cycle Fatigue Testing

Presented by Dr-Ing. Yevgen Gorash
Weir Advanced Research Centre
University of Strathclyde

Tuesday, November 16, 2021

The Challenges of Very High Cycle Fatigue Testing

Abstract

There is a limited data on VHCF for structural steels and their weldments for >10^7 cycles. Unalloyed low-carbon steel grades S235, S275 and S355 (EN 10025) are common structural materials for the components made for the minerals and mining applications. The purpose of current research is an investigation of the gigacycle domain for structural steel grades that are expected to perform for years at normal frequencies (10-20 Hz) of loading with low stress amplitudes. The work focuses on ultrasonic fatigue testing of steels in both as-manufactured and pre-corroded conditions. As the vibration-induced 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. However, it becomes not straight forward with introduction of air-cooling guns, which performance has shown to be unstable.

The frequency effect is assessed by comparing the fatigue test data at 20kHz and conventional frequency of 15-20Hz. 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. Therefore, the effect of frequency sensitivity is quantified by calculating the difference in terms of stress amplitude between corresponding SN curves. The whole set of technical challenges associates with both implementation of testing and interpretation of the obtained results is discussed this lecture.

About the presenter, Dr-Ing. Yevgen Gorash, University of Strathclyde

Dr Yevgen Gorash works as a Research Fellow at the Department of Mechanical & Aerospace Engineering in the University of Strathclyde (Glasgow, Scotland, UK). He obtained his PhD degree with distinction in Mechanical Engineering at Martin Luther University Halle-Wittenberg (Germany) in 2008. Then worked for three years as a lecturer in the National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine). In 2011, Yevgen joined the University of Strathclyde as a postdoc. He has been working on the variety of industry-funded research projects related to structural integrity and equipment reliability improvement. Research interests are non-linear mechanics of materials, Finite Element Analysis and Computer Aided Design. He is an author of 67 publications including 17 papers in international peer-reviewed journals, 2 book chapters and 36 international conference papers. Last two years, Yevgen has been focussed on the experimental-based research related to accelerated fatigue testing using ultrasonic technique in application to structural steels.

Prenscia Technology Days – 2021
Virtual Seminar Series
2nd, 9th and 16th of November

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The Challenges of Very High Cycle Fatigue Testing

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Contents

1. Introduction and Motivation

1. Introduction and Motivation

1.1 About us – collaboration and research

Weir 150 1871-2021

Weir Advanced Research Centre

- established in 2011
- dozens of research projects annually

University of Strathclyde Engineering

Entering the group's 150th year, Weir has been transformed into a premium mining technology provider that will help its customers become more sustainable and efficient and deliver the essential resources demanded by demographic trends and the fight against climate change.

Crushing and Grinding

Classification and Separation

Slurry transportation

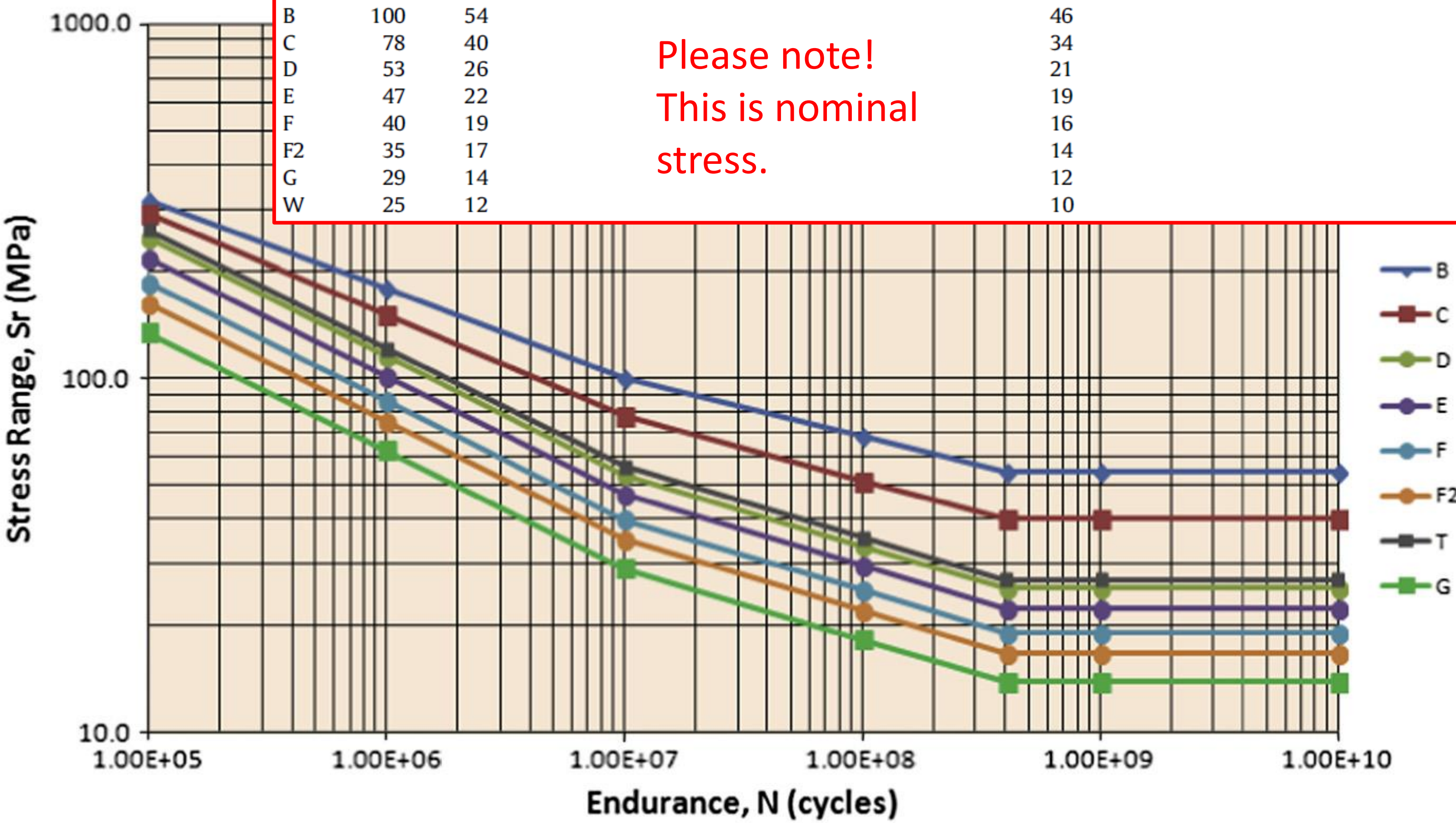
1. Introduction and Motivation

1.2 Currently used design approach and data

Endurance limit for alternative interpretation of S–N line

Weld detail	S_o 10^7 cycles	Endurance limit for typical conditions on vibrating screens, S_r at 4×10^8 cycles, knee at 10^7, slope = $m + 2$	Endurance limit for areas at bottom of screen that are exposed to corrosion, S_r at 1×10^9 cycles, knee at 10^7, slope = $m + 2$
B	100	54	46
C	78	40	34
D	53	26	21
E	47	22	19
F	40	19	16
F2	35	17	14
G	29	14	12
W	25	12	10

Please note!
This is nominal stress.



Fry P.R. (2014) "HCF of welded structures." Engineering Failure Analysis. 46: 179–187.

1. Introduction and Motivation
1.3 Structural steel grades of interest {1}

Chemical composition according to EN 10025-2:2019

Designation		Method of deoxi-dation b	C in % max. for nominal product thickness in mm			Si % max .	Mn % max .	P % max. d	S % max. d e	N % max. f	Cu % max .	Other % max. g l
Steel name	Steel number		≤ 16	> 16 ≤ 40	> 40 c							
S235JR	1.0038	FN	0,19	0,19	0,23	-	1,50	0,045	0,045	0,014	0,60	-
S235J0	1.0114	FN	0,19	0,19	0,19	-	1,50	0,040	0,040	0,014	0,60	-
S235J2	1.0117	FF	0,19	0,19	0,19	-	1,50	0,035	0,035	-	0,60	-
S275JR	1.0044	FN	0,24	0,24	0,25	-	1,60	0,045	0,045	0,014	0,60	-
S275J0	1.0143	FN	0,21	0,21	0,21 h	-	1,60	0,040	0,040	0,014	0,60	-
S275J2	1.0145	FF	0,21	0,21	0,21 h	-	1,60	0,035	0,035	-	0,60	-
S355JR	1.0045	FN	0,27	0,27	0,27	0,60	1,70	0,045	0,045	0,014	0,60	-
S355J0	1.0553	FN	0,23	0,23 i	0,24	0,60	1,70	0,040	0,040	0,014	0,60	-
S355J2	1.0577	FF	0,23	0,23 i	0,24	0,60	1,70	0,035	0,035	-	0,60	-
S355K2	1.0596	FF	0,23	0,23 i	0,24	0,60	1,70	0,035	0,035	-	0,60	-
S460JR j	1.0507	FF	0,23	0,23 i	0,24	0,60	1,80	0,040	0,040	0,027	0,60	k
S460J0 j	1.0538	FF										
S460J2 j	1.0552	FF										
S460K2 j	1.0581	FF										
S500J0 j	1.0502	FF	0,23	0,23	0,24	0,60	1,80	0,040	0,040	0,027	0,60	k

JR+AR subgrade is in focus

Structural steel grades of interest

1. Introduction and Motivation

1.3 Structural steel grades of interest {2}

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Tensile and yield strength according to EN 10025-2:2019

Designation		Minimum yield strength R_{eH} [a] MPa Nominal thickness mm									Tensile strength R_m [a] MPa Nominal thickness mm				
Steel name	Steel number	≤ 16	> 16 ≤ 40	> 40 ≤ 63	> 63 ≤ 80	> 80 ≤ 100	> 100 ≤ 150	> 150 ≤ 200	> 200 ≤ 250	> 250 ≤ 400	< 3	≥ 3 ≤ 100	> 100 ≤ 150	> 150 ≤ 250	> 250 ≤ 400
S235JR	1.0038														
S235J0	1.0114	235	225	215	215	215	195	185	175	165	360 to 510	360 to 510	350 to 500	340 to 490	330 to 480
S235J2	1.0117														
S275JR	1.0044														
S275J0	1.0143	275	265	255	245	235	225	215	205	195	430 to 580	410 to 560	400 to 540	380 to 540	380 to 540
S275J2	1.0145														
S355JR	1.0045														
S355J0	1.0553	355	345	335	325	315	295	285	275	265	510 to 680	470 to 630	450 to 600	450 to 600	450 to 600
S355J2	1.0577														
S355K2	1.0596														
S460JR [b]	1.0507														
S460J0 [b]	1.0538	460	440	420	400	390	390	-	-	-	-	550 to 720	530 to 700	-	-
S460J2 [b]	1.0552														
S460K2 [b]	1.0581														
S500J0 [b]	1.0502	500	480	460	450	450	450	-	-	-	-	580 to 760	560 to 750	-	-

Significant variation of both yield and tensile strength

1. Introduction and Motivation

1.3 Structural steel grades of interest {3}

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Elongation after fracture according to EN 10025-2:2019

Designation		Orientation of test pieces [a]	Minimum percentage elongation after fracture [a] %										
			L_0 = 80 mm Nominal thickness mm					$L_0 = 5{,}65\sqrt{S_0}$ Nominal thickness mm					
Steel name	Steel number		≤ 1	> 1 ≤ 1,5	> 1,5 ≤ 2	> 2 ≤ 2,5	> 2,5 < 3	≥ 3 ≤ 40	> 40 ≤ 63	> 63 ≤ 100	> 100 ≤ 150	> 150 ≤ 250	> 250 ≤ 400
S235JR S235J0 S235J2	1.0038 1.0114 1.0117	l t	17 15	18 16	19 17	20 18	21 19	26 24	25 23	24 22	22 22	21 21	21 21
S275JR S275J0 S275J2	1.0044 1.0143 1.0145	l t	15 13	16 14	17 15	18 16	19 17	23 21	22 20	21 19	19 19	18 18	18 18
S355JR S355J0 S355J2 S355K2	1.0045 1.0553 1.0577 1.0596	l t	14 12	15 13	16 14	17 15	18 16	22 20	21 19	20 18	18 18	17 17	17 17
S460JR [b] S460J0 [b] S460J2 [b] S460K2 [b]	1.0507 1.0538 1.0552 1.0581	l	-	-	-	-	-	17	17	17	17	-	-
S500J0 [b]	1.0502	l	-	-	-	-	-	15	15	15	15	-	-

Actual elongation is ~20% for S355 & ~30% for S275 and ~40% for S235

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1. Introduction and Motivation
1.4 Comparison of structural steel grades {1}

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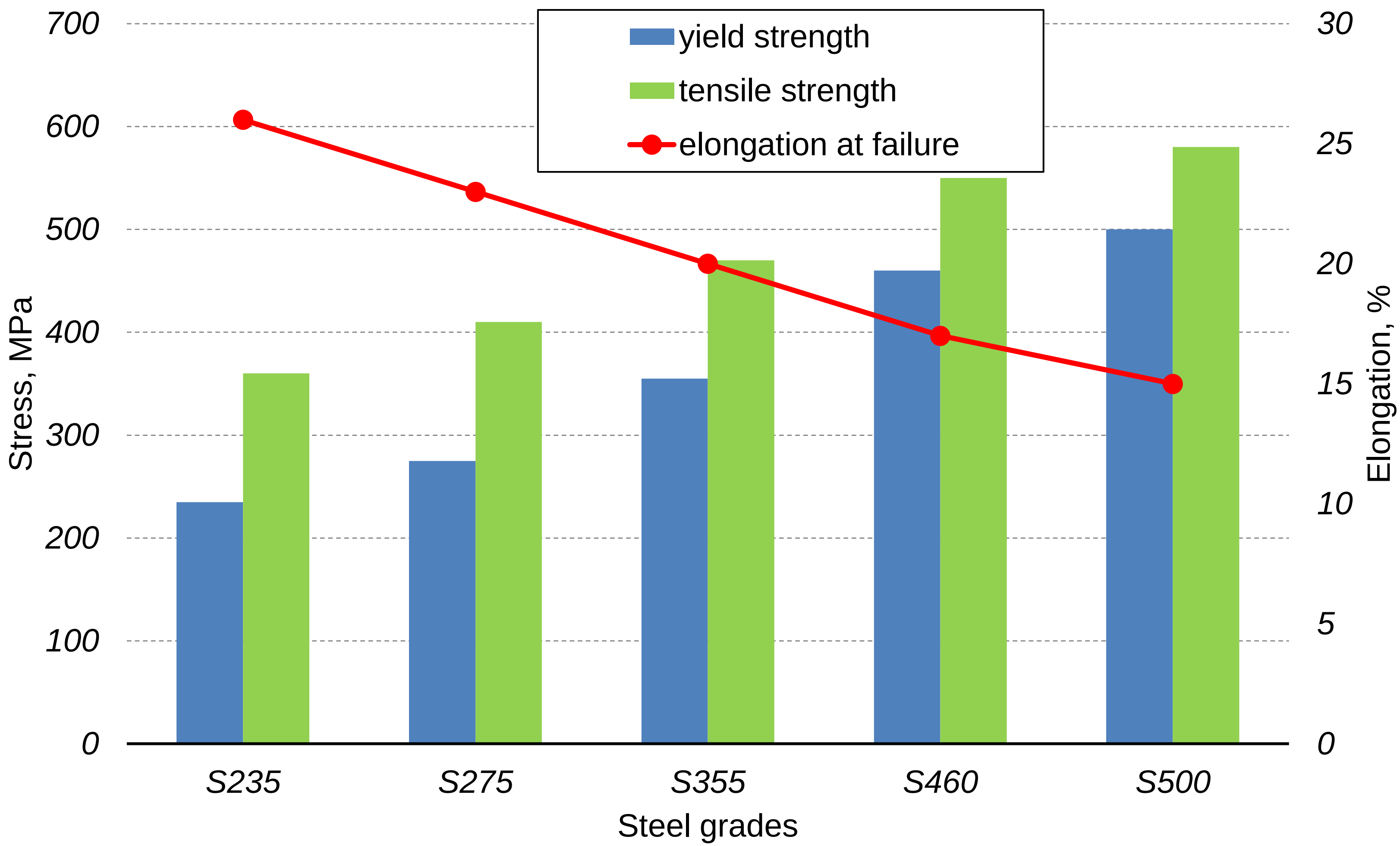
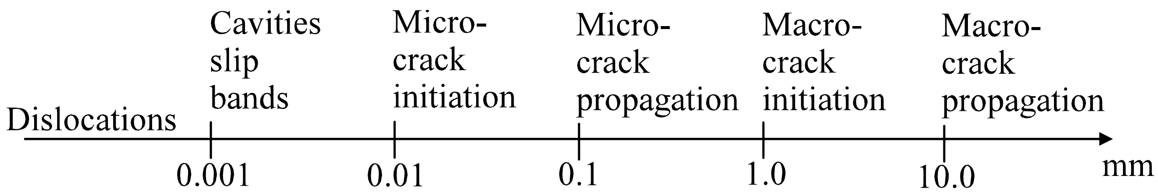
Correlation of minimum standard values from EN 10025-2:2019



1. Introduction and Motivation
1.4 Comparison of structural steel grades {2}

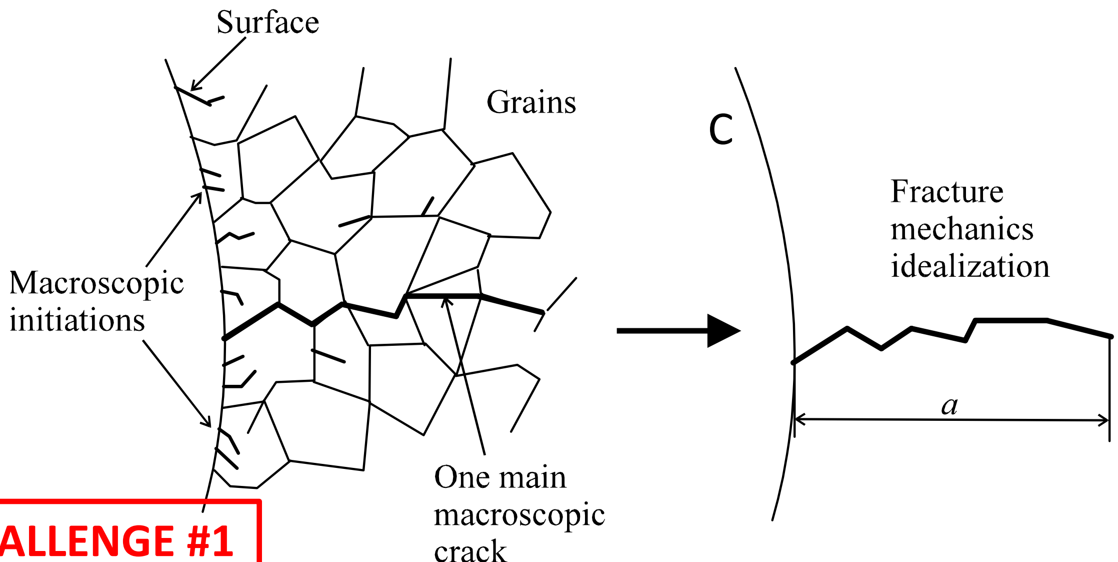
University of Strathclyde Engineering



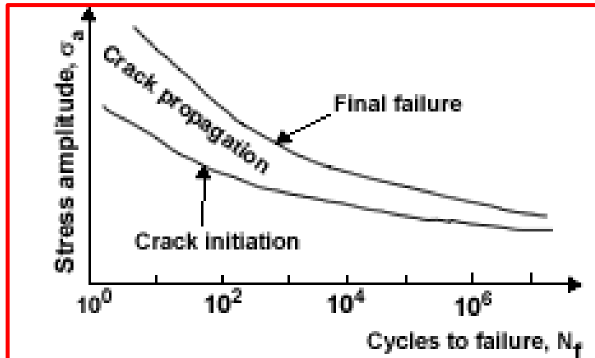
Size of defects

Damage Mechanics (CDM)

Fracture Mechanics (FM)



Crack initiation
+ Crack propagation
= Total fatigue life



% of initiation phase depends quality of specimen

CHALLENGE #1

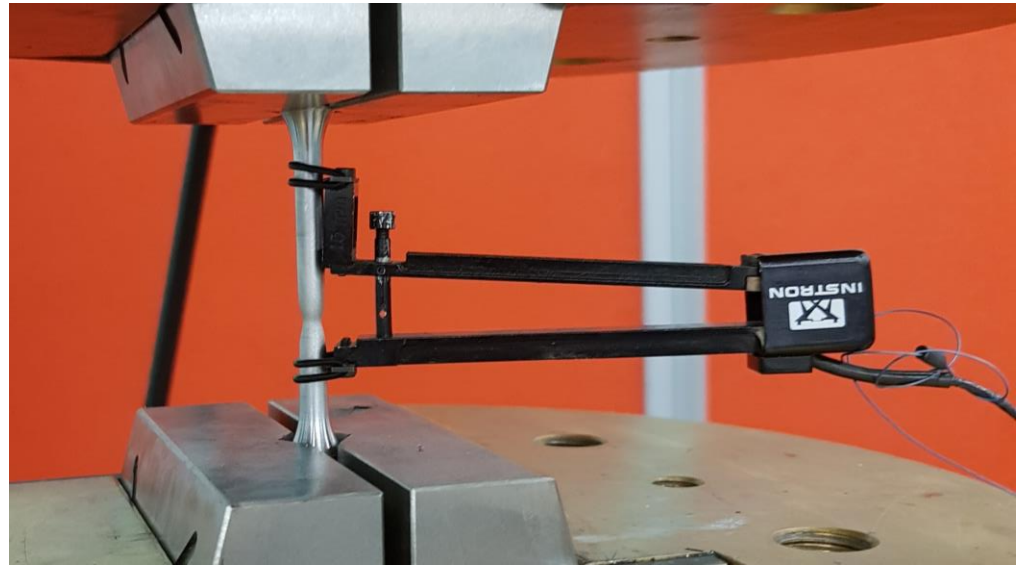
Assumption: higher yield strength improves crack initiation fatigue resistance & higher ductility improves crack propagation fatigue resistance

Question: which grade is better in total life considering environmental effect?

Chaboche, J.L. (1988) "CDM: Part I—General Concepts." ASME. J. Appl. Mech., 55(1): 59–64.

2. Experimental setup, specimens, testing

2. Experimental setup, specimens, testing
2.1 Tensile testing of S275JR+AR



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 BS EN 10025-2: 2019

2. Experimental setup, specimens, testing
2.2 Ultrasonic fatigue testing system {1}

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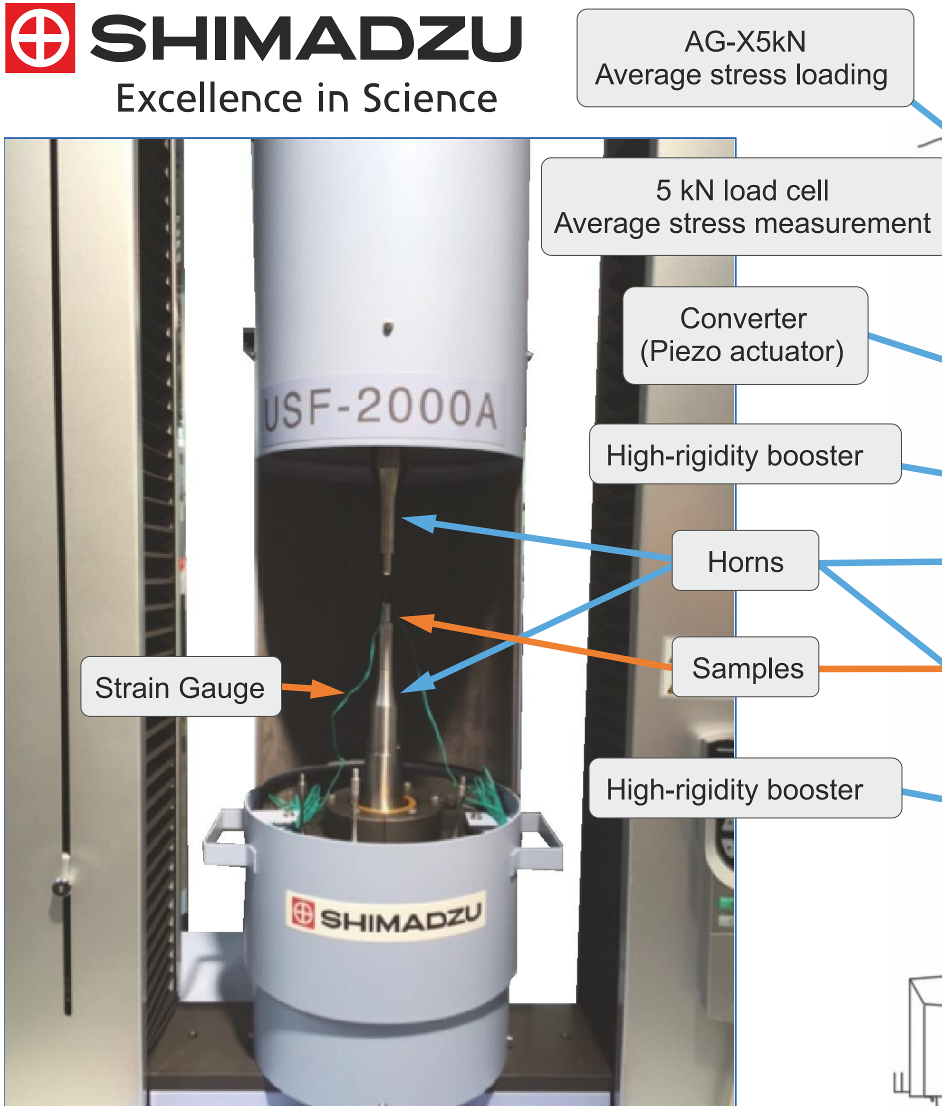
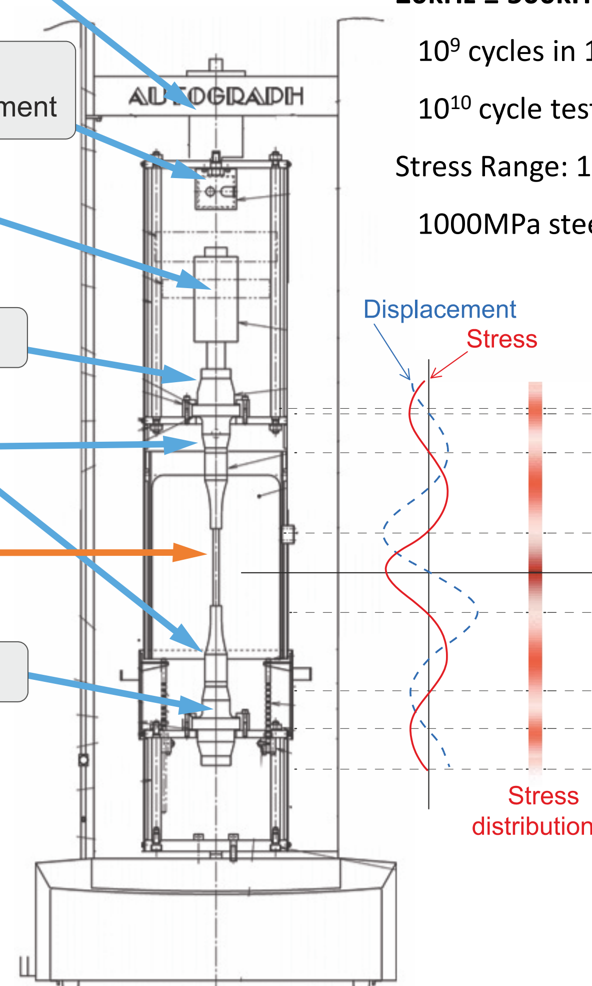
Excellence in Science





20kHz ± 500kHz test frequency

- 10^9 cycles in 14 hours (1.6 years at 20Hz)
- 10^{10} cycle tests in 6 days (years…)

Stress Range: 100MPa to 1,200MPa

- 1000MPa steels may be tested

2. Experimental setup, specimens, testing
2.2 Ultrasonic fatigue testing system {2}

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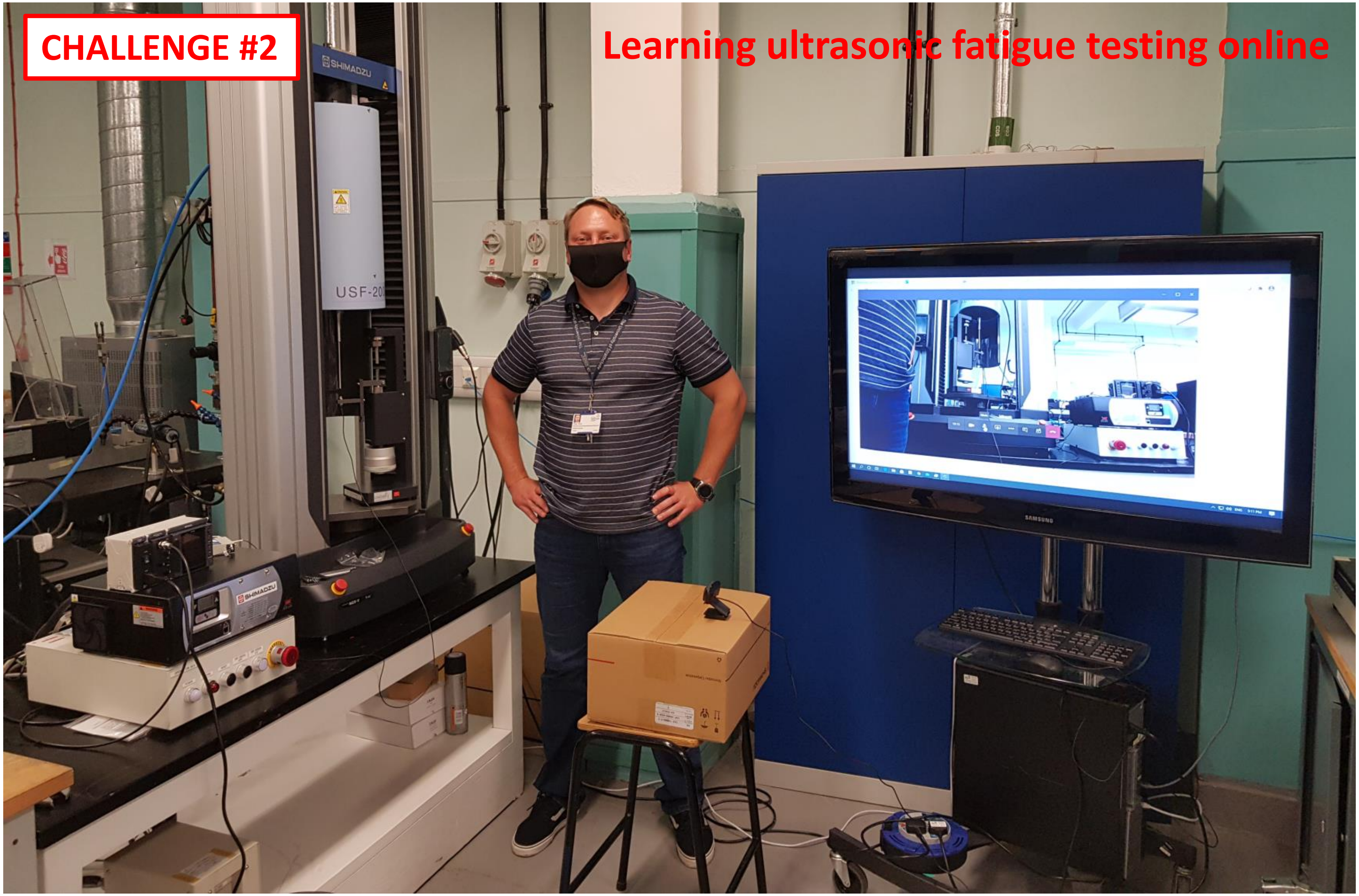
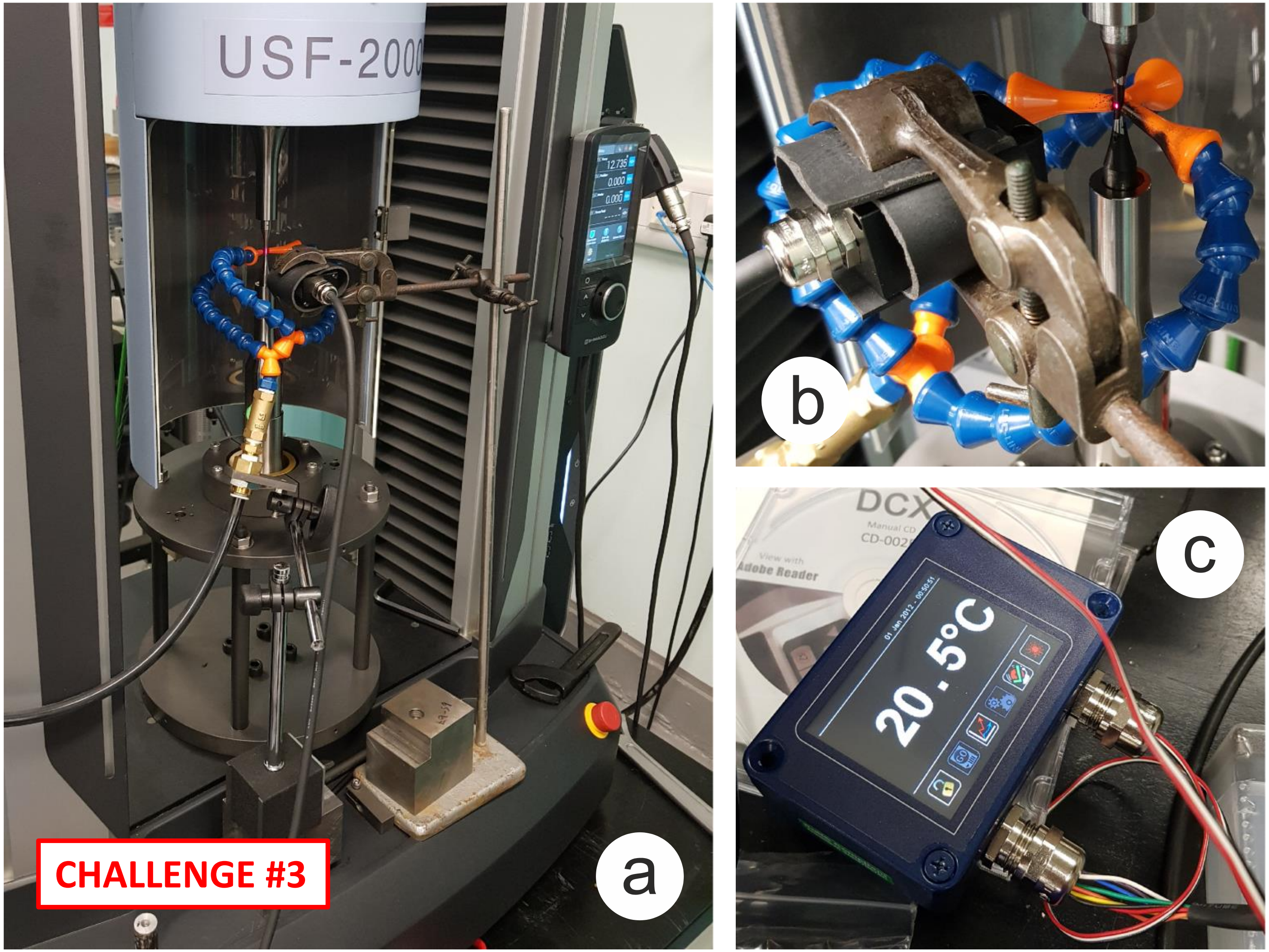


2. Experimental setup, specimens, testing
2.2 Ultrasonic fatigue testing system {3}



Arrangement for temperature control of the ultrasonic test:

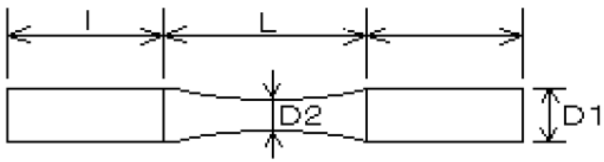
a) USF-2000A with average stress loading mechanism;

b) Pyrocube IR temperature sensor;

c) touch screen display for PyroCube.

2. Experimental setup, specimens, testing
2.3 Manufacturing & preparation of specimens {1}

Shimadzu Excel spreadsheet:



Young's modulus(MPa)	Density(g/cm^3)			
210000	7.85			
D1 (large diameter)(mm)	diameter)(mm)	(all bowstrings)(mm)	part(mm)	stress(MPa)
10	3	40	10.1143278	1033.422748
				Minimum
				103.3422748

$$l = \frac{c}{\omega}\tan^{-1}\left[\frac{c}{\omega}\left(\beta\coth(\beta\cdot\frac{L}{2}) - b\tanh(b\cdot\frac{L}{2})\right)\right]$$

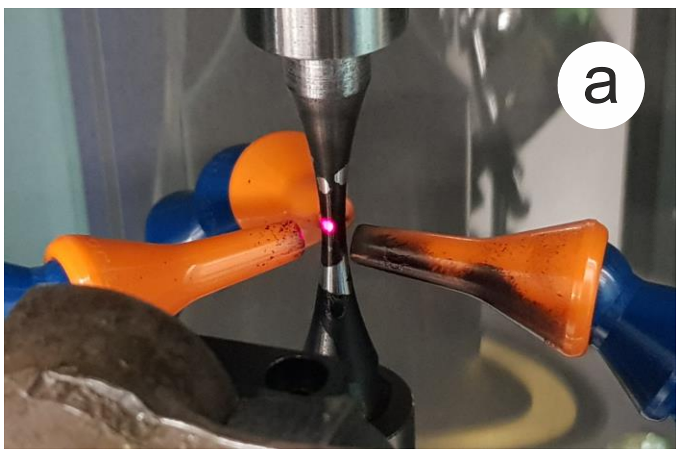
$$b = \frac{2}{L}\cosh^{-1}\left(\frac{D1}{D2}\right)$$

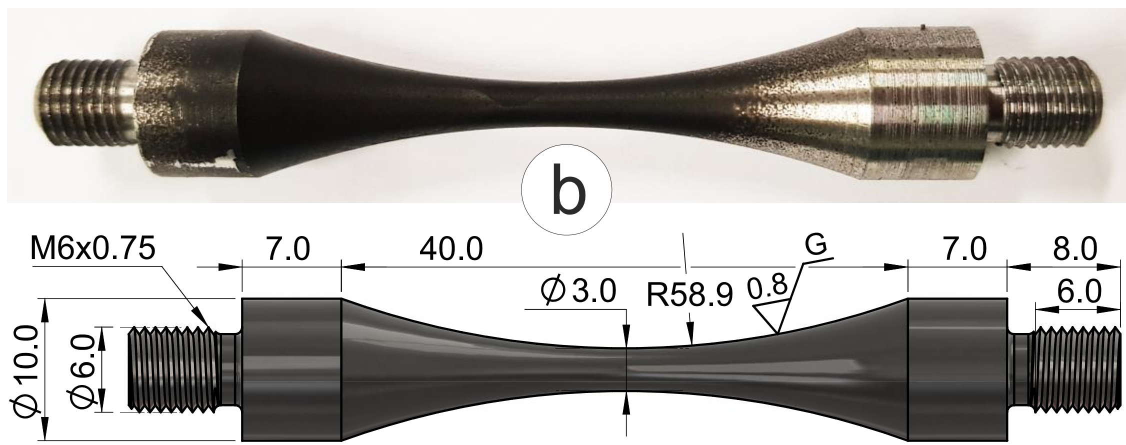
$$\beta = \sqrt{b^2 - (\frac{\omega}{c})^2}$$

$$S = a*E*\beta*\cos\left(\frac{\omega\cdot l}{c}\right)*\cosh bg*\left(\frac{1}{\sinh \beta g}\right)$$

CHALLENGE #4

Accurate geometry





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

2. Experimental setup, specimens, testing
2.3 Manufacturing & preparation of specimens {2}

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CHALLENGE #5

Making samples

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2. Experimental setup, specimens, testing
2.3 Manufacturing & preparation of specimens {3}

CHALLENGE #5

Making samples

2. Experimental setup, specimens, testing
2.4 Preparation of pre-corroded specimens {1}

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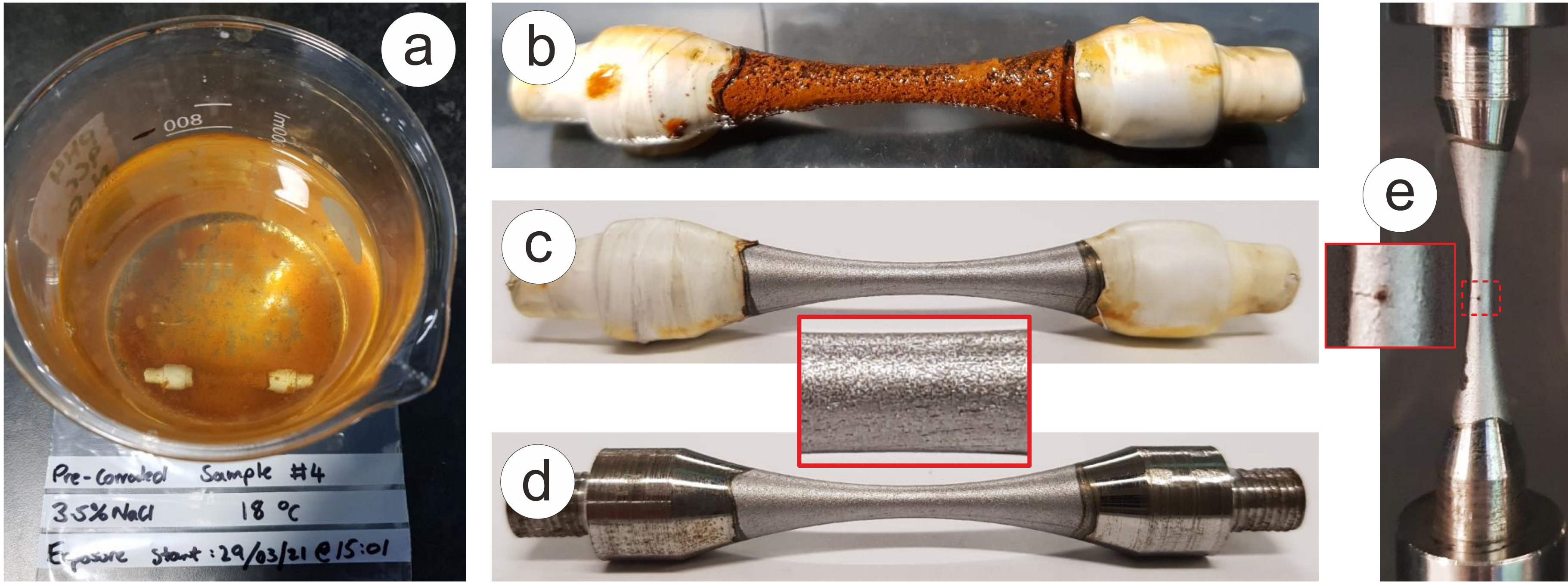

Pre-corroded specimen for ultrasonic test:
a) 3.5% NaCl solution with the submerged specimen;
b) rust layer on the specimen after 15 days;
c) washed specimen with thread seal tape;
d) specimen ready for testing;
e) specimen at the end of the test with a crack in the middle.

The 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.

2. Experimental setup, specimens, testing
2.4 Preparation of pre-corroded specimens {2}

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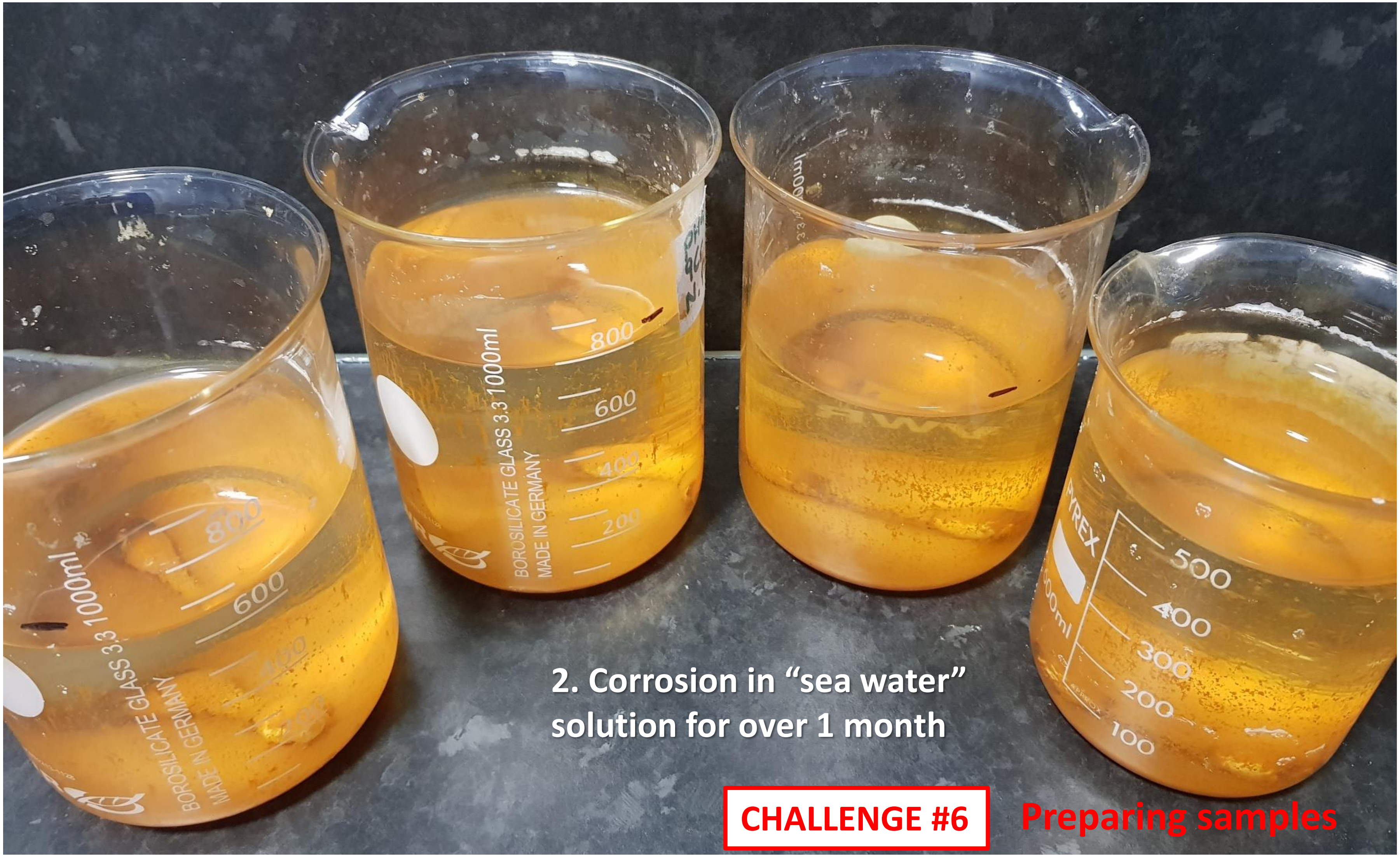
1. Protecting the threads from corrosion with PTFE thread seal tape

2. Experimental setup, specimens, testing
2.4 Preparation of pre-corroded specimens {3}



2. Experimental setup, specimens, testing
2.4 Preparation of pre-corroded specimens {4}

3. Layer of rust formed on corroded specimens after 1 month

2. Experimental setup, specimens, testing
2.4 Preparation of pre-corroded specimens {5}

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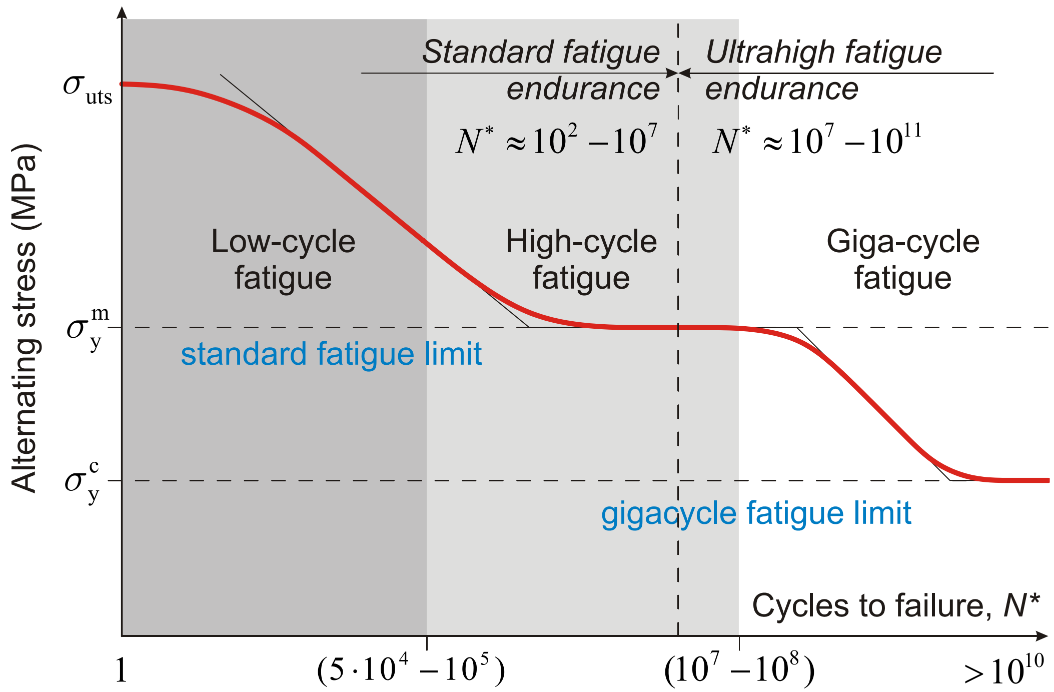
4. Washed samples with heavily pitted surface ready for testing

2. Experimental setup, specimens, testing
2.4 Preparation of pre-corroded specimens {6}

2 weeks of corrosion

1 month of corrosion with weekly washing

3. Current results and discussion



3. Current results and discussion
3.1 Summary of current fatigue testing results {1}

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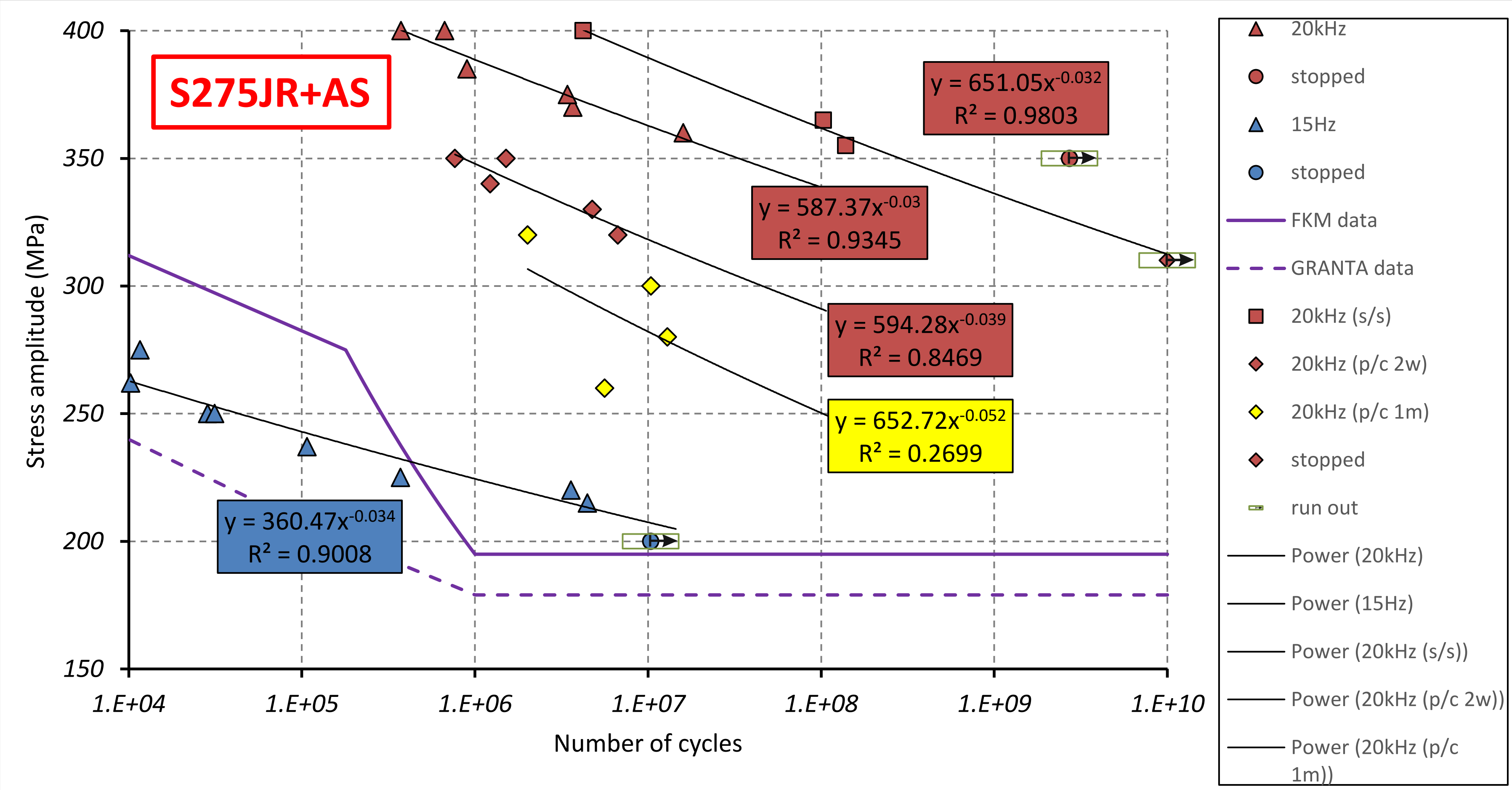
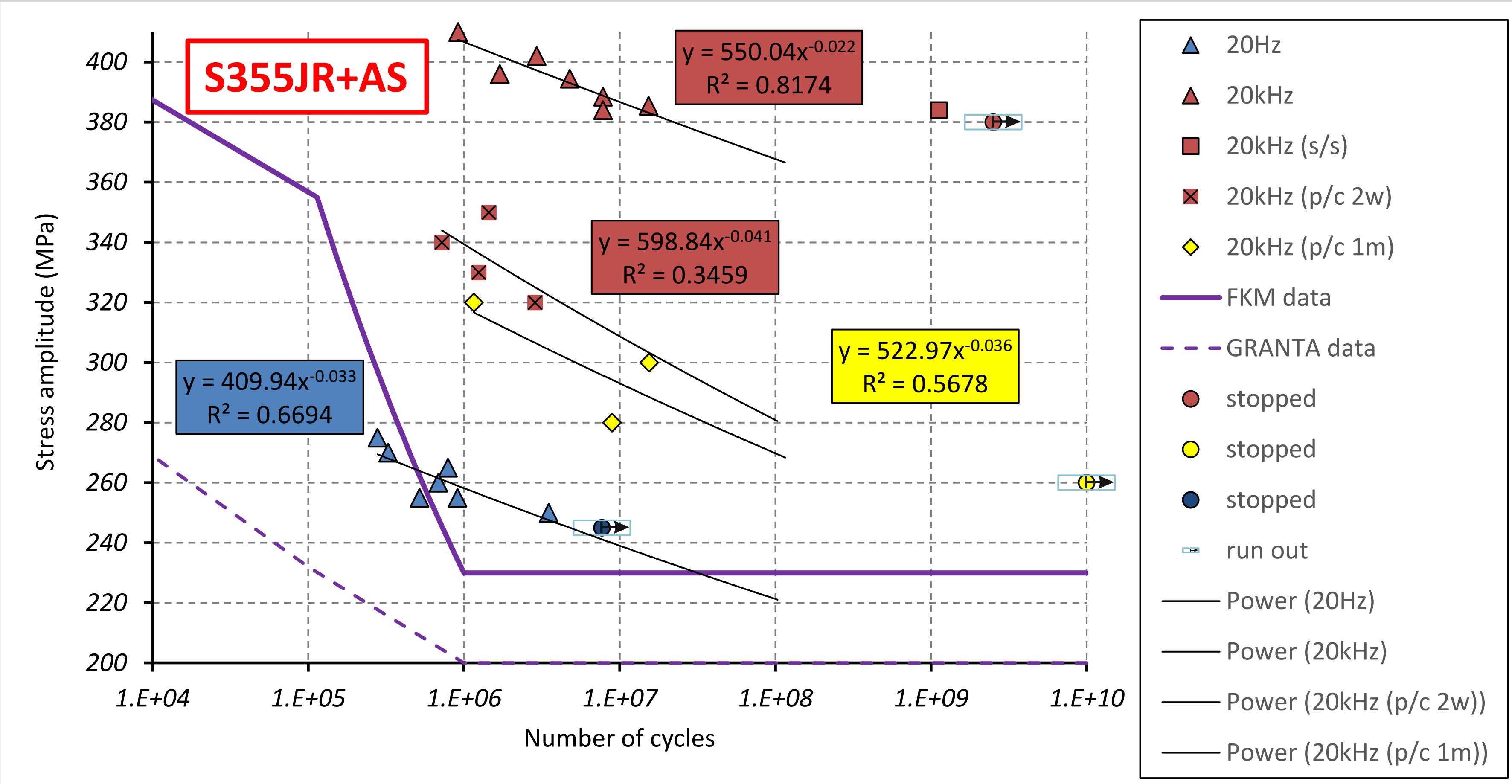


$\Delta\sigma(U\text{-}L) \approx 150$ MPa ➔ $\sigma_f \approx 200$ MPa (predicted) vs 210 MPa (measured)

CHALLENGE #7

Interpretation of results

3. Current results and discussion
3.1 Summary of current fatigue testing results {2}



$\Delta\sigma$(U-L) ≈ 145 MPa ➔ σf ≈ 230 MPa (predicted)
vs 235 MPa (measured)

CHALLENGE #7

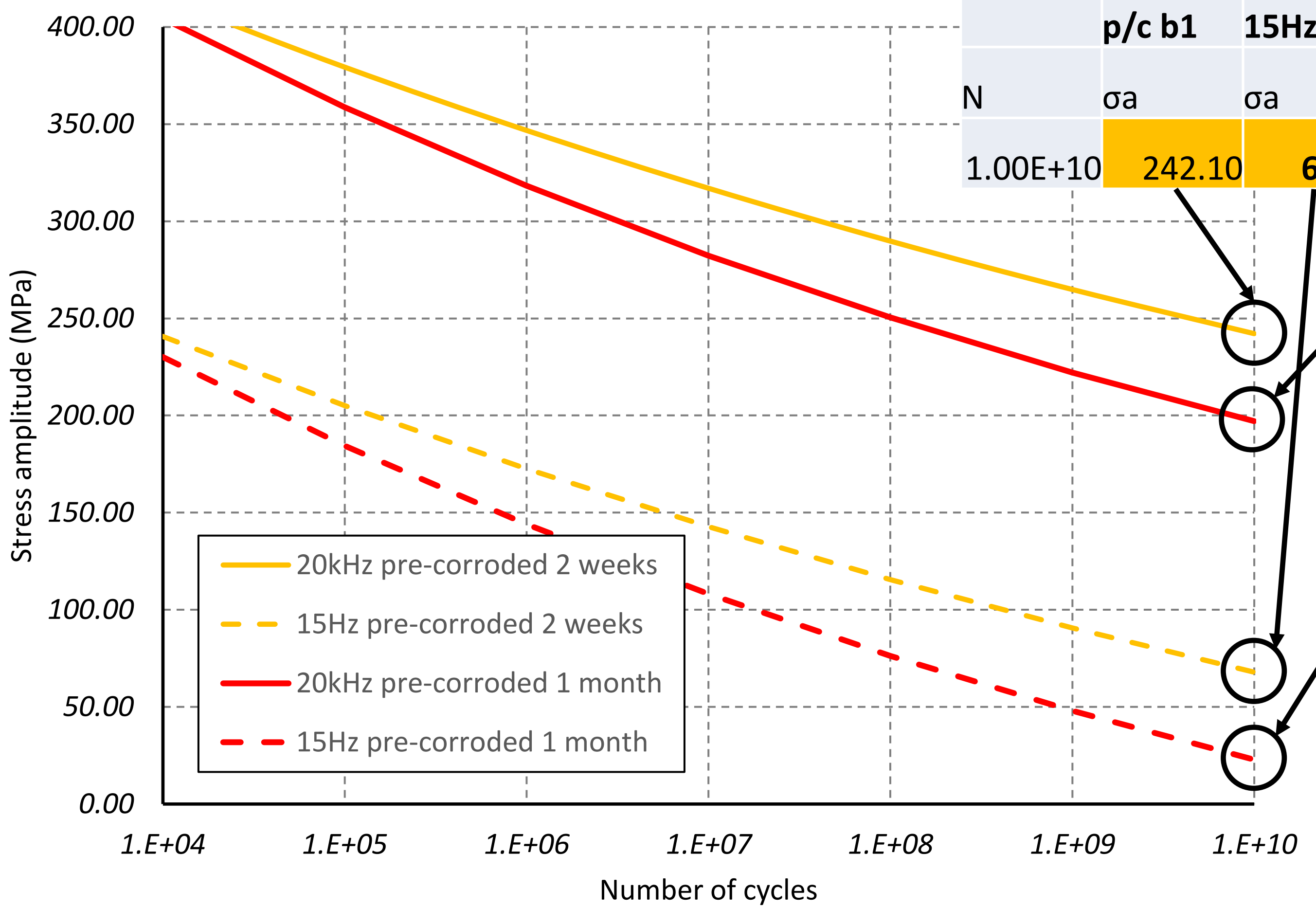
Interpretation of results

3. Current results and discussion

3.2 Extrapolation considering frequency effect {1}

Pre-corroded SN curves for S275JR+AR at 15Hz and 20kHz

	p/c b1	15Hz	p/c b2	15Hz
N	σa	σa	σa	σa
1.00E+10	242.10	**67.90**	197.12	**22.92**



CHALLENGE #8

Making predictions

3. Current results and discussion

3.2 Extrapolation considering frequency effect {2}

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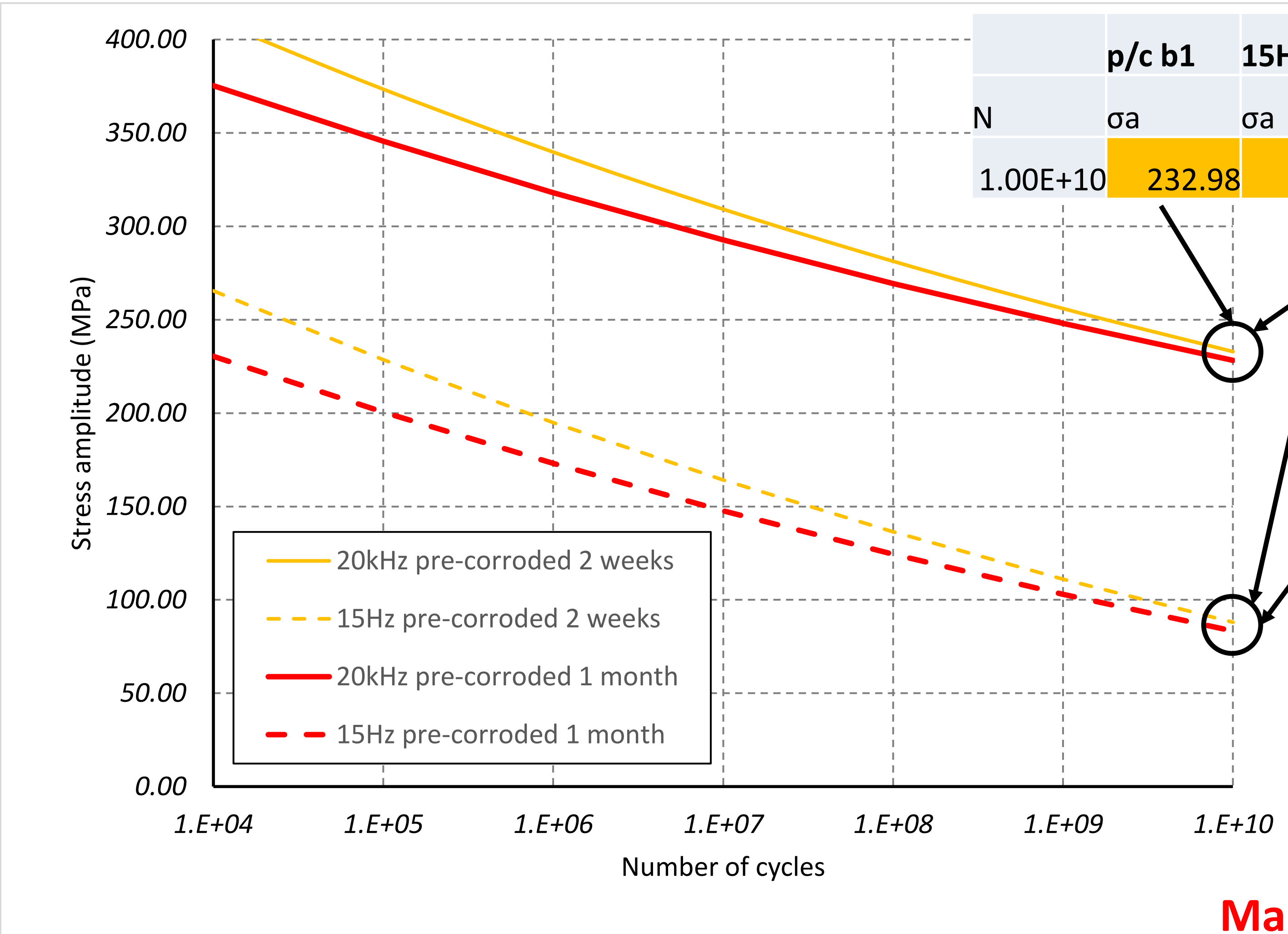
Pre-corroded SN curves for S355JR+AR at 15Hz and 20kHz



	p/c b1	15Hz	p/c b2	15Hz
N	σa	σa	σa	σa
1.00E+10	232.98	**87.98**	228.28	**83.28**

CHALLENGE #8

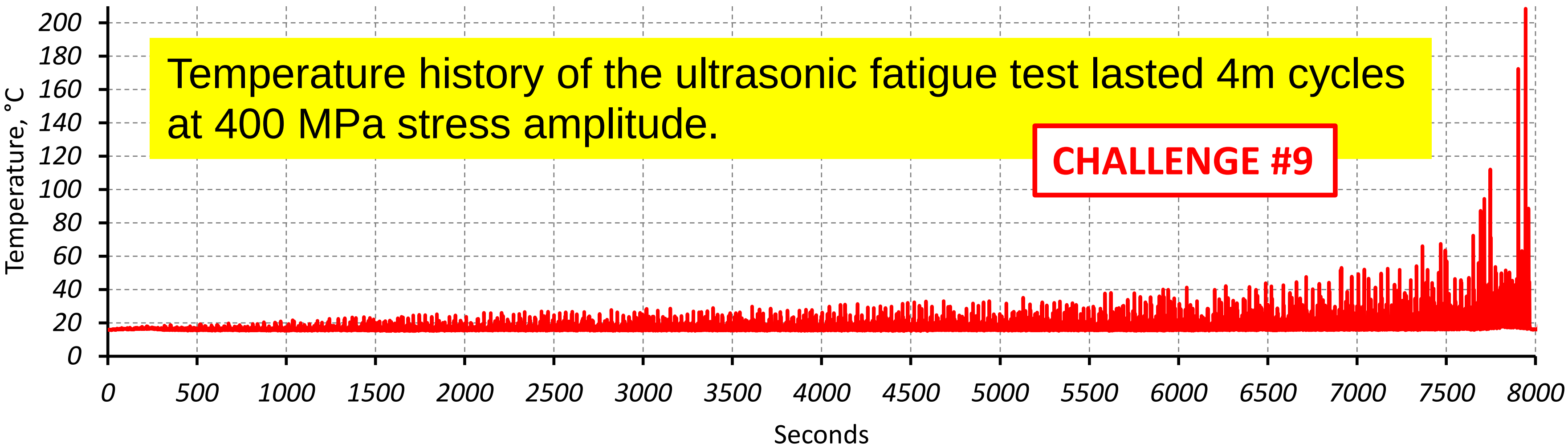
Making predictions

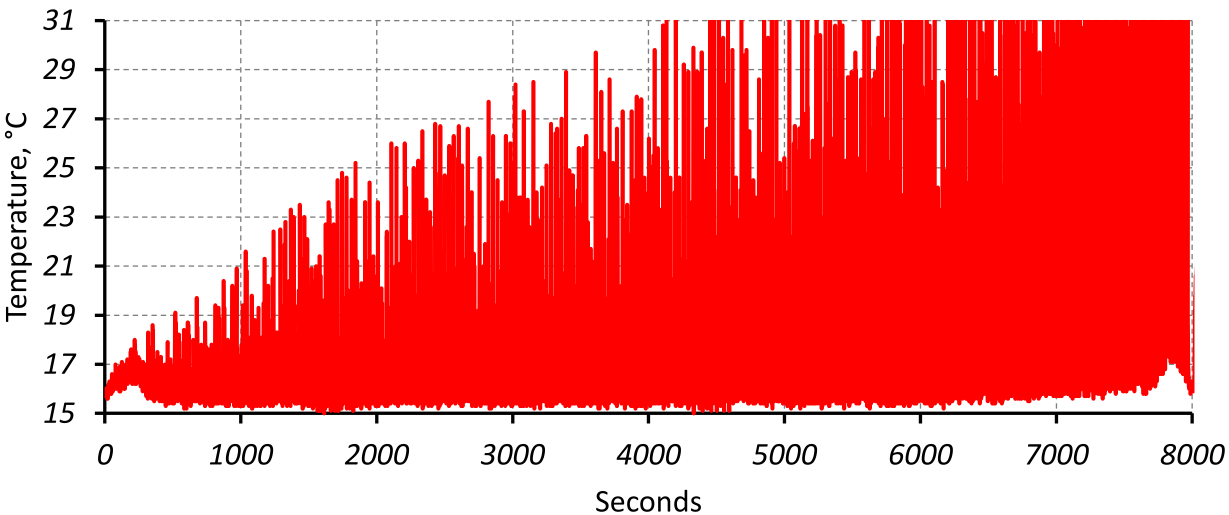
3. Current results and discussion

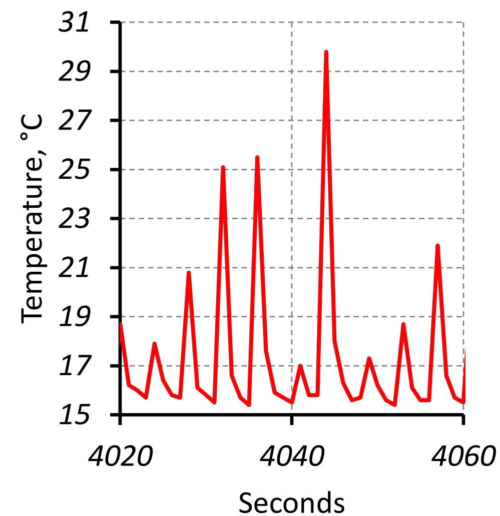
3.3 Heat generation technical challenge {1}

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

CHALLENGE #9







3. Current results and discussion
3.3 Heat generation technical challenge {2}

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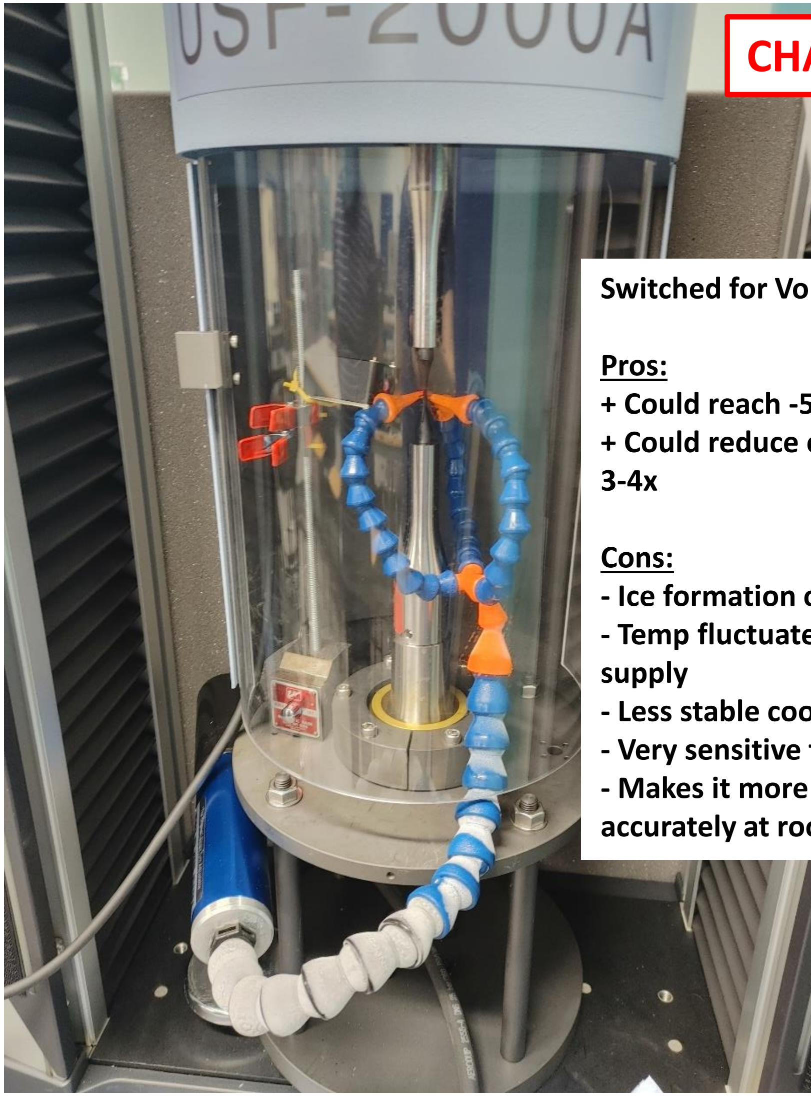
CHALLENGE #9



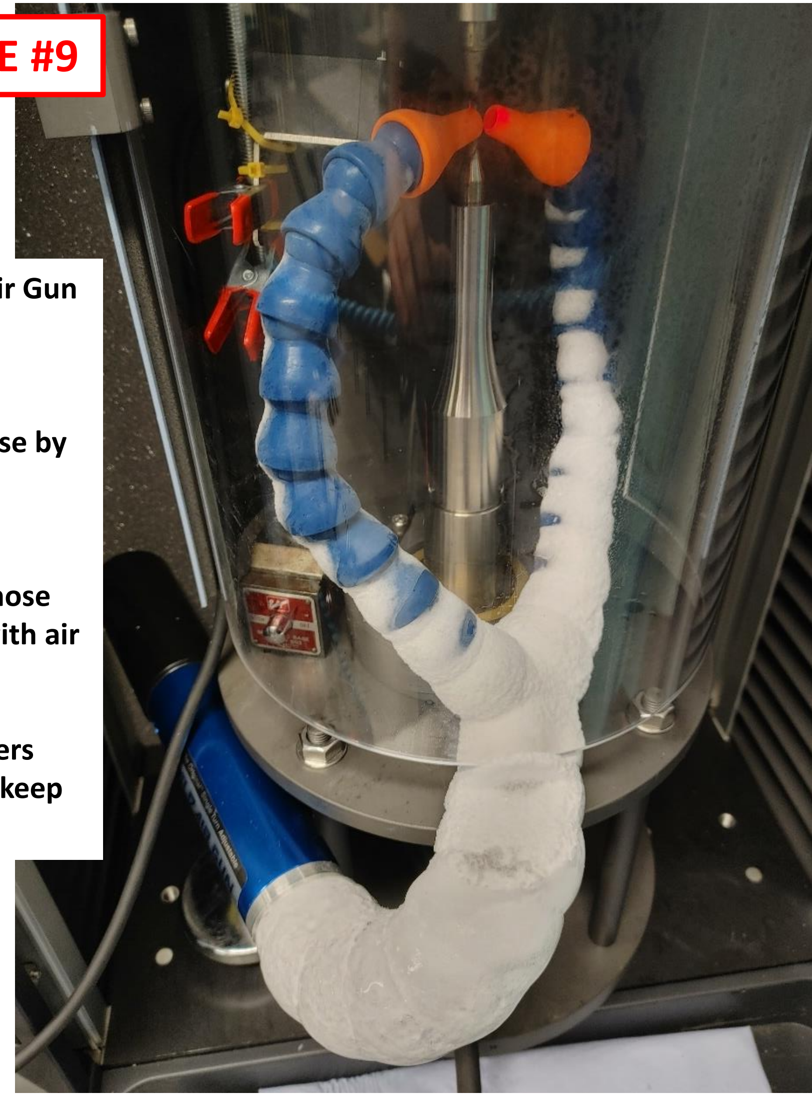
Switched for VorTec Cold Air Gun

Pros:

+ Could reach -5 to -10C
+ Could reduce cooling pause by 3-4x

Cons:

- Ice formation on cooling hose
- Temp fluctuates slightly with air supply
- Less stable cooling
- Very sensitive to parameters
- Makes it more difficult to keep accurately at room temp

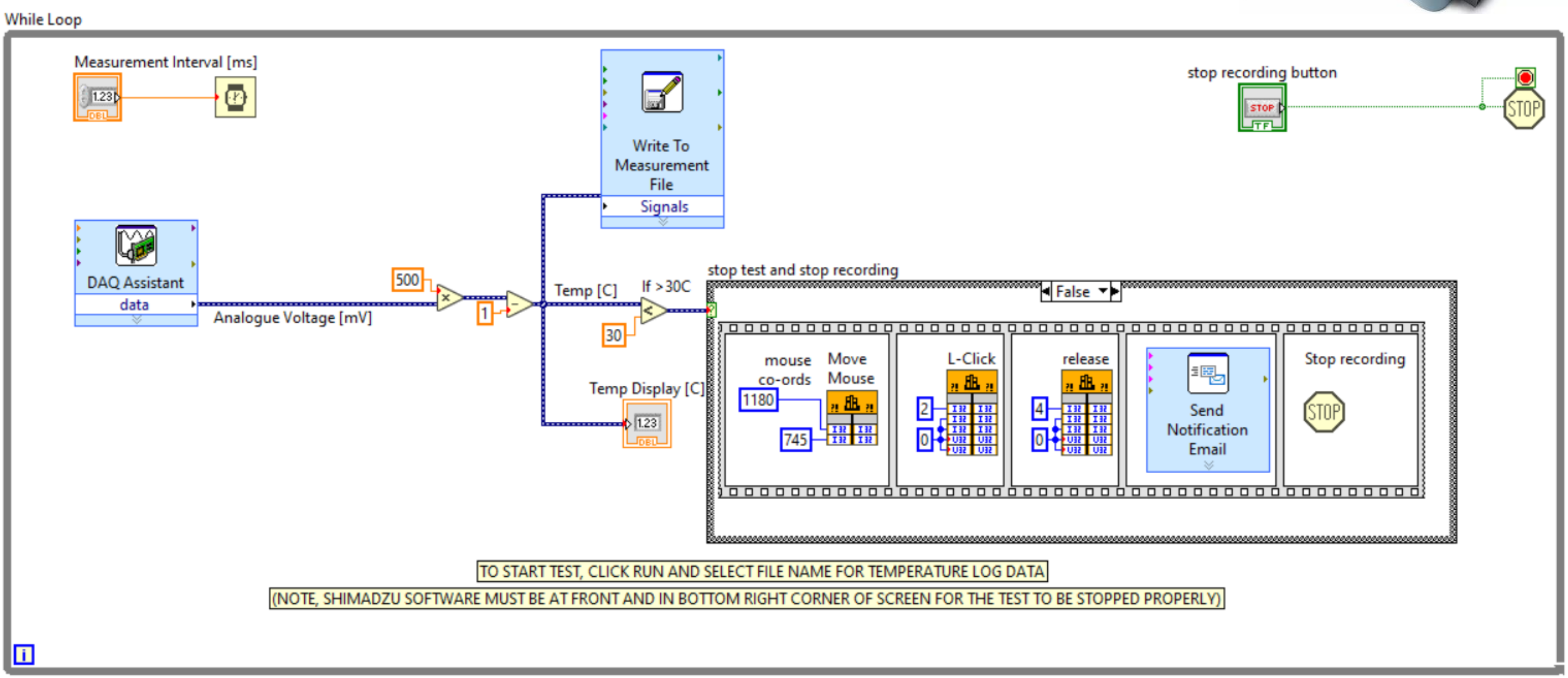


3. Current results and discussion

3.3 Heat generation technical challenge {3}

1. Connected to PC using NI USB Multifunction DAQ data acquisition card for:
   - Higher sampling rate
   - Monitoring through remote desktop
   - Auto stop test if overheating
2. Wrote a Labview program that:
   - Displays temperature
   - Logs temperature data
   - Stops test if >30C and sends emails

CHALLENGE #9



3. Current results and discussion
3.4 Investigation of the fracture surface {1}

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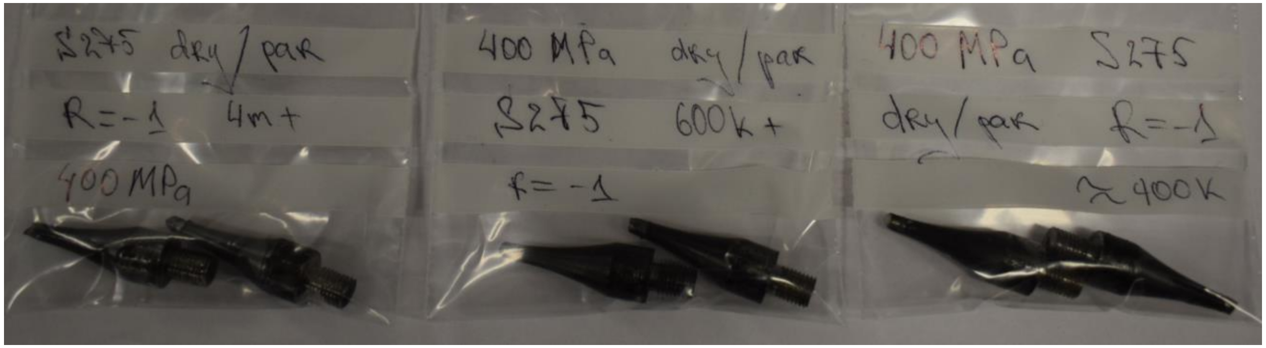
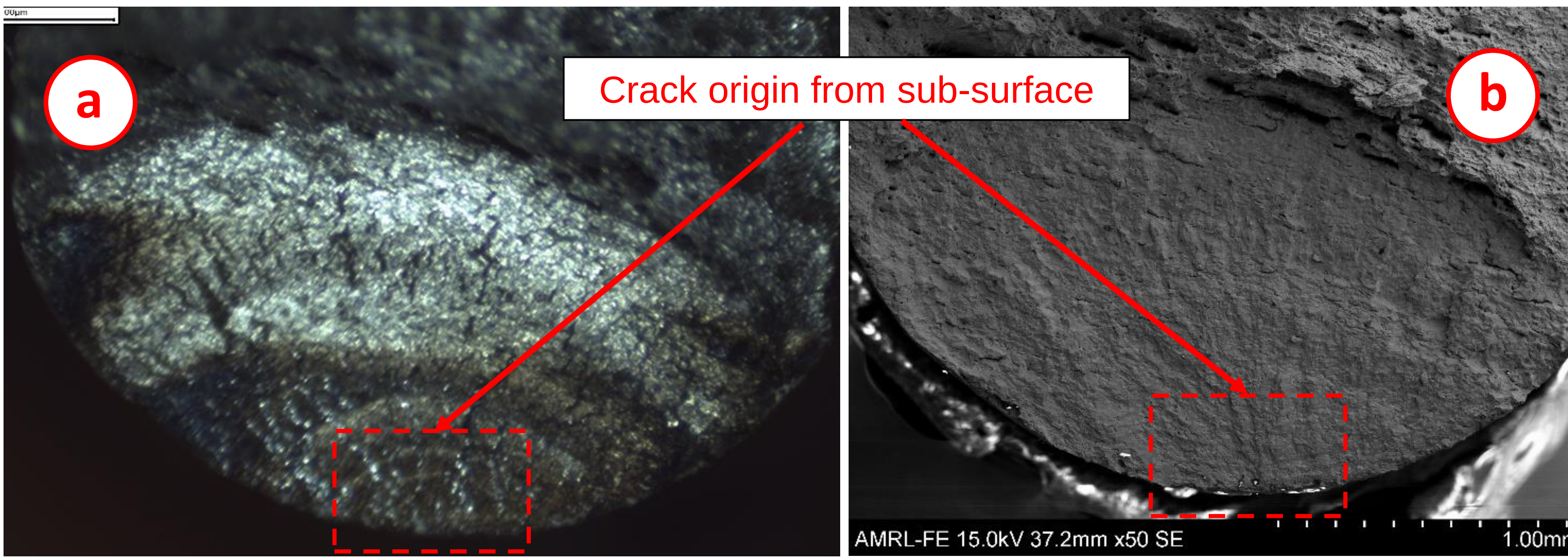


Investigation of the fracture surface of the sample run at 400 MPa stress amplitude with a subsurface crack origin for over 4 million cycles using: a) optical microscopy; b) SEM microscopy.



3. Current results and discussion

3.4 Investigation of the fracture surface {2}

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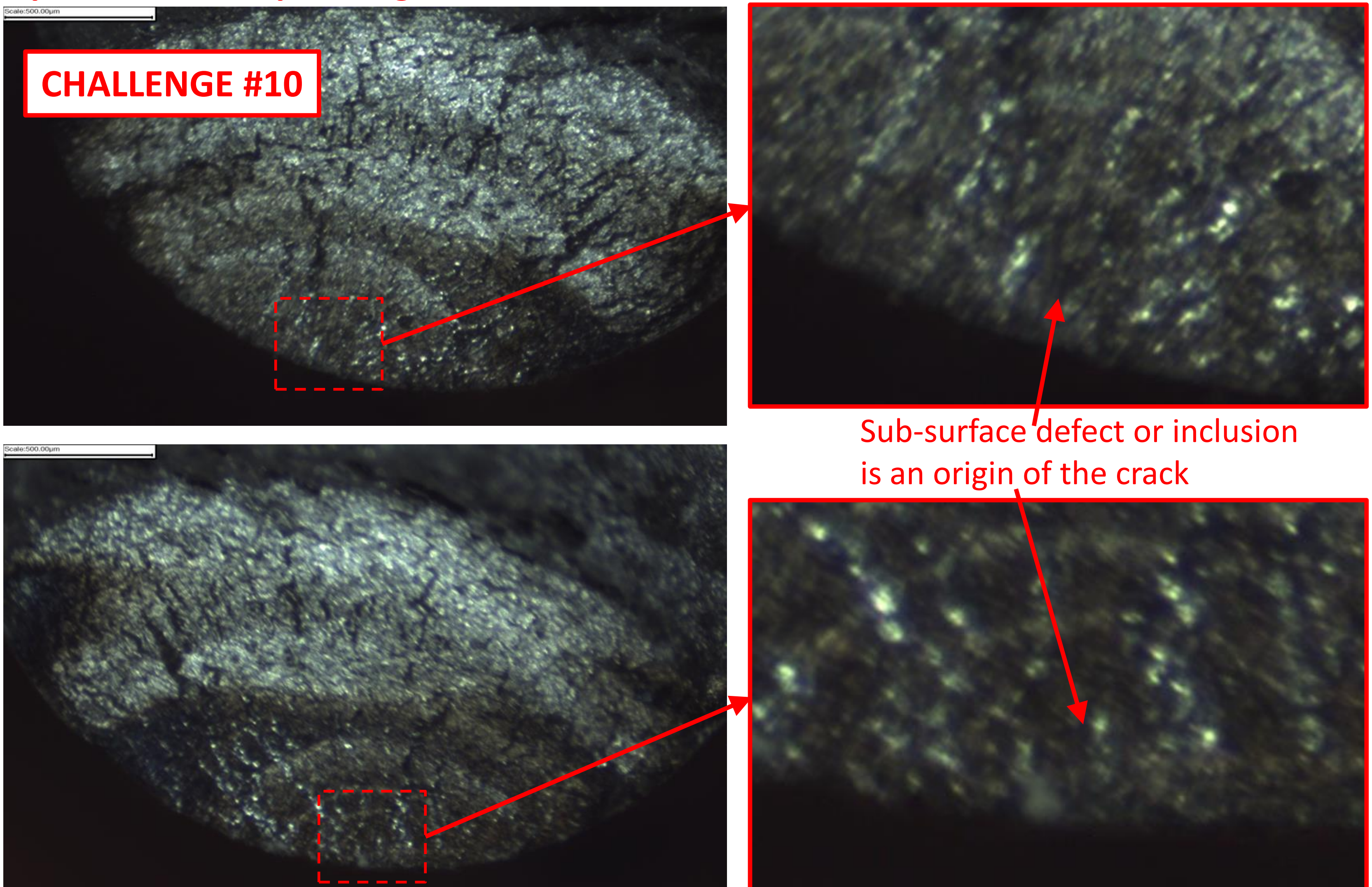
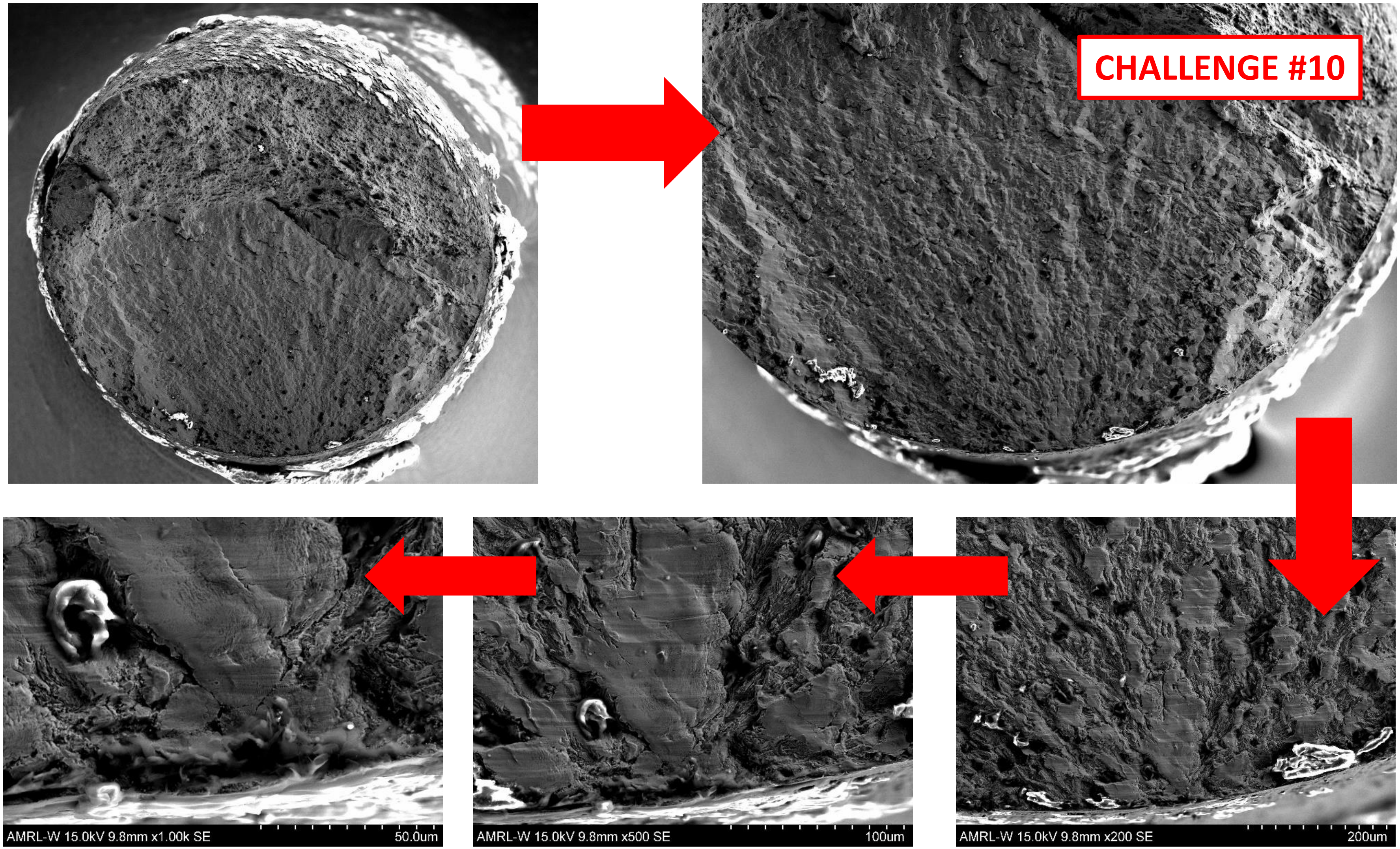
Optical microscopic images of fracture surfaces for test no. 1 at 400 MPa



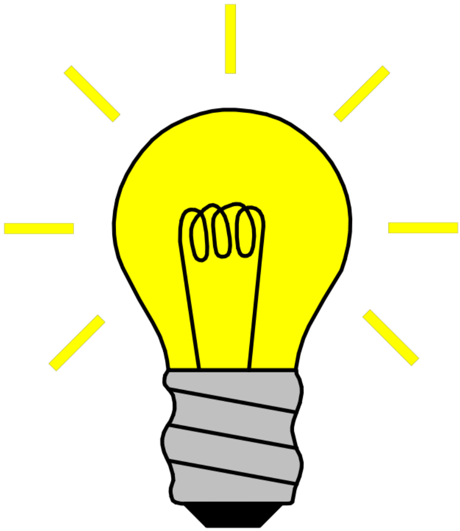
3. Current results and discussion

3.4 Investigation of the fracture surface {3}

SEM microscopic images of fracture surfaces for the test at 355 MPa



6. Summary and conclusions



6. Summary of the challenges

1. To recognize what is more important – crack initiation or crack propagation
2. Learning ultrasonic fatigue testing online
3. Arrangement of the temperature control for the ultrasonic test
4. Machining the accurate geometry of the sample with perfect surface finish
5. Equipment for the manufacturing of the samples
6. Preparation of the pre-corroded samples
7. Interpretation of the obtained results considering frequency effect
8. Making predictions of the design stresses for giga-cycle domain
9. Suppressing and keeping heat generation under control
10. Investigation of the fracture surface and finding the crack origin

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New PhD study: "**Investigation of Strain-rate Effects on Giga-Cycle Fatigue Testing of Low Carbon Steels"** by Lewis Milne (lewis.milne.2015@uni.strath.ac.uk) supervised by Dr. Yevgen Gorash, Dr. Tugrul Comlekci & Prof. Donald MacKenzie

Thank You for Your Attention!

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Virtual Seminar Series – Tuesday 2, 9, 16 November

Challenges of Very High Cycle Fatigue Testing

Presented by Dr-Ing. Yevgen Gorash
Weir Advanced Research Centre
University of Strathclyde

Tuesday, November 16, 2021