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REVIEW: CORROSION AND STRESS CORROSION CRACKING OF WROUGHT AND ADDITIVELY MANUFACTURED 17-4 PH STAINLESS STEEL

YUE ZHANG

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Yue Zhang

Electrochemistry Group

ABSTRACT

In the context of the potential use of additively manufactured (AM) 17-4 PH stainless steel (SS) for steam turbine blades, the present review briefly summarises existing information on the corrosion resistance and stress corrosion cracking (SCC) behaviour of wrought and AM 17-4 PH SS. The threshold chloride concentration for pitting corrosion is reviewed for the wrought steel, and the impact of cyclic stress on corrosion potential and pit initiation is also assessed. Failure analyses on centrifugal compressor impellers and sailboat propeller shafts have linked crack initiation with corrosion pits, but only a limited number of studies concerning SCC testing of wrought 17-4 PH SS are available in the literature. An overview is given of AM processes and their influence on microstructural complexity and inhomogeneity, and their impact on corrosion and fatigue behaviour of 17-4 PH SS is discussed in the context of implications for future testing.

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of NPLML by
Gareth Hinds, Science Area Leader
Electrochemistry Group

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1 INTRODUCTION

Precipitate hardened martensitic stainless steel 17-4 PH is widely used for the last stage blades in the low pressure (LP) steam turbines in conventional fossil fuel and nuclear power plants. The material is known to exhibit enhanced mechanical properties, including higher ductility and strength, and better corrosion resistance when compared with conventional blade steels (11-13Cr). However, the primary causes of failure for the 17-4 PH turbine blades, albeit rare, are corrosion fatigue and/or stress corrosion cracking (SCC), which are often associated with corrosion pits [1]. The aim of this review is to provide a brief overview of corrosion (especially pit initiation) and SCC of wrought 17-4 PH SS, as well as a summary of recent developments on additively manufactured (AM) 17-4 PH SS materials.

Turbine blades are subject to high-frequency cyclic stresses caused by vibration of the blade. Meanwhile, although the steam itself is not aggressive (minimal chloride concentrations, high pH), a highly aggressive chemical deposit can build up near the dry-wet transition stage of the LP steam turbine. It has been reported that this aggressive chemical deposit can consist of 22 wt% NaCl solution at pH 4 and 80 °C, whilst the O_2 concentration is below 20 ppb [1]. The impurities in the steam condensate originate from the leakage of seawater from the condenser and often include chloride, O_2 and CO_2. These impurities are the main root-cause for corrosion, pitting, fatigue and SCC failures of LP blades [1].

2 PITTING OF WROUGHT 17-4 PH SS

2.1 CHLORIDE THRESHOLD FOR PIT INITIATION

The operational conditions and typical impurities in condensates, liquid films and deposits have been previously discussed in detail [2]. It was established that, for pitting of 17-4 PH SS to occur, the solution environment needs to be aerated, temperature needs to be elevated, and a mechanism must exist for concentrating the chemical impurities. Previous unpublished work at NPL was conducted to reveal the threshold chloride concentration for pitting under full immersion, in the absence of static or fatigue loading. Pit initiation in wrought 17-4 PH SS was evaluated by exposure to aerated solutions with progressively increasing chloride concentration from 3,000 ppm to 60,000 ppm at 90 °C. At test termination, it was revealed that the threshold chloride concentration for pit initiation is between 30,000 ppm and 60,000 ppm (5%-10% NaCl) under fully immersed test conditions at 90 °C.

2.2 IMPACT OF SIMUTANEOUS FATIGUE LOADING ON PIT INITIATION AND GROWTH

The impact of cyclic stress or fatigue loading on the threshold chloride concentration for pit initiation was also investigated. Previous unpublished work at NPL was conducted under two stress ranges ($\Delta\sigma = \sigma_{max} - \sigma_{min}$) of 600 MPa or 650 MPa (with σ_{max} of 630 MPa or 682.5 MPa respectively), a frequency of 25 Hz and R ratio of 0.048. Increasing chloride concentration in a step-wise fashion from an initial value of 5,000 ppm, it was found that the threshold chloride concentration for pit initiation is above 15,000 ppm, which is consistent with the chloride concentration range identified in the absence of fatigue loading (i.e. 30,000 ppm to 60,000 ppm). No significant effect of fatigue loading was observed on the corrosion potential of wrought 17-4 PH SS exposed to aerated chloride solution from 5000 ppm to 15,000 ppm at 90 °C. It was also observed that no large growing pits were formed on the surface after exposure to aerated solutions of 15,000 ppm chloride. The results suggested that simultaneous fatigue loading has no significant impact on pit initiation of 17-4 PH SS. Therefore, pit initiation in 17-4 PH SS is dependent predominantly on the inclusion size and local chemistry, rather than the formation of microcrevices between the inclusions and the matrix under cyclic stress.

3 STRESS CORROSION CRACKING OF WROUGHT 17-4 PH SS

The primary cause of steam turbine blades component failure in service is corrosion fatigue and/or SCC, which is associated with a corrosion-initiated crack development phase, followed by a pit-to-crack transition phase driven by cyclic and/or static loads [3]. Limited studies are available in the literature on SCC crack growth measurement of 17-4 PH SS in chloride containing environment. It is expected that a similar failure mechanism for 17-4 PH SS exists whereby crack initiation occurs when the pit exceeds a threshold size (related to a threshold stress concept) in combination with a crack growth rate that exceeds the pit growth rate [3].

Burns et al. carried out fracture-mechanics based testing to quantify corrosion fatigue and SCC behaviour of precipitate-hardened martensitic stainless steel (Custom 465) under full immersion in chloride containing environment with applied potential [4]. The alloy under investigation, Custom 465, is also a martensitic age-hardenable stainless steel originally designed to be used in the aerospace industry. As shown in Figure 1, Stage I cracking occurs above a K_{ISCC} of ≈75 MPa√m, which is characterised by a rapid increase in da/dt with increasing K. Stage II cracking is observed with a plateau in da/dt at $\approx 10^{-5}$ mm/s in a range of 120-160 MPa√m. Further increase in K leads to a rapid increase in growth rate as K approaches and exceeds the critical stress intensity for fracture. Fractography is shown in Figure 2 (cracking from right to left) with evidence of intergranular stress corrosion cracking (IGSCC) under a test protocol of slow rising K [4].

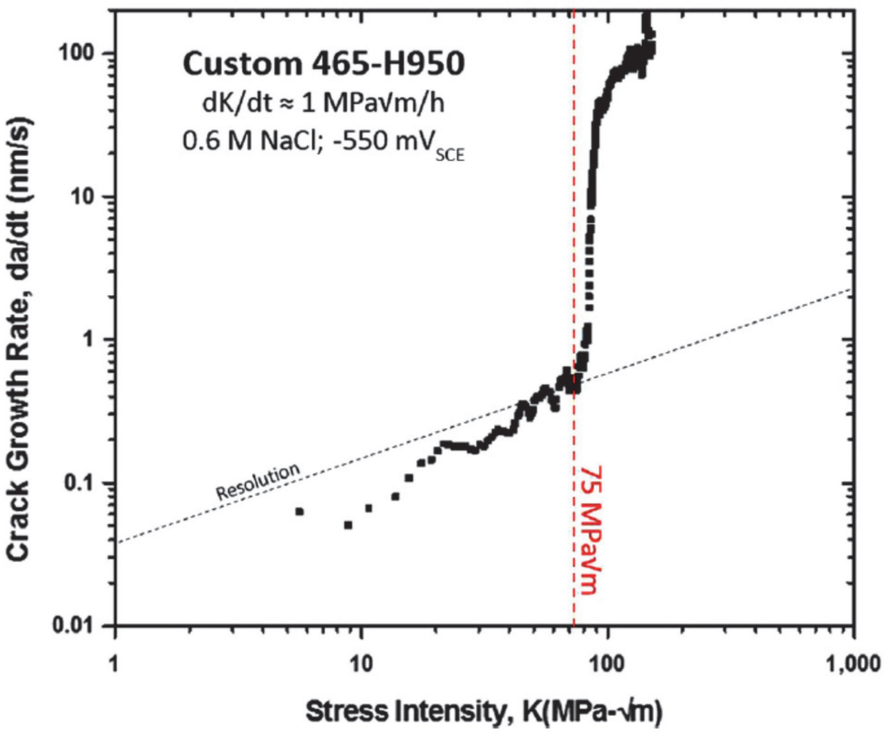

Figure 1. SCC rate vs. stress intensity for Custom 465 tested using slow rising displacement (equivalent to dK/dt ≈ 1 MPa/$\sqrt{m}$/h prior to the onset of cracking) in 0.6 M NaCl at -500 mV (vs. SCE) [4].

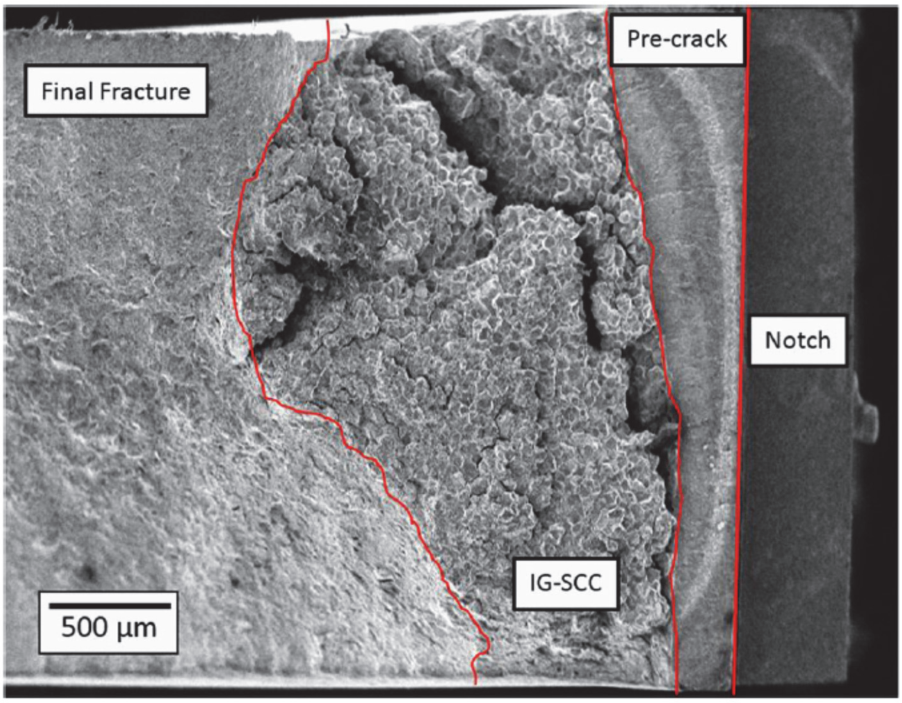

Figure 2. Fractography of Custom 465 tested at a slow rising displacement (corresponding to dK/dt ≈ 1 MPa/$\sqrt{m}$/h prior to the onset of cracking) in 0.6 M NaCl at -500 mV (vs. SCE) [4].

Other studies, including slow strain rate testing and U bend testing, were conducted to evaluate the impact of precipitate chemistry on environmentally assisted cracking. The environmental cracking behaviour of U bend specimens of 17-4 PH SS was studied in 3.5 wt% NaCl at pH 2 at applied anodic and cathodic potentials [5]. It was claimed that under anodic potentials the observed cracking is associated with active path dissolution, while under cathodic potentials it is associated with hydrogen absorption. Slow strain rate testing was also conducted in deaerated 20 wt% NaCl solution at pH 3 and pH 7, and 90 °C [6]. Electrochemical noise measurements, e.g. potential transients, were used to correlate with crack nucleation and propagation [6].

Failure analysis of 17-4 PH SS components in service has shown that the observed cracking is often associated with the early development phase of corrosion pits. Fantechi et al. [7] reported failure analysis of a 17-4 PH SS component used in centrifugal compressor impellers, which was employed in a gas lifting service in which the fluid entrained water with a high level of salinity. It was considered that the cracks and pits observed were related. Arisoy et al. [8] also investigated a failure analysis associated with chloride induced SCC of 17-4 PH SS used in a sailboat propeller shaft. The primary causes of failure were torsional fatigue and SCC. It was reported that sulphur containing inclusions and chromium carbides were present, favouring pit initiation and acting as crack precursors. The crack propagation was transgranular in a martensite matrix.

4 ADDITIVELY MANUFACTURED 17-4 PH SS

The corrosion resistance and fatigue behaviour of AM 17-4 PH components are often linked to microstructural features influenced by AM processing which is nominally using electron (laser) based melting technique [9]. Such microstructure features include porosity, grain structures, dislocations, residual stress, solute segregation [9], and other impactful factors such as surface finish, build orientations. These features combine as a characterisation of the material, which needs to be carefully assessed prior to any corrosion and/or SCC testing.

4.1 CORROSION OF AM 17-4 PH SS

Despite the various benefits of AM techniques [9], technical challenges still hinder the full impact of AM, including the standardisation of printing methods and consistent production of qualified components. The formation of complex microstructures as a result of AM processes leads to changes in electrochemical properties of AM materials and hence their corrosion resistance. Schaller et al. [10] carried out corrosion testing on a laser powder bed fusion (LPBF) AM 17-4 PH SS alloy in 0.6 M NaCl solutions. It was shown that the LPBF manufactured counterparts have reduced corrosion resistance in terms of reduced passivity range and higher rates of active corrosion compared with its conventional wrought counterpart. The reduced corrosion resistance of AM samples was related to the formation of pores with diameters ≥ 50 µm in the microstructure. Detailed microstructural examination was carried out to evaluate the impact of inhomogeneous features on corrosion resistance, including Cr segregation and the size and distribution of porosity. It was discovered that the presence of pores can impact the corrosion type directly, with active corrosion associated with the large pores (≥ 50 µm) and passive corrosion associated with smaller pores (≤ 10 µm). It was also reported that initiation of corrosion was found at or near pores. It was suggested that post-processing treatments would be needed, which would be expected to dramatically enhance the corrosion resistance.

The effect of post-build heat treatment on pitting of Selective Laser Melting (SLM) 17-4 PH specimens was investigated by Stoudt et al. [11]. A systematic corrosion study with electrochemical measurements in deaerated 0.5 M NaCl solutions was carried out with SLM as-built 17-4 PH SS components, SLM components with post-processing heat treatment (AM + HT, i.e. homogenising, to eliminate segregation and produce a uniform microstructure), and traditional wrought components [11]. It was observed that pitting potentials were generally higher for the SLM 17-4 PH with heat treatment than that of the wrought alloy. The difference was attributed to the finer microstructure with more homogeneously distributed NbC precipitates than that in the wrought alloy, as well as the more stable passive film from the absorbed nitrogen in the AM+HT alloy. It was claimed that the corrosion resistance of AM 17-4 PH with homogenisation treatment was not inferior to that of the wrought component in chloride environment.

4.2 FATIGUE OF AM 17-4 PH SS

The impact of complex microstructure on fatigue strength and fatigue crack growth was also evaluated, highlighting the importance of microstructure homogeneity [12-15]. Romano et al. [12] investigated the effect of surface quality (i.e. surface roughness) and sub-surface porosity on high cycle fatigue (HCF) behaviour of 17-4 PH SS fabricated using LPBF. The as-built specimens were compared with oversized specimens with further machining. It was found that the machining process resulted in smaller and more uniformly distributed porosity, whereas the as-built components presented large sub-surface, close-to-surface pores. It was demonstrated that the machining process enhanced the fatigue performance compared with that of the as-built counterparts.

Yadollahi et al. [15] carried out investigations to evaluate the effects of build orientation and heat treatment (solution annealing and peak-ageing) on fatigue of SLM 17-4 PH SS. It was highlighted that post-SLM heat treatment is necessary to improve tensile strength and fatigue behaviour in low cycle fatigue (LCF) to minimise the pronounced effect of microstructural impurities. In contrast, the heat treatment resulted in precipitation hardening which led to the SLM parts being more sensitive to impurities in HCF where crack initiation dominates the total fatigue life. The influence of building direction on fatigue was also characterised and its role was found to be dependent on the relative orientation of deposited layers with respect to the applied load.

4.3 FUTURE SCC TESTING OF AM 17-4 PH SS

It is clear from previous studies that a range of unique microstructure features and/or defects can be detrimental, or beneficial, on corrosion and/or crack initiation and propagation from fatigue or SCC. Such defects are unique to AM processes, can vary over a few orders of magnitude in length scale, and are distinct from the conventional wrought process. For example, dislocation networks and solute segregation can vary from the nm to the μm scale, whereas porosity and residual stress can vary in size up to meters [9]. It can also be stated that although numerous studies have been carried out on corrosion and mechanical testing of AM produced 17-4 PH, there is a lack of standardisation of the AM method or manufacturing parameters to control the final microstructure.

For future proposed SCC testing of AM 17-4 PH SS, materials characterisation is vital prior to any corrosion or SCC testing. Depending on the method of AM, different aspects of materials characterisation should be considered [9]:

- Surface roughness (R_a). High R_a obtained from SLM process e.g. 10 μm - 30 μm compared to conventional methods such as milling (1 μm - 2 μm) [16]
- Non-equilibrium microstructures due to rapid heating and cooling rates in AM [17]
- Porosity
- Residual stress

Post-processing heat treatment should be considered to avoid the pronounced effect of microstructure defects and inhomogeneities on corrosion and SCC behaviour of 17-4 PH SS.

5 CONCLUSIONS

Several studies have been reviewed herein for corrosion and/or SCC of 17-4 PH SS materials fabricated from both wrought and AM processing routes. The role of chloride concentration on pit initiation of wrought specimens was discussed, and a threshold concentration of 30,000 ppm to 60,000 ppm was reported from previous unpublished work. It was also suggested that simultaneous fatigue loading has no obvious impact on pit initiation of 17-4 PH SS. Limited studies are available for SCC of wrought 17-4 PH SS in chloride containing environments. One study reported a K_{ISCC} value of 75 MPa MPa/$\sqrt{m}$ for a similar alloy in 0.6 M NaCl at an applied potential of -500 mV vs SCE.

The AM processed 17-4 PH SS components exhibit a range of unique microstructure features that have either beneficial or detrimental effects on corrosion resistance, and possibly also on SCC behaviour. It is essential to carry out comprehensive characterisation of the material prior to any corrosion or SCC testing. Such features include porosity and non-equilibrium microstructures, including the formation of precipitates and solute segregations, surface roughness and residual stress.

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