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Stress Corrosion Cracking Behavior of Stainless Steel 310S in Supercritical Water

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ABSTRACT

Recent interest in nuclear power technologies is directed to small modular reactors (SMR). The possible and believed option is the one cooled by supercritical water (SCW-SMR). The main objectives of the project ECC-SMART, which is based on SCW technology, are to define the design requirements for the future SCW-SMR, to develop the pre-licensing study and guidelines for the demonstration of safety in the further development stages of the SCW-SMR concept. Based on the scientific results, the stainless steel 310S and other alloys have been selected as the most promising commercially produced materials for application as the cladding material in SCW-SMR. Slow strain rate tests in combination with scanning electron microscopy were used to evaluate the stress corrosion cracking (SCC) susceptibility in SCW.

1 INTRODUCTION

As a result of concerns about fossil fuel resource availability and environmental issues, interest in nuclear power technologies has been growing over the last decades. After a period in which large units were developed and privileged, there is currently a revival of interest concerning the small and simpler reactors for electricity generation, heat production, cogeneration, and desalination, the so-called small modular reactors (SMRs). SMR technologies using various concepts are being developed worldwide. It is believed that the most promising concept of SMR is the water-cooled one since they inherit experience gained by most of the power reactors operating worldwide. In this frame, the supercritical water (SCW) with a temperature above 374 °C and pressure of 22.1 MPa technology can play an important role, representing a natural evolution of current advanced water-cooled nuclear reactor technologies, while integrating much of the advances in SCW technology used in modern conventional fossil power plants. It is expected that SCW-SMR will improve the standard of living and technological development not only in cities but also in remote areas and small towns [1].

To increase the level of knowledge and to demonstrate the benefits of the SCW-SMR concept, the Horizon 2020 project Joint European-Canadian-Chinese Development of Small Modular Reactor Technology – ECC-SMART was approved. The consortium consists of 20 partners around the world working mainly in three work packages dealing with corrosion of materials, thermo-hydraulics, and neutron physics. The main goal is to create a list of requirements for the design of SCW-SMR and to identify the key obstacles to future SMR licensing.

SCW-SMR concept should work at temperatures between 280 up to 550 °C and 25 MPa, expected average temperature on cladding is ~ 380 °C. Cladding should be in a horizontal position and there will be only a primary cycle with burn-up for 2 years at least. Stress corrosion cracking (SCC) and Intergranular Stress Corrosion Cracking (IGSCC) were identified as the main problems and a gap in knowledge about cladding materials in SCW-SMR. Corrosion tests and slow strain rate tests are done under higher temperatures (500 °C/25 MPa) and at pseudo-critical points of water (380 °C/25 MPa) due to the changes of properties and behaviour of water and thus the effect on the process of corrosion at all. For more, the influence of irradiation is also studied in this project.

Based on the scientific results [2],[3] and previous projects, the stainless steel 310S and alloy 800H have been selected as the most promising commercially produced materials for application as the cladding in SCW-SMR.

Alloy 310 (UNS S31000) is an austenitic stainless steel developed for use in high-temperature corrosion-resistant applications. The alloy resists oxidation up to 1100°C under mildly cyclic conditions. At a higher temperature, the alloy is subjected to sigma phase precipitation. The σ-phase is a tetragonal crystal structure, and its precipitation temperature is between 600 and 1000 °C [4], [5].

2 EXPERIMENTAL

2.1 Material and specimens

The material used in this research was austenitic stainless steel 310S. The chemical composition is shown in Table 1. To be closer to the real conditions, tensile specimens were cut out from a 1 mm thick tube and the dimensions of the testing specimens are shown in Fig 1. Specimens were cleaned with acetone in an ultrasonic bath for 15 min.

Table 1: The chemical composition of material 310S (wt%).

Elements	**C**	**Si**	**Mn**	**P**	**S**	**Ni**	**Cr**	**Mo**	**Fe**
310S	0.060	0.39	1.190	0.024	0.0006	21.45	25.27	0.250	Bal.

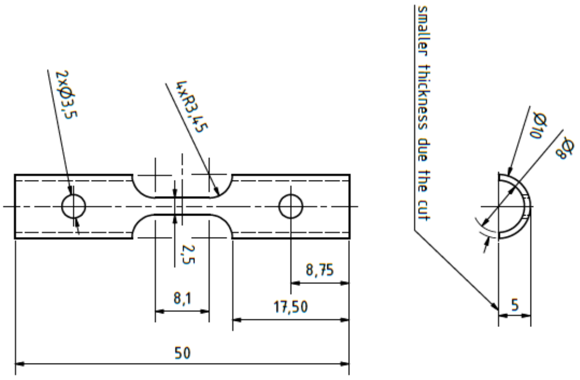

Fig 1. The dimensions of tensile specimens.

2.2 Slow strain rate tests (SSRT) conditions and post analysis

SSRT was performed in SCW at 380 °C under a pressure of 25 MPa. The conductivity of the inlet water fed to the autoclave was controlled under 0.08 μS/cm, with pH 6.8, and dissolved oxygen concentration was set at 150 ppb and with flow 1 volume of autoclave per hour. Two strain rates 10^{-6} s^{-1} and 10^{-7} s^{-1} were applied. Both these tests were done at Amalia laboratories, JRC Petten. As a reference, SSRT was done in the air at 20 °C and 380 °C under atmospheric pressure with two different strain rates: 10^{-3} and 10^{-6} s^{-1}, done at CVR – Pilsen. After testing, the strain-stress curves and fracture surfaces were analysed by SEM to identify the mechanical properties and fracture morphology.

3 RESULTS AND DISCUSSION

3.1 Stress-strain curves

The stress-strain curves of all tested specimens are shown in Fig 2 and the results are shown in Table 2. Many serrations occurred in the plastic area when tested at 380 °C in air and SCW. A short softening part before the rupture on all specimens at 380 °C. The ultimate tensile strength (UTS) is strongly dependent on the test temperature in air, also yield strength (YS) is decreasing with increasing temperature. When we compare curves of the same strain rate 10^{-6} s^{-1} in air and in SCW, we can see that the UTS decreased significantly from 771 to 630 MPa and elongation increased from 36.5 to 47 %, while the YS showed just a slight decline from 395 to 370 MPa. That means that the pressurized environment influenced the material behaviour. For SSRT in SCW, the strain rate plays a main role. We can observe strengthening of the material - an increase of YS and UTS with a lower strain rate 10^{-7} s^{-1}.

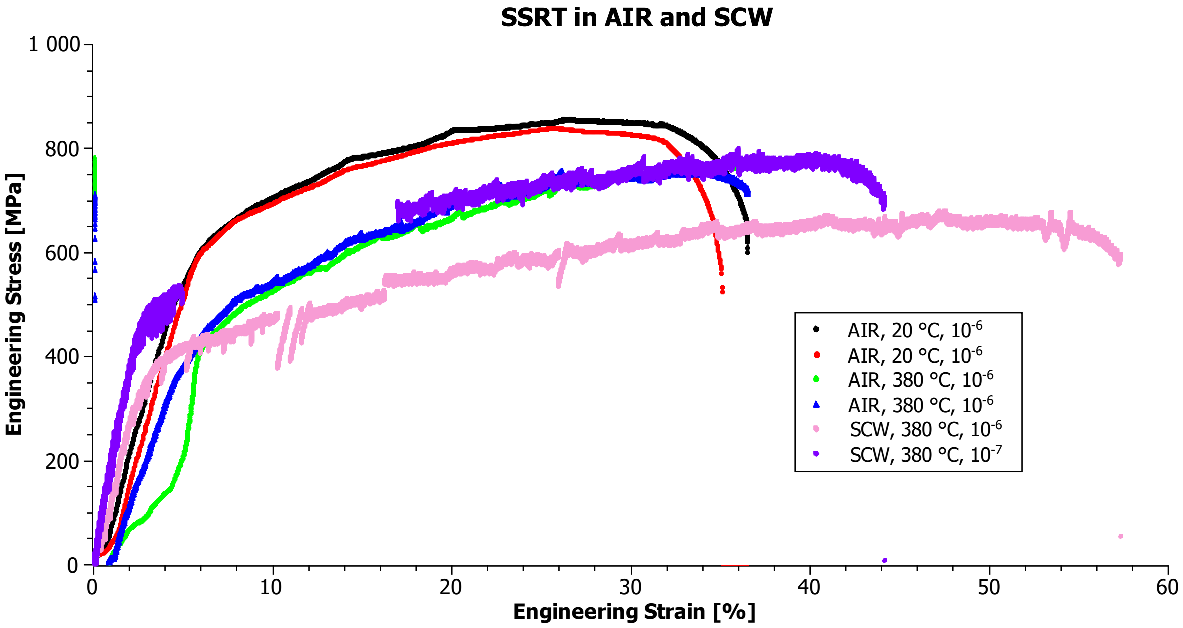

Fig 2. Stress-strain curves of 310S specimens in: a) AIR at 20 °C, 10^{-6} s^{-1} (black, red line), b) air at 380 °C, 10^{-6} s^{-1} (green, blue line), c) SCW at 380 °C, 10^{-6} s^{-1} (pink line), 10^{-7} s^{-1} (purple line).

Table 2: Summarized results of SSRT in AIR and SCW

Material 310S	**Yield strength YS [MPa]**	**Tensile strength UTS [MPa]**	**Elongation A [%]**
20 °C, AIR 10^{-6} s^{-1}	570 ± 20	849 ± 8	30.5 ± 0.5
380 °C, AIR, 10^{-6} s^{-1}	395 ± 5	771 ± 12	36.5 ± 0.5
380 °C, SCW 10^{-6} s^{-1}	370	630	47
380 °C, SCW, 10^{-7} s^{-1}	450	750	36

3.2 Fracture surface analysis

Fig 3 and 4 show SEM images of the fracture surface of 310S after SSRT in SCW at strain rates 10^{-6} s^{-1} and 10^{-7} s^{-1}. The fracture surface is ductile with dimples with no IG or TG cracking in both cases. Only initiation of SCC near the surface was observed, but initiations did not grow into the material. That means the failure of both specimens at 380 °C was mainly due to the ductile-dimple mechanism.

Fracture surfaces after SSRT in the air were not analysed, because the corrosion environment was not present, which means that SCC on these specimens is not expected.

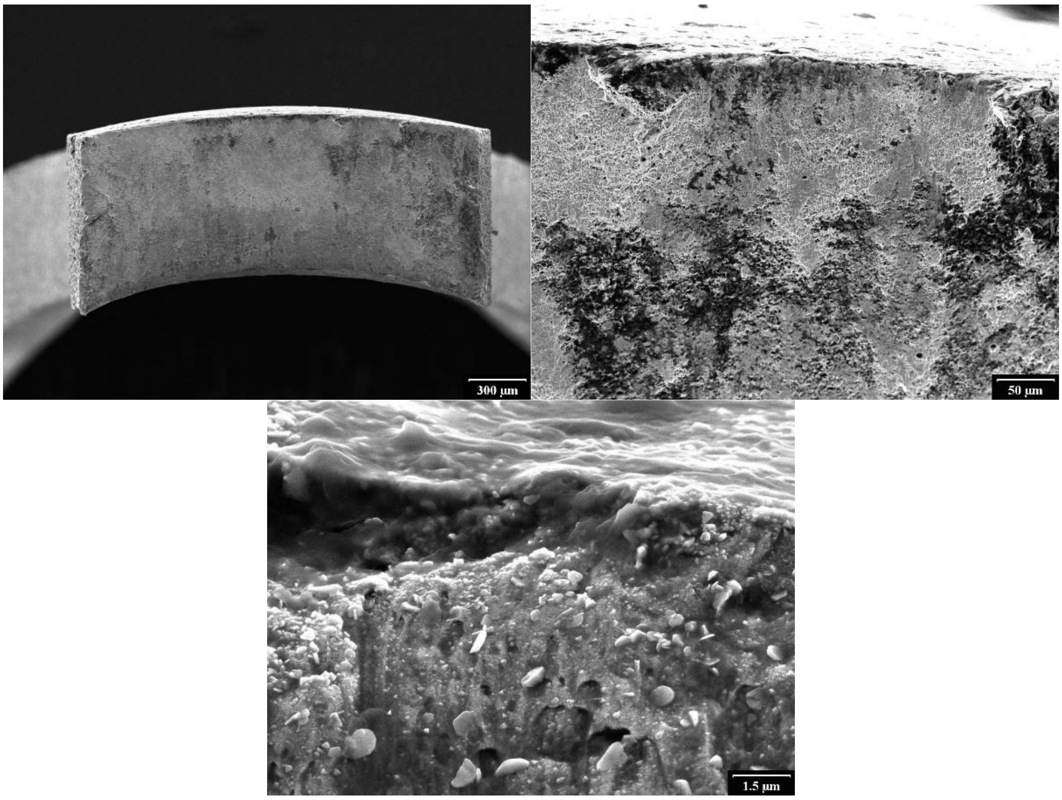

Fig 3. Fracture surface of 310S after SSRT in SCW with strain rate 10^{-6} s^{-1}. From lower magnification (left up), to higher (right up), to the detailed interface (down).

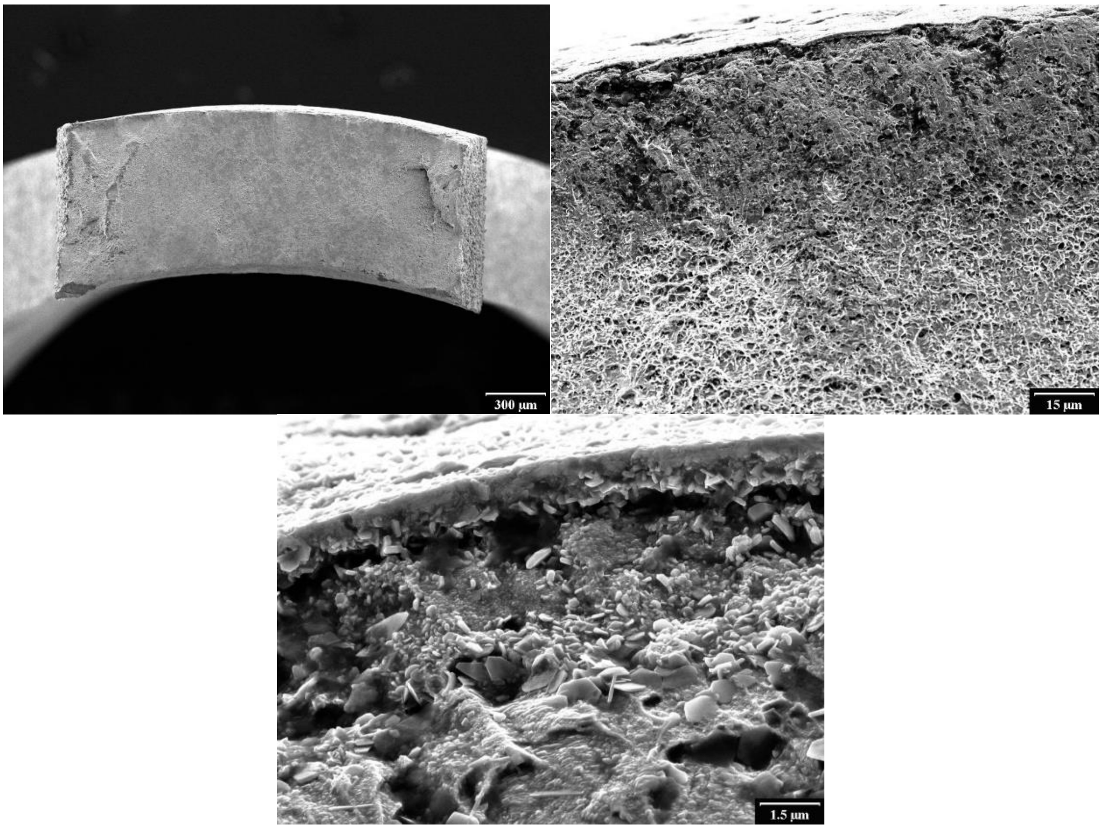

Fig 4. Fracture surface of 310S after SSRT in SCW with strain rate 10^{-7} s^{-1}. From lower magnification (left up), to higher (right up), to the detailed interface (down).

4 CONCLUSIONS

SSRT tests of 310S were carried out in SCW at a temperature 380 °C and pressure of 25 MPa, with two strain rates of 10^{-6} s^{-1} and 10^{-7} s^{-1} to observe mechanical behaviour (reference SSRT in the air at 20 °C and 380 °C and atmospheric pressure were also done) and if there is an indication of SCC in the fracture surface in SCW.

The main results can be summarized as follows:

- YS and UTS decrease with higher temperatures and with a more oxidizing environment.
- 10^{-6} s^{-1} vs 10^{-7} s^{-1} in SCW – with lower strain rate increase of YS and UTS - strengthening of material occurs. Strain rate plays a role.
- Fracture surface in SCW - the ductile-dimple mechanism - no IG or TG fracture observed at 380 °C.
- Slow indications of SCC near the surface, but it did not grow into the material.

ACKNOWLEDGMENTS

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