

INTERNAL PRESSURE CREEP TESTING OF WELDED JOINTS IN AUSTENITIC HEAT-RESISTANT STEELS

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Abstract

One of the approaches to simulate creep testing conditions as close as possible to the real service conditions of boiler tubes is the use of internal pressure creep tests (burst tests). This paper describes the implementation and results of such creep tests performed on welded joints of superheater tubes $\varnothing 44 \times 6.3$ mm made of HR3C steel, welded by the TIG process using a filler material based on the nickel superalloy Inconel 617. The tests were carried out at two temperatures, 730 °C and 760 °C, under internal pressures up to 29 MPa. The experimentally obtained times to failure exceeded the values predicted by parametric calculations based on available material data. Significant tube bulging was observed, and failure was mainly located in the HR3C base material in the vicinity of the weld. Metallographic analysis confirmed a dominant intergranular creep damage mechanism characterized by the formation of chains of cavities and microcracks initiated from the outer surface. Close to the weldment, the presence of δ -ferrite and precipitates of σ -phase were also detected along grain boundaries in HR3C steel.

Keywords: Internal pressure creep testing (burst test), welded joint, HR3C steel, Inconel 617 filler metal, intergranular creep damage, σ -phase precipitation

1. INTRODUCTION

The design and calculations of pressure components are usually based on data corresponding to a uniaxial stress state, especially since almost all the data relevant to these calculations are generated by tests performed under uniaxial loading, which is the simplest to design and interpret. However, calculations, which are given in practically all standards, are based on the effective stress concept and are commonly used to calculate the creep life of a material loaded with triaxial stress. This concept is based on the principle that the life of a component with multiaxial effective stress corresponds to the time to fracture at the same uniaxial stress.

Ideally, creep tests would be performed on tubes/pipes for the energy industry to obtain their creep characteristics using the technique of bursting the pipes by internal overpressure, because these conditions best correspond to the actual operation [1]. Performing such tests is more complicated and more expensive, so they are used primarily in specific cases, especially in tests of "inflating" materials in nuclear power during emergency situations [2] or for analyzing the method of crack propagation under conditions as close as possible to real operation [3]. For ordinary purposes, test specimens of cylindrical diameter are often made from the wall of the pipe, and these specimens are tested by uniaxial tension. Assuming an ideally isotropic material and constant internal overpressure, the following equation for calculating the tangential stress in the thin-walled tubes and/or pipes is valid:

$$\sigma_h = \frac{p \cdot r}{t} \quad (1)$$

where:

σ_h - the tangential (hoop) stress (MPa)

p – pressure (MPa)

r - the internal pipe diameter (mm)

t – tube/pipe wall thickness (mm)

Without applying any additional (tensile or compressive) load, the ratio of axial stress to tangential stress is equal to 2, i.e. the axial stress reaches half the value of the tangential stress.

Kanemaru et al. [4] and other researchers [5] compared the results of uniaxial tension creep tests and internal overpressure tests of 2.25Cr-1Mo and 9Cr-1Mo steels and found that the creep strength of tests with internal overpressure was practically the same as that from uniaxial tension creep tests. This demonstrates that simple tensile creep tests provide results that are very comparable for predicting the time to fracture and remaining service life, instead of the more complicated internal overpressure creep tests (**Figures 1 and 2**).

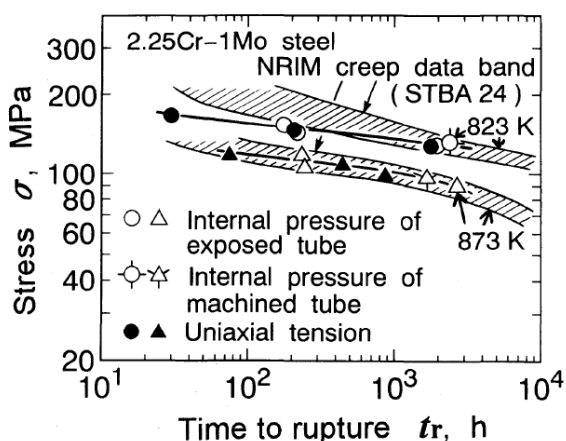


Figure 1 Comparison of results of internal pressure and uniaxial creep test for 2.25Cr-1Mo steel [4]

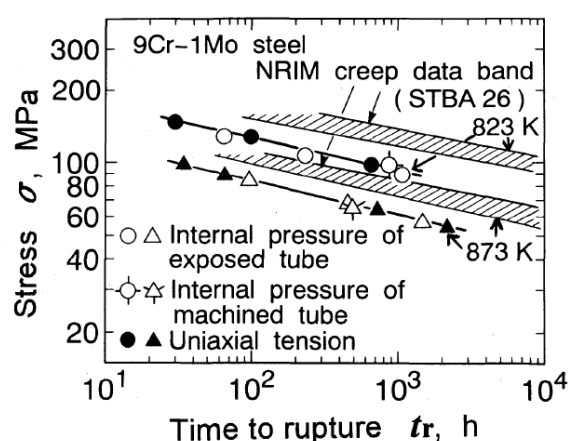


Figure 2 Comparison of results of internal pressure and uniaxial creep test for 2.25Cr-1Mo steel [4]

While the significant advantage of uniaxial tension creep tests lies in their simplicity, these tests can never fully capture the actual development of creep deformation around the circumference of a pipe or along its length. In these areas, creep tests with internal pressure provide much more accurate and detailed information about the real behaviour of tubes and pipes exposed to high temperatures and pressure.

2. EXPERIMENTAL MATERIAL AND TESTING PARAMETERS

For internal pressure creep testing, a superheater tube ($\varnothing 44 \text{ mm} \times 6.3 \text{ mm}$) made of HR3C steel was used. The tube was welded to a hollow cylinder with a solid bottom of the same diameter as the tube and to a specially designed fixture for connection to a pressure gauge for continuous pressure monitoring, **Figure 1**. The cylinder was made of Inconel 617 alloy, and all weldments were made using the TIG welding (141) with a nickel-based filler material, Thermanit 617. To obtain required rupture times, the original wall thickness of 6.3 mm had to be reduced on the inner surface to 4 mm. The chemical composition of the tube and filler metal is stated in **Table 1** and the final image of the test specimen is shown in **Figure 3**.

Table Chemical composition of steel HR3C and filler metal Thermanit 617 (wt%)

Element	C	Mn	Si	S	Cr	Ni	Nb	Mo	Co	V	Ti	N	B	Fe
Tube	0.085	1.26	0.77	0.005	25.81	19.10	0.53	0.18	0.18	0.048	0.005	0.18	0.070	bal.
Filler metal	0.056	0.12	0.24	0.005	22.61	bal.	0.016	9.43	10.36	0.005	0.28	-	0.060	3.10



Figure 3 Final image of the test specimen

The main limiting factors in internal-pressure creep testing were the leak-tightness and reliability of the welded fixture and the connected pressure gauge, as well as safety considerations arising from the risk of a sudden release of the working medium (water vapour) in the event of tube-wall failure. For these reasons, the maximum overpressure inside the tube during testing was limited to 30 MPa. After the first test which was interrupted after nearly 1,500 hours, the testing temperature was increased from 730 °C to 760 °C. The maximum allowable overpressure of 30 MPa induces, according to equation (1), an average tangential (hoop) stress in the tube wall of 135 MPa. Parameters (stress) for the tests were calculated using the parametric equation developed formerly in SVÚM [6] using the mean creep strength values stated for steel HR3C (1.4952) in the material datasheet (VdTÜV-Werkstoffblatt WB 546 [7]), as this steel has not yet been included in the European standard for seamless pipes for pressure purposes (EN 10 216-5);

3. RESULTS OF INTERNAL PRESSURE CREEP TESTS

After the first test was interrupted, the subsequent internal pressure creep tests continued until fracture, see **Table 2**. During the tests, a gradual decrease in internal overpressure occurred throughout the testing period for each sample. This phenomenon started very soon after the tests began, and therefore it cannot be linked to the development of creep deformation and the "swelling" of the tube. It is possible that this is a result of minor leaks through the compression fitting joint at the end of the test specimen, or possibly the result of condensation of water vapor at the end of the small tube, which is attached to the test and leads to the pressure gauge. However, it never exceeded the generally accepted limit, which is defined as a pressure drop of more than 10 % from its nominal value.

Table 2 Results of the conducted internal pressure creep tests

Sample	Temperature	Pressure	Hoop stress	Time to rupture	Remark
	(°C)	(MPa)	(MPa)	(h)	
Sample 1	730	30	135	(1495)	Interrupted
Sample 2	760	30	135	356	leakage
Sample 3	760	27	121.5	984	leakage
Sample 4	760	25	112.5	1675	leakage

Figure 4 shows the results of these internal pressure creep tests plotted in a stress-time to rupture diagram with curves showing creep strength at 700 °C, 730 °C and 760 °C, as determined for nominal data of HR3C steel calculated using the SVÚM equation. Due to the applied stress limitations, the results are confined to a relatively narrow time range between 1,000 and 2,000 hours. Although the experimental results follow the slope of the isothermal curves, they all lie above the curve corresponding to the stress dependence of time to fracture at 760 °C and practically coincide with the curve for 730 °C. While Kanemaru et al.'s and other findings [4,7] suggest that uniaxial tension creep tests can be an effective and simplified method to predict creep life in steels under pressure, the results from this study demonstrate that HR3C steel probably does not follow this pattern. **Figure 5** then shows the appearance of the area of final failure of the tube wall on the outer and inner surfaces.

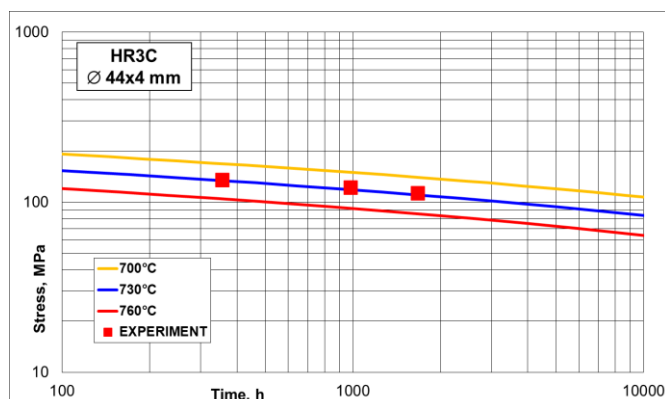


Figure 4 Stress-time to rupture diagram of HR3C steel with results of internal pressure creep tests



Figure 5 Creep damage on the outer (above) and inner surface of sample 3

4. METALLOGRAPHIC ANALYSIS OF INTERNAL PRESSURE CREEP TESTS AFTER FRACTURE

A detailed metallographic analysis was focused on identifying the microstructure and cavitation around the damaged area in the transverse section and at various distances from the weld in the longitudinal section. A coarse main crack, extending through the entire thickness of the tube wall, originated from the outer surface and propagated diagonally across the tube wall, **Figure 6a**. Several finer cracks were observed along the outer surface, **Figure 6b**. Shallow cracks were detected along the inner surface of the tube and numerous chains of cavities were found on grain boundaries in the matrix, **Figure 6c, d**.

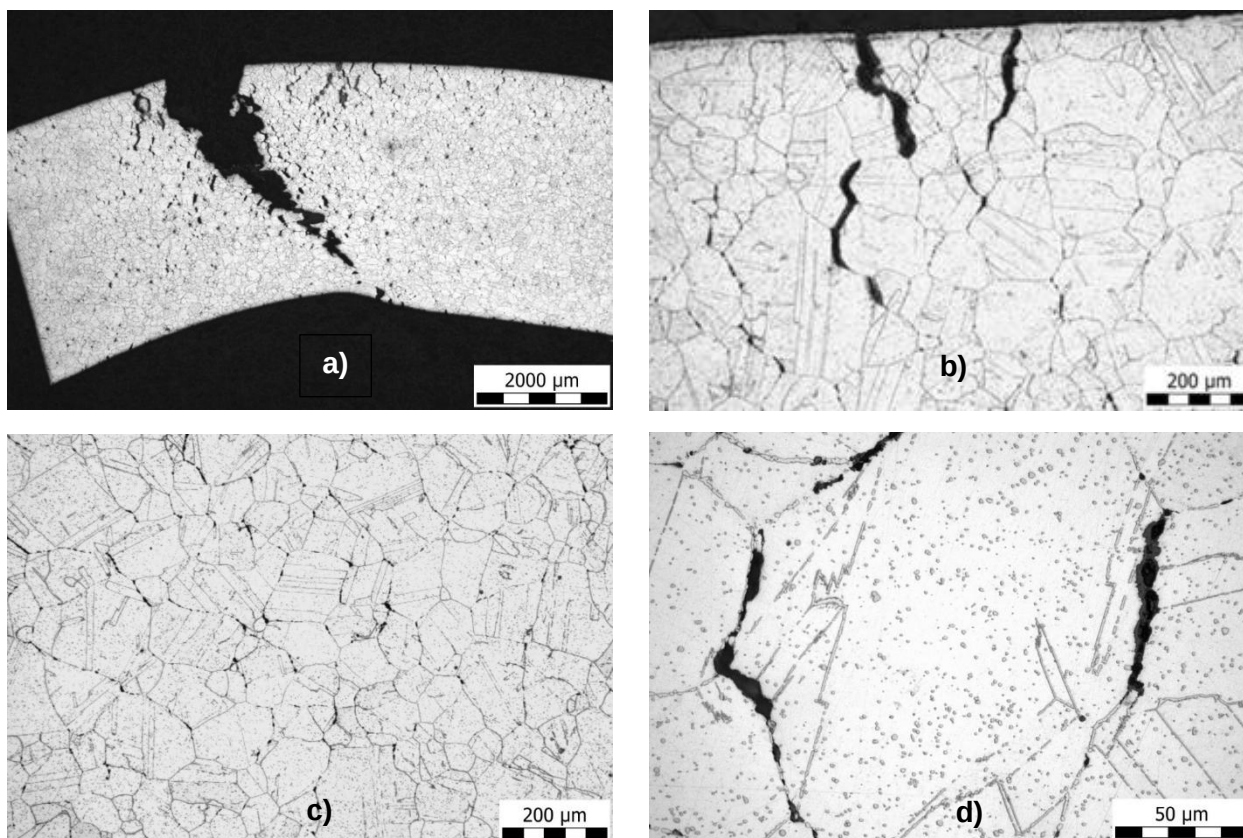


Figure 6 Transverse section of sample 3, a) main crack, b) surface cracks, c) cavitation and microcracks inside tube wall, d) detail of microstructure with fine carbides and chains of cavities on GB

Analysis of longitudinal section (performed outside of the area of maximum creep damage) revealed that cavitation occurred along the entire length of the sample but stopped just at the fusion line, **Figure 7a**. Intensity of cavitation damage increased with the distance from the fusion line up to the area of maximum damage approximately 20 mm away from the fusion line, **Figure 7b, c, d**.

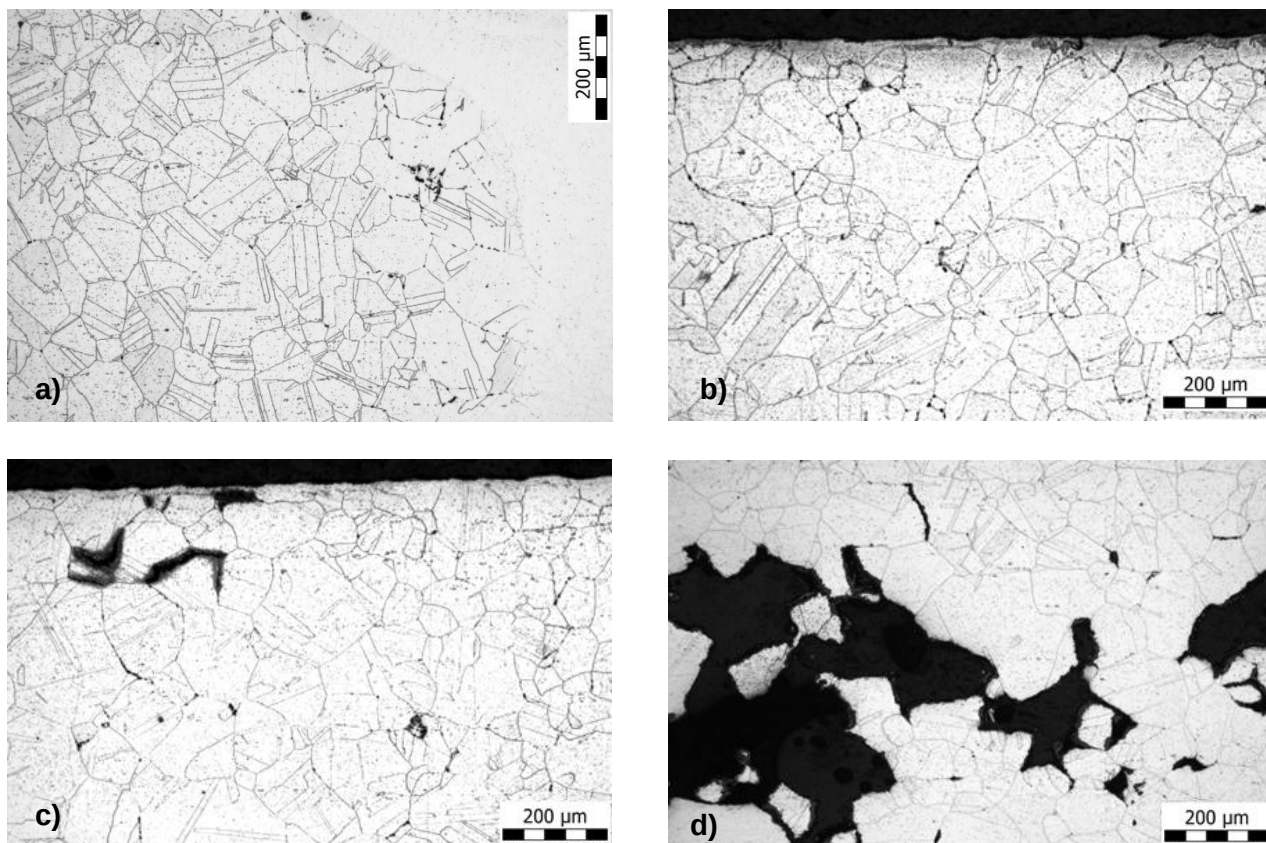


Figure 7 Cavitation damage along longitudinal section of sample 3, a) at the fusion line, b) on the surface 1 mm from the fusion line, c) on the surface 10 mm from the fusion line, d) 20 mm from the fusion line

EBSD-based phase analysis revealed the predominant presence of $M_{23}C_6$ carbides precipitated along grain boundaries, together with σ -phase particles located at triple points of grain boundaries and at boundaries between austenitic grains and δ -ferrite. Cavities were observed almost exclusively in the vicinity of σ -phase at triple points, which promoted their growth and coalescence, thereby accelerating creep damage, **Figure 8**.

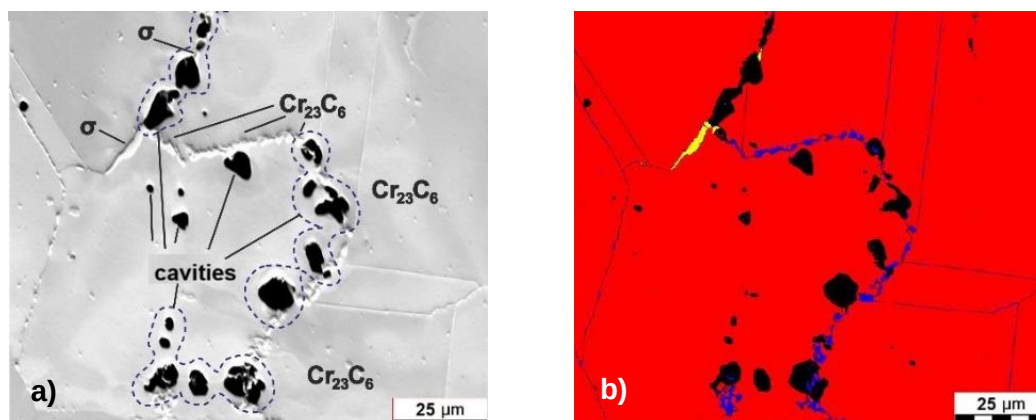


Figure 8 EBSD analysis of cavitation damage of HR3C steel in sample 3, a) - analysis of particles and cavities on grain boundaries, b) - phase map, red: γ -Fe, blue: $Cr_{23}C_6$, yellow: σ

5. CONCLUSION

Internal pressure creep tests showed that creep rupture is localized in the base material adjacent to the weld, but outside the HAZ. The dominant degradation mechanism was identified as intergranular creep damage, characterized by cavity formation and microcrack initiation at the outer surface. The presence of σ -phase along grain boundaries appears to further accelerate this damage process. The measured rupture times significantly exceeded those predicted from the mean standardized creep strength of HR3C steel, indicating that a straightforward direct comparison between burst tests and uniaxial tensile creep tests may not always provide equivalent results.

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