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Characterisation and simulation of the creep behaviour of Nicrofer 6025HT wire material at 650 °C

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ABSTRACT

Thermal efficiency of combined cycle power plants can be improved by increasing temperature and pressure in the steam turbine. Since typical power plant materials have presently reached their operation limit with higher steam temperature, the application of a new cooling system could reduce the material temperature to tolerable conditions. For this purpose, a new sandwich structure was developed comprising a woven wire mesh interlayer between two plane sheets. Cooling steam is fed into the interlayer where it can flow without severe losses. This sandwich structure is applied to the steam turbine casing as a wall cladding.

Due to the combination of constant overpressure of cooling steam and high temperature exposure of hot steam, the structures are stressed parallel and perpendicular to the intermediate layer primarily by creep loads. To simulate the creep behaviour via the finite element method the exact knowledge of the creep behaviour of the constituents, the wire and the sheet, is essential. Therefore, creep tests at 650 °C on wire material, manufactured from the nickel base alloy Nicrofer 6025HT, were carried out to determine constitutive equations. The creep behaviour was simulated on the basis of the concept of the internal backstress, which was implemented in an adequate user subroutine of the commercial FEM-software Abaqus.

1. Introduction

Within the release of the latest climate report the discussion about global warming gains in importance. Causing 68% of all CO_2 emissions, industry and power plants are requested by politics to react to the situation. In order to reduce the emission quantity of combined cycle power plants, it is essential to improve thermal efficiency. In case of modern steam turbines this improvement can be achieved by increasing steam temperature and pressure. Since typical power plant materials have presently reached their operation limit with higher steam temperature, the application of a new cooling system could reduce the material temperature to tolerable conditions. In the context of the collaborative research program SFB 561, a new sandwich structure (Fig. 1) was developed comprising a woven wire mesh interlayer between two plane sheets [1]. Cooling steam is fed into the interlayer where it can flow without severe losses [2,3]. Joining the constituents wire mesh and face sheets was achieved by capacitor discharge resistance welding. Compared with the conventional resistance welding process [4], this joining method is characterised by a very localised thermal effect on the weld spots of the wire mesh-sheet-joints. This sandwich structure is planned to be applied to the steam turbine casing as a wall cladding. Due to constant overpressure of cooling steam in combination with high temperature loads during operation, the structures are primarily subjected to creep deformation. To simulate the creep behaviour of the structure via the finite element method the exact knowledge of the creep behaviour of the constituents, the straight wire and the sheet is essential. In the context of this work creep tests at 650 °C were carried out on wire material, which was manufactured from the nickel base alloy Nicrofer 6025HT. Constitutive equations were derived from the test results and implemented in an adequate user subroutine of the commercial FEM-software Abaqus. On basis of the concept of the internal backstress in combination with a new empirical damage description the creep behaviour was simulated with good accuracy.

2. Investigated constituent material Nicrofer 6025HT

The material of the constituents wire and sheet is a high-carbon nickel–chromium–iron–alloy with alloying additions of titanium, zirconium, aluminium and yttrium. The nominal chemical composition is given in Table 1. Nicrofer 6025HT is characterised by great

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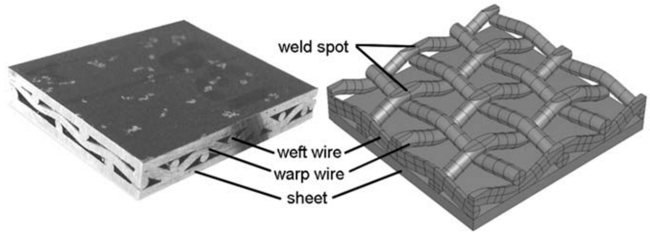

Fig. 1. Layout of the cooling structure and corresponding FEM model.

Table 1
Nominal chemical composition of Nicrofer 6025HT (%).

Ni	Cr	Fe	C	Al	Ti	Zr	Y
Rem.	24.0–26.0	8.0–11.0	0.15–0.25	1.8–2.4	0.1–0.2	0.01–0.10	0.05–0.12

high-temperature creep strength. The grain size of the microstructure can be established by different solution annealing temperatures [5]. Optimum properties concerning the creep behaviour were achieved by solution annealing the structures and the constituents at 1220 °C in a vacuum furnace for 1 h [6] and cooling in nitrogen with a cooling rate of approximately 10 K/min leading to a grain size greater than 70 μm. The wire material of the woven wire mesh is normally used as a filler metal for welding processes and was delivered in the cold drawn condition. Due to the fact that the mechanical high temperature behaviour of the whole structure was investigated in the as welded and in the heat treated condition, creep tests at 650 °C on wire material were carried out in the cold drawn and in the heat treated condition. Fig. 2 shows the corresponding creep test configuration.

3. Experimental results of creep tests at 650 °C

Fig. 3 represents the time-to-rupture-curves of Nicrofer 6025HT wire material in the as delivered and in the heat treated condition. Due to the manufacturing process of the wire the as delivered condition exhibits a very high dislocation density, which probably leads to higher creep strength than the heat treated condition in the range of great stresses. With increasing testing time the dislocation density seems to be reduced by the high temperature influence. Nicrofer 6025HT is strengthened by solid solution hardening and by precipitation of $Cr_{23}C_6$ carbides, which can be found on the grain boundaries and inside the grains. Due to the solution annealing process the average grain size of the heat treated material was increased. In comparison to the as delivered material this results in rising difference of creep strength with increasing testing time.

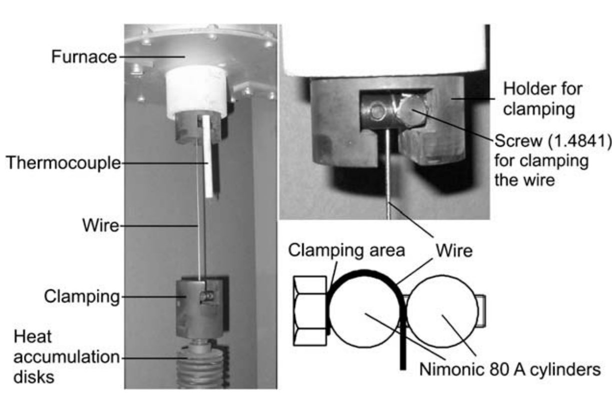

Fig. 2. Test configuration for creep tests on wire material.

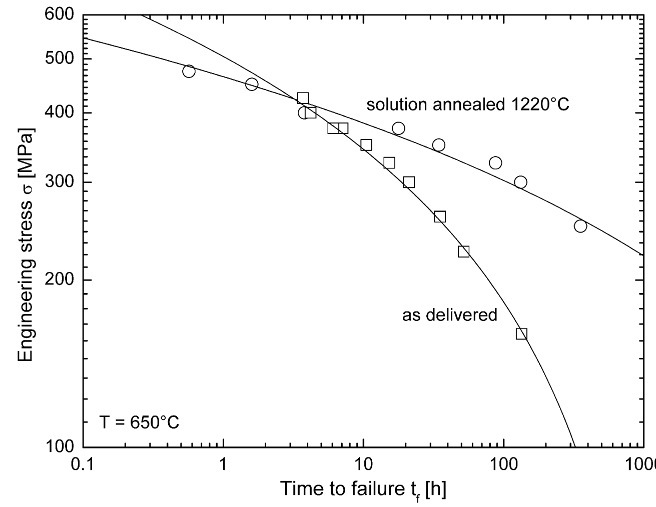

Fig. 3. Time-to-rupture-curves of Nicrofer 6025HT wire material in the as delivered and in the heat treated condition.

The dependency of the minimum creep rate on the applied stress (Fig. 4a) can be described for both conditions with good accuracy by the Soderberg relation [7]

$$(d\varepsilon/dt)_{\min} = A \cdot e^{\beta\sigma} \quad (1)$$

where $(d\varepsilon/dt)_{min}$ is the minimum creep rate, σ is the applied stress and A and β are constants. By coupling this relation with the Monkman–Grant relation [8]

$$t_f = B \cdot (d\varepsilon/dt)^{c}_{\min} \quad (2)$$

in Fig. 4(b), where t_f is the time to rupture and B and c are constants, the time-to-rupture-curves can be described by

$$\sigma = \frac{\log t_f - \log B - \log A \cdot c}{c \cdot \beta \cdot \log e} \quad (3)$$

The corresponding parameters are listed in Table 2.

4. Concept of the internal backstress

The creep behaviour of the wire material was described by the concept of the internal backstress [9–12], which is based on the Norton–Bailey power creep law

$$(d\varepsilon/dt)_{\min} = K \cdot (\sigma - \sigma_i)^n \cdot \mathrm{sgn}(\sigma - \sigma_i) \quad (4)$$

where σ is the applied stress, σ_i the internal backstress and K and n are constants. The model assumes that creep deformation proceeds due to an effective stress $(\sigma - \sigma_i)$, which results from the difference between the outer and the internal stress. The evolution of the internal backstress in the primary creep stage and the quasistationary value of the internal backstress in the secondary creep stage can be determined with so-called Strain-Transient-Dip-Tests. By reducing incrementally the applied outer stress to different remaining stresses, the internal backstress can be detected as the remaining stress, under which the momentary creep rate directly after stress reduction assumes the value zero. As an example Fig. 5(a) shows the result of such a Dip-Test for the as delivered condition in the secondary creep stage.

The beginning of strain evolution was described by a polynomial function and was afterwards derivated with respect to time. Fig. 5b shows the spontaneous creep rate after stress reduction as affected by the remaining stress. The quasistationary internal