A PREDICTIVE LAW TO ADDRESS CREEP DAMAGE IN WELDED JOINTS OF 316L(N) STAINLESS STEEL.

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ABSTRACT

The present work investigates creep damage in welded joints of 316 L(N) stainless steel using a local approach in order to define a predictive law for creep fracture.

The material of the study is a weld metal deposit aged for 2000 hours at 600°C. Elastic-plastic and creep behaviour were characterised using smooth specimens. Notched specimens were creep tested. Tests were interrupted prior to rupture. These specimens were then calculated by the finite element method.
Microstructural observations and EBSD complementary analysis reveals that creep cavities are preferentially located along the austenite grain boundaries. Measurement of intergranular damage on cross sections of notched specimens is conducted to obtain a predictive damage law, which could be used to estimate the lifetime of welded joints. Further mechanical tests on CT and tubular cracked specimens are performed to validate the creep law identified.

FORMER RESULTS AND METHODOLOGY

The present work investigates creep damage in welded joints of a 316 L(N) stainless steel using a local approach in order to define a predictive law for creep fracture. This paper is the continuation of the work presented in the last ECF12 [1] to which one shall report for more details on microstructure, ageing, creep phenomenon and creep behaviour characterisation.

The elaboration of the material was made through multi-bead deposition process. The composition of the filling metal is a 316L(N) type 19Cr-12Ni-2Mo stainless steel. Magnetic measurements showed that most of the ferrite phase disappeared after 1500 hours at 600°C [1]. In order to try and discorrelate creep behaviour and ageing, the material was heat-treated for 2000 hours at 600°C to stabilise the microstructure prior to mechanical testing. Based on the creep tests of two different geometries of notched specimens which differ in notch-root radius ρ (1 and 4 mm), the approach consists in studying the relevant local parameters responsible for creep cavitation. Through image analysis, quantitative measurements of damage were achieved in the cross-section of those specimens. In parallel, creep behaviour was identified using creep tests on smooth specimens. Constitutive equations were implemented in the CASTEM 2000 finite element code [2] and notched specimens creep state calculated, then correlated to damage quantification to propose a phenomenological law to predict damage occurrence. Based on critical value of creep damage D_c, an attempt is made to show how a crack initiates under mode I and mode II creep loading conditions.

ANALYSIS OF AGEING, BEHAVIOUR AND DAMAGE

Microstructural ageing

Similar studies of weld metal existed in the literature but conclusion was clear that precipitation process varied with the composition, even for minor elements [3,4]. Hence TEM samples were observed of material aged for 2000 hours and 10000 hours at 600°C. With the present composition and welding parameters [1], ageing process takes place in the ferrite which tends to disappear to the benefit of chromium carbides and σ-phase formation as shown in figure 1. Laves phases have also been identified, as well as secondary austenite. Chromium carbides of small size precipitate as well in the few γ–γ boundaries deprived of ferrite. Similar results for the characterisation of a weld metal can be found in detail in [5]. As far as the mechanical behaviour analysis is concerned, ageing and creep are intimately combined, even after a 2000 hours 600°C heat treatment as discussed later.

Constitutive equations

The first set of coefficients identified and reported in [1] failed in reproducing well the behaviour of notched specimens. A new identification was performed and the following coefficients were obtained with ε in % and σ in MPa:

primary creep: $\varepsilon = C_1 \sigma^{n_1} t^{C_2}$ n_1= 3.63 ; C_1=0.1999 10^{-9} ($MPa^{-n_1} s^{-C_2}$) ; C_2=0.3144

secondary creep: $\dot{\varepsilon} = C\sigma^n$ n= 11.47 ; C=0.413 10^{-29} ($MPa^{-n} s^{-1}$)

Tertiary creep stage was not modelled. Comparison between experiment and model for the notched specimens are to be based on a same strain basis. The new values for the parameters given here make no change to the results obtained on figure 3 of (1) relative to the distribution of maximum principal stress in the notched section of the axisymmetrical specimens. Stress is maximum at the centre of the 4-mm notch radius specimens when it tends to be closer to the notch tip for the 1-mm radius specimens. Damage could not be observed in the material at the end of the secondary creep stage. Some tests were interrupted after the onset of the tertiary stage in order to study creep damage micro-mechanisms.

Creep damage. Qualitative analysis

Creep cavitation in the weld metal is intergranular, as in the base metal [6]. Figure 2 presents a SEM photograph showing the formation of a real alignment of cavities of sub-microscopic size along a γ–γ grain boundary. Electron Back Scatter Diffraction (EBSD) analysis was used to characterise those boundaries from a crystallographic point of view. The light micrograph of figure 3a) shows the cross section of a crept notched specimen. The microstructural features have been revealed with oxalic acid, showing indiscriminately in dark grey colour ferrite, precipitates, grain boundaries and cavities. It has to be noticed that damage tends to be located at the centre of the notched part of the 4-mm notch radius specimens whereas it can be seen closer to the notch tip for the 1 mm notch radius ones.

Orientations of the austenite grains of this area were obtained using the EBSD automatic mapping technique (figure 3b). Each colour corresponds to a specific orientation. It is clear from this experiment that cavities, sometimes large enough here to be called micro-cracks, are located along the γ–γ grain boundaries. Furthermore, measurements of misorientation angles between grains on each side of the boundary [reported table 1] prove that damage is located at high angle boundaries.

DAMAGE LAW IDENTIFICATION

Piques [6] defined for the base metal an incremental damage law having the following expression (where Σ is the maximum principal stress and ε_{eq_cr} the equivalent creep strain):

$$dD = A. < \Sigma >^{\alpha} \ \varepsilon_{eq\_cr}^{\beta} .d\varepsilon_{eq\_cr}$$

It has been experimentally observed that damage in the weld metal was intergranular, as in the base metal, though microstructure and ageing are very different. The same approach was successfully applied by Chabaud [7] on simulated heat affected zone.

The parameters A, α and β were identified for the weld metal. Eight specimens (table 2) were used to identify the parameters. Those notched specimens were tested under various loads for creep tests interrupted at various stages. A good database was necessary, as it appears that, due to the heterogeneity of the microstructure, among the eight specimens the results obtained for two did not match the general trends. Technically, to identify the law, A, α and β coefficients were optimised to minimise the value of the difference between damage calculated using the law and measured damage, this being done on all the analysed area at the same time [8]. The result is:

$$dD = 4.10^{-14}. < \Sigma >^{6} \ \varepsilon_{eq\_cr}^{-0.8} .d\varepsilon_{eq\_cr}$$

The value of damage D is not here normalised to the total length of grain boundary, as did Chabaud [7] in order to get *D* in %, since grain boundaries are difficult to reveal metallographically on the weld metal. Given the results obtained on notched specimen for the value of *D*, a critical value D_c of about one hundred was defined for damage value beyond which a crack is ready to propagate. The exponent of 6 for Σ, large in comparison with the value of 2 identified for the base metal [6], is characteristic of a creep brittle material.

As the law was identified using creep-tensile tests, it appeared necessary to validate this law for other loading conditions and in particular in the case of multi-axial loading conditions.

VALIDATION AND DISCUSSION

Validation took place in two steps, the first in testing the critical value D_c using CT specimens, the second through an original mode II experiment on a notched tubular specimen.

CT creep tests

Three CT specimens were creep tested under various tensile loads at 600°C. the potential drop technique allowed to follow the initiation and propagation of the crack. For the lowest imposed load, the crack never began to propagate, while for higher loads, crack propagation started quickly. Calculations were performed of those tests in order to estimate the damage state at a characteristic distance of 300 µm from the crack tip using the damage law identified. Figure 4 shows a qualitatively good agreement between experiments and calculation, though another result would be of great value for an applied load a little higher than the lowest one in order to determine the threshold D_c more precisely.

Mode II tests

Tubular notched specimens were designed to evaluate the creep damage law on base metal. Details on this experiment have been given in [9]. The objective here is to test the damage law identified in mode I, under a different loading condition. Arrows on figure 5 schematically show the torque τ applied on the specimen. The creep test was conducted at 600°C under τ = 62 N.m and interrupted after 3500 hours. Metallographic work showed the propagation of a short crack from each tip of the notch. The local stress and strain fields at the notch tips were calculated, using a 2D simulation of a notched infinite plate. The results (figure 6) showed that damage location and crack direction were driven by the maximum principal stress, for the equivalent creep strain would enforce a crack in the axis of the notch when experimentally it was shown to grow at an angle of approximately 65° from the axis. The model (figure 5) gave a good prediction of the location and direction of the damage. The calculated value for the damage confirmed the threshold D_c of approximately 100. Three-dimensional finite element simulation confirmed that the crack propagated in the direction where the calculated damage was maximal.

Discussion

Validation tests showed that the damage law identified on axisymmetric notched specimens gave good predictions for creep damage occurrence under various loading conditions. A threshold of damage of D_c = 100 seems to be a good criterion for crack propagation. Two additional points are to be discussed in more detail, the tertiary creep stage and the impact of the heterogeneity of the material on damage modelling.

The weld metal shows an important tertiary stage of creep (accounting for more than a half of the life of the specimens). In the present study, this tertiary creep has not been modelled since its origin appeared unclear. In [1], the hypothesis was made that it originated from a structural factor. In the present study, further calculations showed that this was not necessarily the case. Cavitation is not a good explanation either since it has been observed only far after the onset of the tertiary stage. Furthermore, TEM studies showed that the microstructural parameters of the material precipitation and dislocations density constantly evolve at 600°C. Such a material effect could possibly explain the constant acceleration of creep strain under constant load.

Our modelling approach is based on the assumption of a continuous, isotropic and homogeneous material. Experiments has shown that the material, heterogeneous in its microstructure, sometimes showed rupture times extremely reduced compared to the one expected, due to the presence of a defect (void mainly but eventually a particularly oriented grain) in the material. Those results have been disregarded and the damage law identified on the tests that followed the usual behaviour of the material. This enabled to obtain a reliable model to predict damage state in axisymmetric specimens as well as in cracked specimens. Nevertheless, defects are present in actual structures. One element to oppose to it is a size effect, which dictated that our specimen would perish, while a larger size structure would bear the defect. Another proposal, which could be considered in future work, would be to use a polycrystalline approach. At least a statistical parameter introducing in the model an orientation distribution effect could be considered for which experimental data would consist in the texture results obtained using neutron diffusion and reported in [10].

At present, reliable results were already obtained, showing that a local approach was transferable to the weld metal and allowing to have a tool for joint design and life prediction in the creep range.

CONCLUSION

(1) A fit of the creep behaviour was obtained, validated by the good description of experimental curves obtained using either smooth or axisymmetric notched specimens.
(2) Microstructural studies were made to identify the precipitation process in the material. At 600°C, ferrite transforms into chromium carbides and σ phase mainly. This has been suggested to play a role in the tertiary creep behaviour.
(3) Damage has been experimentally shown to be intergranular and located at high-angle γ-grain boundaries.
(4) An incremental damage law based on the evolution of maximum principal stress and equivalent creep strain was identified. This law constitutes a tool for lifetime assessment in the weld metal under creep conditions.
(5) Mechanical tests on CT specimens and mode II notched tubular specimen allowed validating the law under various stress states. A critical value D_c was defined and tested. Mode II tests allowed to study geometrically the respective influences of maximum principal stress and equivalent creep strain on damage occurrence, showing that the maximum principal stress was the driving force.

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REFERENCES

1. Bouche, G., Allais, L., Lezaud, V., Piques, R. and Pineau, A. (1998). In: *European Conference on Fracture 12: Fracture from defects*, pp. 357-362, Brown, M.W., De los Rios, E.R. and Miller, K.J. (Eds). Emas, England.
2. CASTEM 2000 (1995), User Manual, *Internal Report CEA/SEMT*, France.
3. Thomas, R.G. and Yapp, D. (1978) *Welding Journal Research Supplement*, 57, **12**, pp. 361-366.
4. Smith, J.J. and Farrar, R.A. (1993) *International Materials Reviews*, 38, **1**, pp. 25-51.
5. Finlan, G.T. (1987). Ph.D. Thesis, University of Bristol, England.
6. Piques, R. (1989). Ph.D. Thesis, Ecole des Mines de Paris, France.
7. Chabaud-Reytier, M. (1999). Ph.D. Thesis, Ecole des Mines de Paris, France.
8. Bouche, G. (2000). Ph.D. Thesis, Ecole des Mines de Paris, France.
9. Poquillon, D., Cabrillat, M.T. and Pineau, A. (1999) *Mat. at High Temperatures*, 16, **2**, pp. 99-107.
10. Bouche, G., Béchade, J.L., Mathon, M.H., Allais, L., Gourgues, A.F. and Nazé, L. (2000*). Journal of Nuclear Materials*, 277, **1**, pp. 91-98.

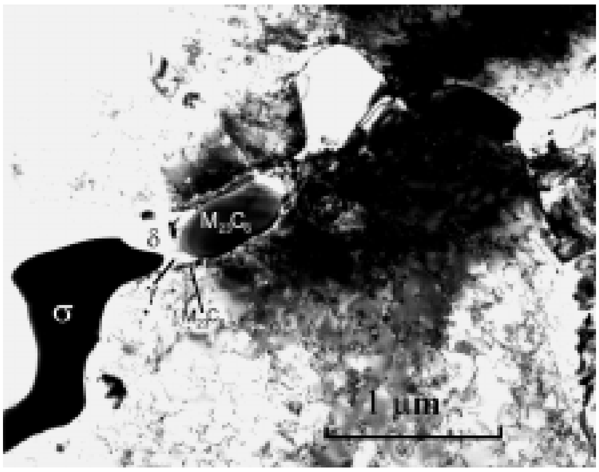


Figure 1: σ phase, $M_{23}C_6$ and secondary γ-austenite. Material aged for 2000 h at 600°C

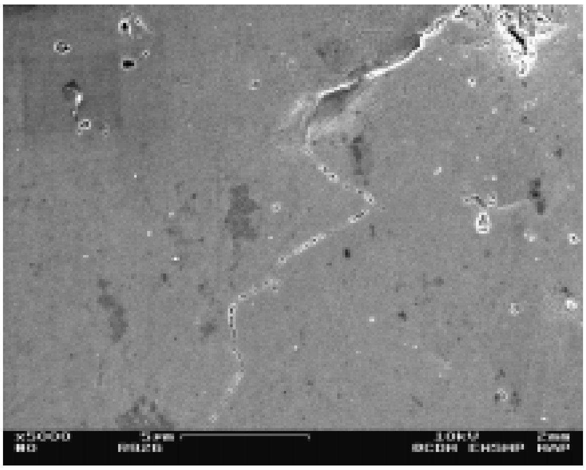


Figure 2: Creep cavitation at a grain boundary observed on a longitudinal section of a notched specimen

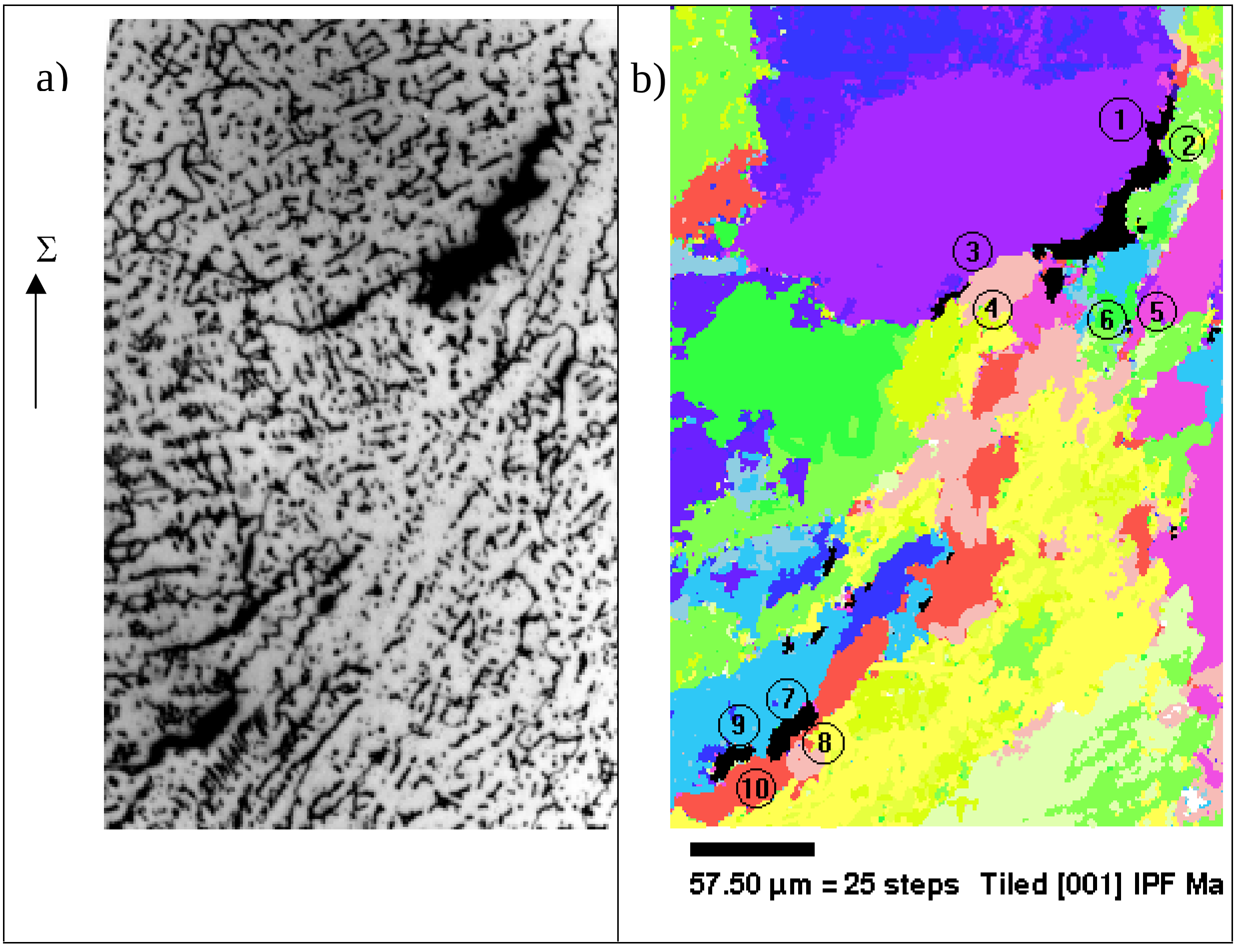


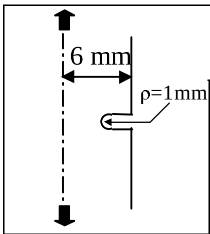
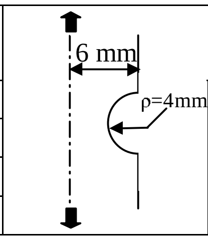
Figure 3: EBSD study of a damaged area

a) Light micrograph of the damaged analysed zone
b) EBSD map

TABLE 1
MISORIENTATION ANGLES BETWEEN ADJACENT AUSTENITIC GRAINS

Grain 1	**Purple 1**	**Purple 3**	**Pink 5**	**Blue 7**	**Blue 9**
Grain 2	Green 2	Green 4	Green 6	Red 8	Orange 10
Rotation Angle	45.8°	37°	29°	57°	58.4°

TABLE 2
SPECIMENS AND NOMINAL STRESS USED TO IDENTIFY THE DAMAGE LAW

	FLE 1-6	Nominal stress		FLE 4-6	Nominal stress
	n°103	300 MPa		n°106	250 MPa
	n° 32	310 MPa		n°117	260 MPa
	n°116	310 MPa		n° 30	270 MPa
	n° 33	320 MPa		n° 29	270 MPa

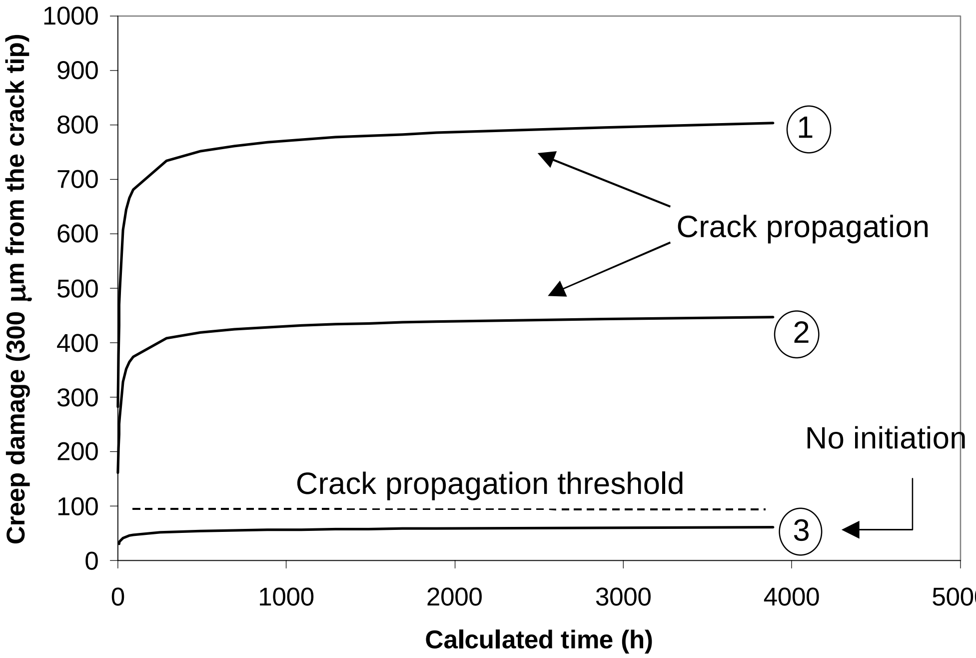


Figure 4: Level of creep damage at 300 µm from the tip of the crack of three CT specimens creep tested under various loads. Metallographic observations showed that the threshold identified was respected

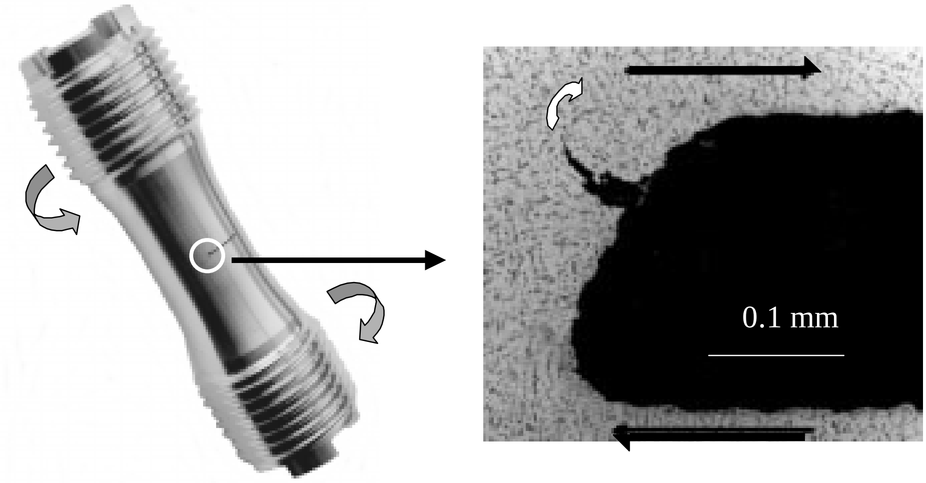


Figure 5: Crack propagation observed on the outer surface at the tip of the notch
Mode II test at 600°C and τ = 62 N.m

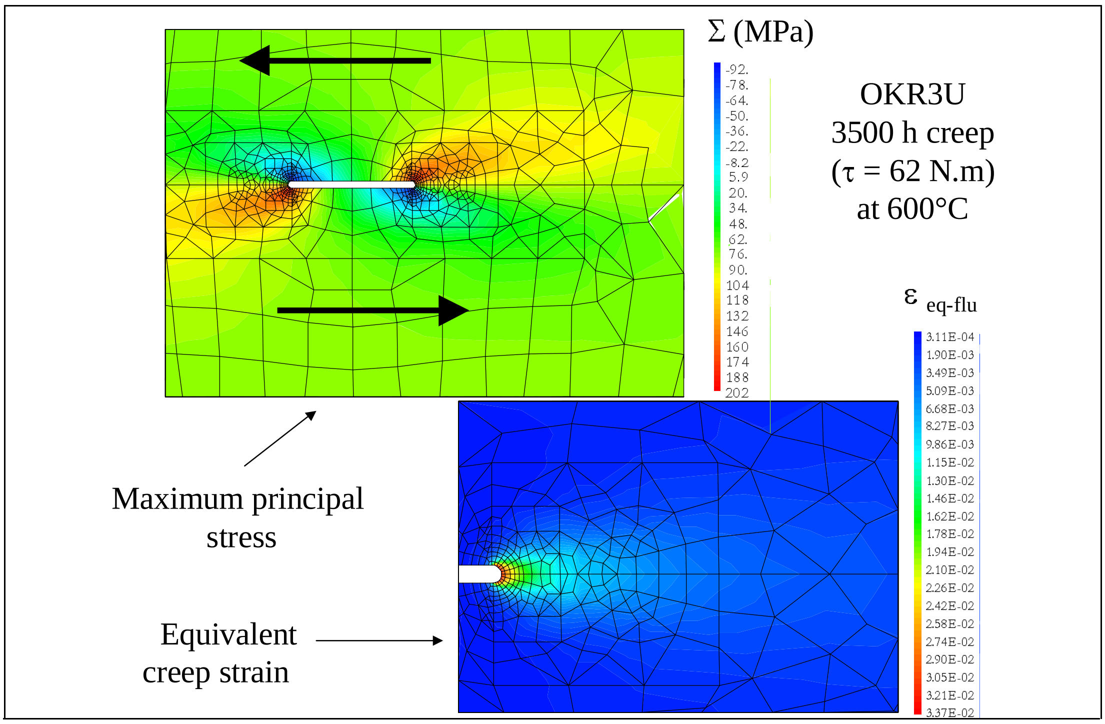


Figure 6: Notched plate under τ = 62 N.m at 600°C for t = 3500 h
Maps of the maximum principal stress and equivalent creep strain