**Load Partitioning between Ferrite/Martensite and Dispersed Nanoparticles
of a 9Cr Ferritic/Martensitic (F/M) ODS Steel at High Temperatures**

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Abstract:

In this study, a high-energy synchrotron radiation X-ray technique was used to investigate the tensile deformation processes of a 9Cr-ODS Ferritic/Martensitic (F/M) steel at different temperatures. Two minor phases within the 9Cr-ODS F/M steel matrix were identified as $\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN by the high-energy X-ray diffraction, and confirmed by the analysis using energy dispersive X-ray spectroscopy (EDS) of scanning transmission electron microscope (STEM). The lattice strains of the matrix and particles were measured through the entire tensile deformation process. During the tensile tests, the lattice strains of the ferrite/martensite and the particles (TiN and $\text{Y}_2\text{Ti}_2\text{O}_7$) showed a strong temperature dependence, decreasing with increasing temperature. Analysis of the internal stress at three temperatures showed that the load

partitioning between the ferrite/martensite and the particles (TiN and $\text{Y}_2\text{Ti}_2\text{O}_7$) was initiated during sample yielding and reached to a peak during sample necking. At three studied temperatures, the internal stress of minor phases ($\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN) was about 2 times that of F/M matrix at yielding position, while the internal stress of $\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN reached about 4.5-6 times and 3-3.5 times that of the F/M matrix at necking position, respectively. It indicates that the strengthening of the matrix is due to minor phases ($\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN), especially $\text{Y}_2\text{Ti}_2\text{O}_7$ particles. Although the internal stresses of all phases decreased with increasing temperature from RT to 600 °C, the ratio of internal stresses of each phases at necking position stayed in a stable range (internal stresses of $\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN were about 4.5-6 times and about 3-3.5 times of that of F/M matrix, respectively). The difference between internal stress of the F/M matrix and the applied stress at 600 °C is slightly lower than those at RT and 300 °C, indicating that the nanoparticles still have good strengthening effect at 600 °C.

Keywords: Synchrotron; Tensile deformation; Nanoscale particles; Microstructure

1. Introduction

Oxide dispersion strengthened (ODS) ferritic/martensitic (F/M) steels are promising candidate structural materials for fusion reactors and Gen IV fission reactors [1]. The well-distributed nanoscale particles, such as Y_2O_3 , Y_2TiO_5 , and $\text{Y}_2\text{Ti}_2\text{O}_7$, in the steels are critical to achieving excellent irradiation resistance, high-temperature strength, and creep properties [2, 3, 4]. These nanoparticles are

effective obstacles for dislocation movement, which provides additional strengthening of the F/M matrix, especially at high temperatures, when compared with reduced activation ferritic/martensitic (RAFM) steels [5]. To study the nature of the nanoscale particles, multiple advanced methods including small-angle neutron scattering (SANS), atom probe tomography (APT), and high-resolution transmission electron microscopy (HRTEM) have been applied to investigate the number density, size distribution, and orientation relationship of these nanoscale particles [6, 7, 8, 9, 10, 11]. The high-energy synchrotron X-ray was recently employed to study the dynamic behavior of nanoparticles during deformation. Mo et al. [12] and Miao et al. [13] have respectively studied 9Cr F/M ODS alloy and 304 ODS alloy using high-energy synchrotron X-ray. However, these tests were conducted at room temperature. As the deformation mechanisms at low temperatures are considerably different from the one at high temperatures, the loading behavior of both metallic matrix and nanoscale particles in the ODS alloys are still unclear at elevated temperatures.

In this study, we applied a high-energy synchrotron X-ray technique to study the response of nanoscale particles to externally applied stresses at high temperatures. This technique has been applied to many different materials systems, including model F/M steels [14, 15], stainless steels [16, 17], ultrahigh-carbon steel [18], Zirconium alloys [19], metallic glasses [20], composite materials [18], and organic materials, such as bones and dentin [21, 22, 23, 24]. The evolution of lattice strains throughout the entire tensile deformation processes of a 9Cr-ODS F/M steel at 300 °C and 600 °C was investigated. The dispersed nanoscale particles were further studied using

transmission electron microscope (TEM) and scanning transmission electron microscope (STEM).

2. Experimental procedure

The starting materials with a nominal composition of Fe-9Cr-0.06C-1.5W-0.18Si-0.5Ti-0.35Y₂O₃ were mechanical alloyed using a planetary ball mill in a pure argon atmosphere at 300 rpm with a ball-to-powder mass ratio of 5:1 for 30 h. The ball-milled powders were then consolidated by hot isostatic pressing (HIP) under a pressure of 110 MPa at 1150 °C for 2 hours. The hot working included two stages with parameters set according to a processing map in previous work [25]. The as-HIPed sample was forged at 1150 °C with a forging ratio of 3:1 and was then hot rolled in three stages with reduction ratio of 30%, 20% and 10%, respectively [26]. Then, the as-rolled sample was quenched in water and tempered at 750 °C to develop the F/M phases.

The in-situ synchrotron tensile tests were conducted at the 1-ID beamline at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL). The as-tempered sample was cut into tensile specimens by electrical discharge machining (EDM) with a gauge section of 1.49 mm × 0.76 mm × 7.60 mm (width × thickness × length). Uniaxial tensile load was applied to the specimens until failure using an MTS closed-loop servo-hydraulic test frame (model 858) [27, 20]. The tensile tests were conducted at three different temperatures: room temperature (RT), 300 °C, and 600 °C. The X-ray diffraction analysis was performed by using a monochromatic 70 keV

synchrotron beam with a $300\text{ }\mu\text{m} \times 300\text{ }\mu\text{m}$ cross-section. The "Hydra" detector array, which is composed of four identical GE angio type 2D detectors, was utilized to collect the diffraction information. Nine positions along the axial direction were scanned for each stress/strain state so as to capture both necking and non-necking regions of the tested samples. Figure 1 depicts the experimental set-up.

The 3 mm TEM discs with a thickness of $100\text{ }\mu\text{m}$ were prepared from the as-tempered 9Cr F/M ODS steel, and then electropolished using a Struers Tenupol-5 with a solution containing 5 v% perchloric acid and 95 v% methanol at $-14\text{ }^{\circ}\text{C}$. The 3 mm TEM discs were then examined by a JEOL 2010 LaB6 TEM. The sample for STEM was fabricated by focused ion beam (FIB), and was examined by EDS on a JEOL 2010F EF-FEG TEM.

3. Results and discussion

3.1 Microstructure and phases identification

Figure 2 shows a typical example of synchrotron X-ray diffraction line profile of the 9Cr F/M ODS specimen at pre-loading and necking position conditions at RT. Two minor phases were identified as: 1) The typical NaCl structure TiN with a reflection (111) and 2) pyrochlore structure $\text{Y}_2\text{Ti}_2\text{O}_7$ with a reflection (222). From the pre-loading to the necking of the sample, the lattice constants of metallic matrix and minor phases increase with deformation. Detailed discussion of lattice constants development will be given in the next section. Figure 3 (a) shows the bright field TEM image of the as-tempered 9Cr F/M ODS steel. The grains were elongated in the rolling direction with a mean length ($0.7\text{ }\mu\text{m}$) to mean width ($0.24\text{ }\mu\text{m}$) aspect ratio of

2.91. The sub-grains and dislocations structures indicate the existence of internal residuals stresses within the alloy. In Figure 3(b), the high number density nanoscale particles are distributed uniformly in a grain. The mean size of these nanoscale particles is less than 10 nm. The other type of particles observed in the alloy is TiN, whose size is in the range of hundreds of nanometers, much larger than the nanoscale oxide particles. Both types of particles (TiN and $Y_2Ti_2O_7$ with a atomic ratio of Y/Ti ≈ 1) were confirmed by EDS, as shown in Figure 3 (c) and 3 (d).

3.2 Macroscopic stress-strain and load partitioning

Figure 4 shows the engineering stress-engineering strain curves for 9Cr F/M ODS steel tested at RT, 300 °C, and 600 °C. The material's yield strength (YS) at these three temperatures was 845 MPa, 665 MPa, and 216 MPa, respectively, and ultimate tensile strength (UTS) was 915 MPa ($\epsilon_{UTS} = 0.061$), 760 MPa ($\epsilon_{UTS} = 0.058$), and 268 MPa ($\epsilon_{UTS} = 0.051$), respectively. The total elongation dropped from 0.16 at RT to 0.117 at 300 °C, and increased to 0.245 at 600 °C, which agreed well with the results of the ODS EUROFER97 alloy reported in ref. [28]. Although the tensile tests were stopped periodically in order to measure responses at different axial position at the same load, the stress-strain curves were smooth with the exception of the curve of 300°C. The serrations in the stress-strain diagram at 300 °C were ascribed to dynamic strain aging (DSA) [29, 30]. The DSA in an RAFM steel has been reported at the intermediate temperature around 650 K, similar temperature to the current study [31]. The serrations were accompanied by an increase in work-hardening and a loss of ductility.

The lattice strain development in the function of the applied stresses was shown in Figure 5. (Noted that the plastic deformation region from necking to failure were not included in the figure) The representative reflection for each phases were chosen as: (211) reflection for F/M matrix; (222) reflection for $Y_2Ti_2O_7$; and (111) reflection for TiN. Details on the selection of representative plane reflection for each phase have been discussed in previous work [12]. The lattice strain ε_{hkl} was determined from the d-spacing by Eq. (1),

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{hkl}^0}{d_{hkl}^0} \quad (1)$$

where d_{hkl} and d_{hkl}^0 are the d-spacings before and after deformation, respectively [18, 32]. The lattice strain development of the F/M matrix can be divided into three stages [14]: In the elastic region, the lattice strains have a linear relationship with applied stress; Then, in the yielding region, the lattice strain in the loading direction begins to show slightly compressive shifts with increasing applied stress, indicating the onset of load partitioning; Finally, plastic deformation occurs, and dislocations accumulate in the sample. Young et al. have showed that both Young's modulus E and Poisson's ratio ν of ferrite and cementite can be interpreted from the slopes of ε_{11} and ε_{22} [18]. Following this method, values of E and ν of F/M matrix at different temperatures were attained and shown in Table 1. The values for the $Y_2Ti_2O_7$ (222) reflection and bulk $Y_2Ti_2O_7$, and the values for TiN (111) reflection and bulk TiN at three temperatures were calculated by Hooke's Law [33] using elastic constants (C_{11} , C_{12} , and C_{44}) from references [34, 35]. The calculated Young's modulus and Poisson's ratio for bulk $Y_2Ti_2O_7$ at RT are 260 GPa and 0.25, respectively, which match well

with the experimental values of 253-265 GPa (0.25-0.27) in ref. [36]. The values (397 GPa (0.35)) of TiN (222) reflection at RT are similar to the results (407 GPa (0.32)) that also base on first principal from Zhang et al. [37] for TiN (222) reflection. And the values (451 GPa (0.24)) for bulk TiN match with 469 GPa (0.25) [38], 427 GPa (0.19) [39], 440 GPa [40]. These indicate that the elastic constants at RT in ref. [34,35] are reliable. At elevated temperatures, both the experimental measurement and modeling prediction of the elastic tensors of these precipitate phases become challenging. As a result, there exist very limited data in literature. In that case, we just use the existing data. The elastic constants for $\text{Y}_2\text{Ti}_2\text{O}_7$ in ref. [34] were fitted well by Varshini model, and the elastic constants for TiN in ref. [35] have normal temperature dependence. Therefore, at least the qualitative comparisons based on these values (Table 1) are reliable.

Figure 6 shows the lattice strain vs. true strain curves for the F/M matrix and the two minor phases (TiN and $\text{Y}_2\text{Ti}_2\text{O}_7$) in the 9Cr F/M ODS steel tested at RT, 300 °C and 600 °C. For all studied temperatures, the lattice strain developments of the matrix and two types of particles are very similar in the elastic region, showing a typical linear relation with the macroscopic strain. After a short range of elastic deformation, the F/M matrix then begins to yield, with plastic deformation preferentially occurring in some grains, while the TiN and $\text{Y}_2\text{Ti}_2\text{O}_7$ particles are still undergoing elastic deformation. The load transfer begins with the elastic-plastic mismatch of the lattice strain between the matrix and the particles around yield point where dislocation movement is activated. Then, the lattice strain continues to increase, until reaching a

peak value when the sample starts to neck. In order to compare the temperature dependence of lattice strain, the maximum lattice strain of each phase at RT, 300 °C and 600 °C are shown in Figure 7. The maximum lattice strain (at necking position) of the $Y_2Ti_2O_7$ decreased 86% from 1.758×10^{-2} (RT) to 2.53×10^{-3} (600 °C), while that of TiN decreased 87% from 7.64×10^{-3} (RT) to 9.79×10^{-4} (600 °C), and that of matrix decreased 85% from 4×10^{-3} (RT) to 5.96×10^{-4} (600 °C). Although the percentage decreases of the lattice strains from RT to 600 °C of the three phases are nearly identical, the maximum lattice strain of the TiN particles is roughly equal to that of matrix at 600 °C, while the maximum lattice strain of $Y_2Ti_2O_7$ particles is much larger than that of TiN from RT to 600 °C, which demonstrates the strong size effect on the particles loading capacities.

3.3 Internal stress

In order to quantify the strengthening effect of different phases at different temperatures, the equivalent von Mises stress σ for a selected plane of each phase was calculated by following [41, 18]:

$$\sigma = \sqrt{(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2} \quad (2)$$

In which, σ_{11} is the principal axial stress, and σ_{22} and σ_{33} are the principal transverse stress, σ_{22} equals to σ_{33} due to the use of flat-plate specimens. The stresses σ_{11} , σ_{22} , and σ_{33} were calculated by Eq. (3) and Eq. (4), respectively.

$$\sigma_{11} = \frac{E}{1+\nu} \epsilon_{11} + \frac{\nu E}{(1+\nu)(1-2\nu)} (\epsilon_{11} + \epsilon_{22} + \epsilon_{33}) \quad (3)$$

$$\sigma_{22} = \sigma_{33} = \frac{E}{1+\nu} \varepsilon_{22} + \frac{\nu E}{(1+\nu)(1-2\nu)} (\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}) \quad (4)$$

, where E is Young's modulus, and ν is Poisson's ratio of the phases. (Table 1)

The internal stress σ of each phases in the entire tensile deformation at RT, 300 °C, and 600 °C is calculated based on the Von Mises criterion in eq. (2) using the parameters given in Table 1, and is shown in Figure 8. It can be seen that the internal stresses of each phases start developing in considerably different amplitudes at yielding point, and all reach maxima when sample's necking at these three temperatures. The macroscopic true stress and internal stresses of each phase at both yielding point and necking position are shown in Table 2. At yielding point, the internal stresses of $\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN are about 1.4 GPa, twice of that of F/M matrix at RT, and about 200 MPa, also twice of that of F/M matrix at 600 °C, respectively. When sample's necking, the internal stresses of $\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN reach maxima of 4.8 GPa and 3 GPa, about 6 times and 3.5 times that of the matrix at RT, respectively. At 300 °C, the maximum internal stress of $\text{Y}_2\text{Ti}_2\text{O}_7$, TiN, and F/M matrix are 2.8 GPa, 2 GPa, and 610 MPa, respectively. With increasing temperature to 600 °C, the internal stress of $\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN decreased to about 570 MPa and 370 MPa, while that of the matrix dropped to about 135 MPa. Although the internal stresses of all phases decrease with increasing temperature from RT to 600 °C, the ratio of internal stresses of each phases always stay in a stable range (internal stresses of $\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN are about 4.5-6 times and about 3-3.5 times of that of F/M matrix, respectively). And at this range of temperatures, the internal stresses of minor phases ($\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN) are

about twice that of F/M matrix at yielding point, while the internal stress of $\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN reach about 4.5-6 times and 3-3.5 times that of the F/M matrix when sample's necking, respectively. This implies that the strengthening of the matrix is due to minor phases ($\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN), especially $\text{Y}_2\text{Ti}_2\text{O}_7$ particles. Comparing the applied stress with internal stresses of different phases, it can be seen that the applied stress is always larger than internal stress of F/M matrix, but smaller than those of minor phases from sample yielding to necking at these three temperatures. In order to compare the strengthening effect of minor phases at different temperatures, the internal stress of the F/M matrix was compared with the applied stress, the difference between internal stress of the F/M matrix and the applied stress were also presented in Table 2. The values at yielding point are 145 MPa (RT), 159 MPa (300 °C), and 115 MPa (600 °C), respectively. The values at necking position are 168 MPa (RT), 192 MPa (300 °C), and 146 MPa (600 °C), respectively. The values at 600 °C are slightly lower than those at RT and 300 °C, This indicates that the nanoparticles still have good strengthening effect at 600 °C.

It is well known that the exceptional mechanical properties of ODS steels have been ascribed to the dispersed nanoscale particles (Orowan strengthening) and the fine grains (Hall-Petch strengthening). Orowan bowing of dislocations between particles is an accepted mechanism for low temperature deformation [42], and Orowan looping predominates up to 700 °C, accounting for about 80% of the total looped and attached dislocations in MA754 [43]. The RT to 600°C testing results of 9Cr F/M ODS steel show that, at RT, the dislocations are pinned by particles and bow

outwards to form dislocation loops around the particles, which cause the effective size of the particles to increase. As deformation increases, the particles bear larger and larger stresses, which induce larger lattice strains of the particles. With the increasing temperature, screw dislocations cross slip and edge dislocations climbing are activated. Thus, the dislocations can move easier under stress at high temperatures. Therefore, the lattice strains of both particles and F/M matrix decrease with increasing temperature. But as the percentage decreases in the lattice strains of each of the three phases decrease from RT to 600 °C are nearly identical and the ratio of internal stress of each phases at necking position stays in a stable range, the nanoscale particles always play main role for strengthening F/M matrix from RT to 600 °C.

4. Conclusions

An application of high-energy synchrotron X-ray diffraction for the study of 9Cr ODS steel was presented. With tensile loading and in-situ X-ray exposure, the lattice strain development was clarified. Lattice strains of the ferrite/martensite and the particles (TiN and $Y_2Ti_2O_7$) decreased with increasing temperature, showing a strong temperature dependence. Analysis of the internal stress showed that the load partitioning between the ferrite/martensite and the particles (TiN and $Y_2Ti_2O_7$) initiated during sample yielding and reached maxima after necking at three temperatures. At yielding point, the internal stresses of $Y_2Ti_2O_7$ and TiN are about 1.4 GPa, twice of that of F/M matrix at RT, and about 200 MPa, also twice of that of F/M matrix at 600 °C, respectively. When sample's necking, the internal stresses of $Y_2Ti_2O_7$ and TiN reach maxima of 4.8 GPa and 3 GPa, 6 times and 3.5 times that of

the matrix at RT, respectively. With increasing temperature to 600 °C, the internal stress of $\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN decreased to about 570 MPa and 370 MPa, while that of the matrix dropped to about 135 MPa. Although the internal stresses of all phases decrease with increasing temperature from RT to 600 °C, the ratio of internal stresses of each phases at necking position stays in a stable range (internal stresses of $\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN are about 4.5-6 times and about 3-3.5 times of that of F/M matrix, respectively). And at this range of temperatures, the internal stresses of minor phases ($\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN) are about 2 times that of F/M matrix at yielding point, while the internal stress of $\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN reach about 4.5-6 times and 3-3.5 times that of the F/M matrix when sample's necking, respectively. It indicates that the strengthening of the matrix is due to minor phases ($\text{Y}_2\text{Ti}_2\text{O}_7$ and TiN), especially $\text{Y}_2\text{Ti}_2\text{O}_7$ particles. The difference between internal stress of the F/M matrix and the applied stress at 600 °C is slightly lower than those at RT and 300 °C, indicating that the nanoparticles still have good strengthening effect at 600 °C.

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Figure(s)

Figure 1: Experimental set-up of the tensile test with in-situ synchrotron X-ray diffraction.

Figure 2: Synchrotron X-ray diffraction line profile of the 9Cr F/M ODS specimen at RT; (F/M matrix phases, along with two minor phases, TiN and Y₂Ti₂O₇, were recognized.)

Figure 3 (a)

Figure 3: (a) and (b): The bright field image of TEM of the as-tempered 9Cr F/M ODS steel; (c) The STEM-EDS analysis on large particle; (d) The STEM-EDS analysis on nanoscale particles.

Figure 3 (b)

Figure 3: (a) and (b): The bright field image of TEM of the as-tempered 9Cr F/M ODS steel; (c) The STEM-EDS analysis on large particle; (d) The STEM-EDS analysis on nanoscale particles.

Figure 3 (c)

Figure 3: (a) and (b): The bright field image of TEM of the as-tempered 9Cr F/M ODS steel; (c) The STEM-EDS analysis on large particle; (d) The STEM-EDS analysis on nanoscale particles.

Figure 3 (d)

Figure 3: (a) and (b): The bright field image of TEM of the as-tempered 9Cr F/M ODS steel; (c) The STEM-EDS analysis on large particle; (d) The STEM-EDS analysis on nanoscale particles.

Figure 4: Engineering stress-engineering strain curves for the 9Cr F/M steel at RT, 300 °C, and 600 °C.

Figure 5: Applied stress vs. lattice strain for all phases (F/M matrix (211) reflection, $Y_2Ti_2O_7$ (222) reflection, and TiN (111) reflection) in the 9Cr F/M ODS steel at 300 °C. ϵ_{22} and ϵ_{11} , are the lattice strains perpendicular and parallel to the tensile loading direction, respectively

Figure 6 (a)

Figure 6: Lattice strain vs. true strain for all phases (F/M matrix (211) reflection, $Y_2Ti_2O_7$ (222) reflection, and TiN (111) reflection) in the 9Cr ODS steel at (a) RT; (b) 300 °C; (c) 600 °C.

Figure 6 (b)

Figure 6: Lattice strain vs. true strain for all phases (F/M matrix (211) reflection, $Y_2Ti_2O_7$ (222) reflection, and TiN (111) reflection) in the 9Cr ODS steel at (a) RT; (b) 300 °C; (c) 600 °C.

Figure 6 (c)

Figure 6: Lattice strain vs. true strain for all phases (F/M matrix (211) reflection, $Y_2Ti_2O_7$ (222) reflection, and TiN (111) reflection) in the 9Cr ODS steel at (a) RT; (b) 300 °C; (c) 600 °C.

Figure 7: The lattice strain at necking position at room temperature, 300 °C, and 600 °C.

Figure 8 (a)

Figure 8: internal stress vs. true strain for all phases (F/M matrix (211) reflection, Y₂Ti₂O₇ (222) reflection, and TiN (111) reflection) in the 9Cr F/M ODS steel at (a) RT; (b) 300 °C; (c) 600 °C.

Figure 8 (b)

Figure 8: internal stress vs. true strain for all phases (F/M matrix (211) reflection, $Y_2Ti_2O_7$ (222) reflection, and TiN (111) reflection) in the 9Cr F/M ODS steel at (a) RT; (b) 300 °C; (c) 600 °C.

Figure 8 (c)

Figure 8: internal stress vs. true strain for all phases (F/M matrix (211) reflection, $\text{Y}_2\text{Ti}_2\text{O}_7$ (222) reflection, and TiN (111) reflection) in the 9Cr F/M ODS steel at (a) RT; (b) 300 °C; (c) 600 °C.

Table 1: The Young's modulus and Poisson's ratio of all observed phases (based on F/M (211) reflection, $\text{Y}_2\text{Ti}_2\text{O}_7$ (222) reflection [34], and TiN (111) reflection [35]).

Phase	Elastic constant (E, GPa & Poisson's ratio (ν))	RT	300 °C	600 °C
Matrix F/M (211)	E	200	196	190
	ν	0.29	0.33	0.34
TiN (111)	E	397	386	373
	ν	0.35	0.35	0.35
$\text{Y}_2\text{Ti}_2\text{O}_7$ (222)	E	245	227	206
	ν	0.39	0.41	0.42

Table 2: The applied stress and internal stress of all phases (F/M matrix, $\text{Y}_2\text{Ti}_2\text{O}_7$, and TiN) in the 9Cr F/M ODS steel at RT, 300 °C, and 600 °C.

Temperature	Position	Applied stress (MPa)	F/M matrix (MPa)	TiN (MPa)	$\text{Y}_2\text{Ti}_2\text{O}_7$ (MPa)	Difference (MPa)
RT	Yielding	845	700	1382	1432	145
	Necking	986	818	2994	4784	168
300 °C	Yielding	665	506	1030	1070	159
	Necking	804	612	2073	2856	192
600 °C	Yielding	216	101	193	203	115
	Necking	281	135	371	573	146