Constitutive equations of structural steel S460 at high temperatures

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ABSTRACT: The knowledge of the stress-strain relationships of structural steel at elevated temperatures is essential for the assessment of the load-carrying capacity of steel structures in case of fire. In the Eurocode 3 Part 1-2 (2006), constitutive equations are given for temperatures up to 1200 °C. They are uniform for steel grades between S235 and S460 and are based on numerous test results predominantly obtained on steel grade S235. For the high strength fine-grained structural steel S460 only very few and widespread test results exist. Especially the creep behaviour at high temperatures has not yet been analysed for this steel type. A current research project comprises transient state tests for numerous commercial fine-grained S460 steels and allows therefore a more precise determination of the stress-strain relationships at high temperatures. Especially the influences of the delivery condition (normalized rolled or thermomechanical rolled) and the chemical composition focussing on certain alloying elements are investigated. Consequences for the fire design of steel structures made of S460 according to EC 3 Part 1-2 are pointed out. A second main work package focuses on the analysis of the time-dependent material behaviour (creep). For this purpose, transient state tests at different heating rates are carried out for the quantification of creep strain. As a result, the constitutive equations can be expressed taking account of the heating rate.

1 INTRODUCTION

The knowledge of the stress-strain relationships of structural steel at elevated temperatures is essential for the assessment of the load-carrying capacity of steel structures in case of fire. In the Eurocode 3 Part 1-2 (2006), constitutive equations are given for temperatures up to 1200 °C. They are uniform for steel grades between S235 and S460 and are based on numerous test results predominantly obtained on steel grade S235. Various existing test results for fine-grained structural S460 steel put the validity of these constitutive equations into question for this particular steel type. Lange & Wohlfeil (2007) compared the temperature dependent yield strength values of the Eurocode for S460 steel with documented research results; see Ruge & Linnemann (1986), C.E.C. Agreement No 7210-SA/505 (1991), Winter (1998) and Outinen et al. (2000). These research results shown in Figure 1 have a wide scatter range and deviate noticeably from the normative standard. One possible reason for the diverging high temperature performance of S460 is the grain-boundary strengthening. This specific strengthening method is mainly responsible for the elevated strength of S460 at room temperature, but it is assessed to be ineffective or even disadvantageous at elevated temperatures.

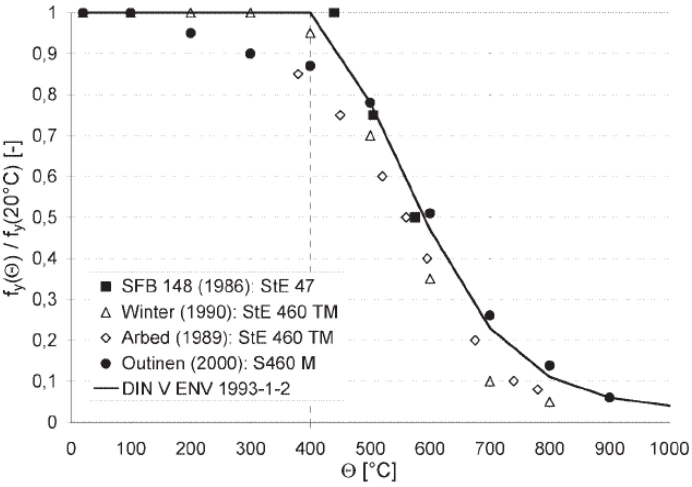

Figure 1. Temperature-depending yield strength reduction ($R_{t2,0}$)
for S460, Lange & Wohlfeil (2007)

Wohlfeil (2006) carried out transient state tests, analysing the high-temperature performance of a normalized rolled S460N and a thermomechanical rolled S460M. The results led to stress-strain relations for temperatures up to 900 °C. In these tests, the thermomechanical rolled steel showed a better performance than it was expected following the Eurocode 3 Part 1-2. According to Wohlfeil, the reason for that lies in the very special rolling process leading to a fine grain microstructure and the niobium and titanium segregations retarding the creep process. The tested normalized rolled steel showed, by contrast, a material behaviour which lay considerably below the values given in Eurocode 3 Part 1-2.

With the objective of a larger data base, extensive experimental tests are currently carried out with numerous commercial high strength fine-grained structural S460 steels. This paper describes the test programme of the present research project and the obtained results and compares them to the actual state of the art.

2 HIGH TEMPERATURE TESTS OF S460 SPECIMENS

2.1 *Test method and experimental set-up*

Stress-strain relationships at elevated temperatures can either be obtained in steady state or transient state tests. Steady state tests are characterized by a constant test temperature while the load is applied. These tests can be conducted stress rate- or strain rate-controlled, and the test duration is short. If time-depending strain components shall be determined, separate creep tests under constant temperature and loading become necessary. During a fire, structural components are normally subjected to a transient temperature history under constant mechanical loads. Therefore transient state tests which are characterized by a constant load in combination with a defined heating process deliver more realistic results concerning the material behaviour in case of fire. Carrying out several tests at different load levels, the result of the transient state tests is a set of temperature-strain curves. After elimination of the thermal strain ε_{th}, stress-strain relationships can be derived from these temperature-strain curves. Strictly speaking, the validity of the obtained stress-strain relationships is limited to the particular heating rate chosen for the testing procedure. Furthermore, the time-independent, load dependent strain ε_s and the creep strain ε_k can no longer be separated from each other. For the current tests the transient test method was chosen. Steady state tests were only carried out complementarily for one of the tested materials in order to have a comparison between the two test methods.

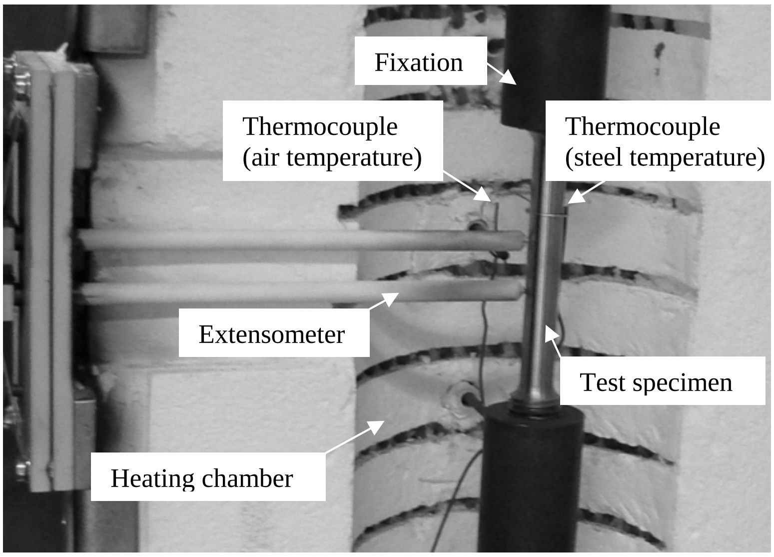

Figure 2. Testing device

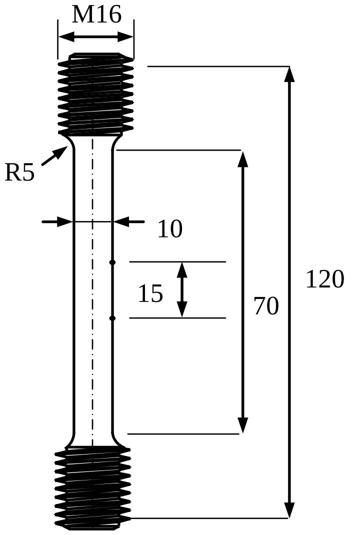

Figure 3. Test specimen [mm]

Figure 2 shows the experimental set-up; Figure 3 shows the shape of the standard test specimen. The dimensions were chosen in accordance with DIN EN 10002 Part 5 (1992). The tests were carried out at the Institute for Physical Metallurgy, Department of Materials Science, TUD, in a furnace which was equipped with three separately controlled heating zones. The gauge length of the extensometer was 15 mm. The temperature of the test specimen was determined by an additional thermocouple attached to the specimen surface.

2.2 *Tested materials and test programme*

The investigated weldable fine grain structural S460 steels are standardized in DIN EN 10025 Parts 3 and 4 (2005) and differ in their delivery conditions (normalized - N - or thermomechanical - M - rolled) as well as in their chemical composition. DIN EN 10025 only gives limit values concerning the proportions of the different alloying elements. In addition, the term “thermomechanical rolled” comprises several production versions, e.g. the ACcelerated Cooling (ACC) or the Quenching and Self-Tempering (QST) which is mainly used for rolled sections.

To investigate the influence of the chemical composition and the delivery condition on the high temperature performance of S460, a total of 8 common materials was tested. The chemical composition and the strength properties are given in Table 1. Special attention has to be paid to the material called “PM” which is a thermomechanical rolled steel for pressure purposes according to DIN EN 10028 Part 5 (2003). All materials were tested under transient state test conditions using a constant heating rate of 10 K/min and the following load levels: 25, 50, 80, 120, 170, 230, 300, 380, 420, and 460 (450 for PM) and, where possible, 500 N/mm². In general, two tests were carried out on each load level. In addition, two quasi-unstressed tests were carried out for each material to determine the thermal expansion.

Material M1 was additionally tested under transient state test conditions using constant heating rates of 3, 6, 20 and 30 K/min and load levels of 50, 120, 170, 230, 300 and 420 N/mm².

Material M4 was also tested under steady state test conditions following DIN EN 10002 Part 5 at temperatures of 200, 300, 400, 500, 600, 700 and 800 °C. Two tests were carried out on each temperature level.

Table 1. Chemical composition according to the melting analysis in % (manufacturer information) and strength values (in rolling direction, own tests)

Steel grade	S 460M				P 420 M	S 460 N		
Shortcut	M1	M2	M3	M4	PM	N1	N3	N4
Fabrication	ACC	ACC	ACC	QST				
Type of product	Plate 25 mm	Plate 25 mm	Plate 58 mm	HEA 320	Plate 60 mm	Plate 60 mm	Plate 35 mm	IPE 550
C	0.090	0.130	0.084	0.070	0.060	0.161	0.170	0.100
Si	0.280	0.300	0.366	0.210	0.257	0.423	0.320	0.220
Mn	1.610	1.520	1.640	1.030	1.260	1.610	1.550	1.660
Nb	0.049	0.038	0.022	0.039	0.020	0.003	0.002	0.030
V	0.004	0.060	0.000	0.010	0.000	0.156	0.163	0.110
Al	0.036	0.028	0.032	0.003	0.034	0.011	0.022	0.026
Ti	0.020	0.015	0.003	0.001	0.002	0.001	0.002	0.000
Cr	0.030	0.060	0.208	0.170	0.047	0.034	0.030	0.050
Mo	0.003		0.009	0.030	0.361	0.035	0.002	0.010
Ni	0.040	0.030	0.034	0.140	0.038	0.131	0.640	0.050
Cu	0.060	0.030	0.026	0.350	0.022	0.015	0.030	0.040
CEV	0.372	0.411	0.405	0.316	0.356	0.484	0.512	0.417
R_{eH} [N/mm²]	525	558	521	509	444	507	489	479
R_m [N/mm²]	598	666	589	584	529	640	644	584

3 TEST RESULTS

3.1 *Transient state tests with 10 K/min heating rate*

Figures 4 and 5 show the yield strength reduction factor (yield strength defined as stress at a strain of 2%) in dependence of the temperature for all tested materials, distinguishing the delivery conditions M and N. Additionally, the reduction factor according to Eurocode 3 Part 1-2 is included. Figures 6 and 7 show the stress-strain relationships for all tested materials for a temperature of 500 °C. They have been constructed from the temperature-strain curves. Generally the mean value of the two test results was used.

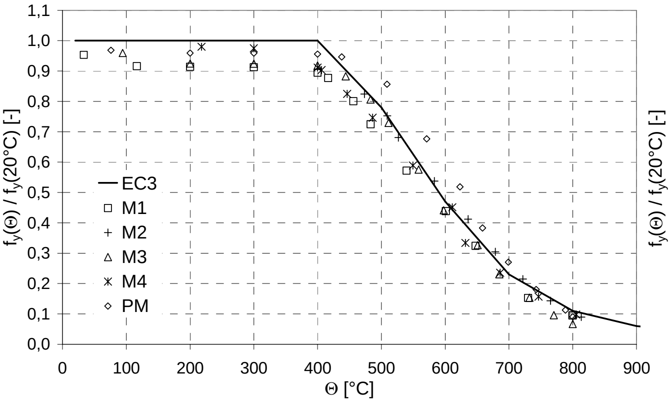

Figure 4. Yield strength reduction factor; Thermomechanical rolled steels

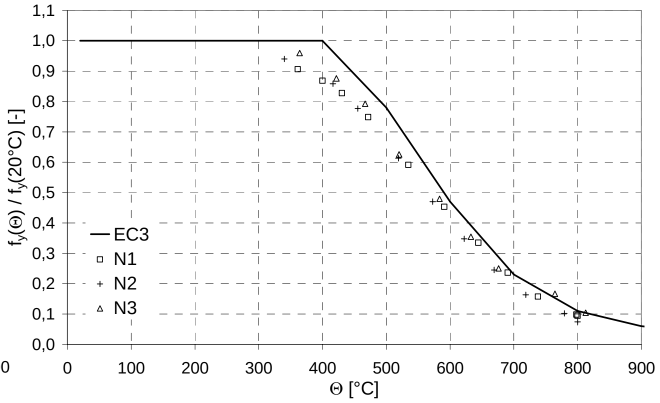

Figure 5. Yield strength reduction factor; Normalized rolled steels

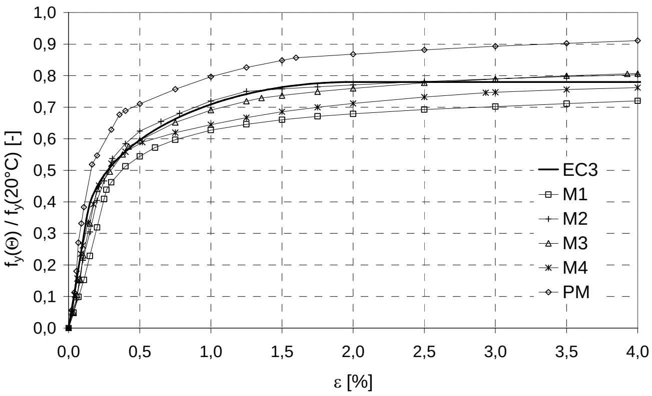

Figure 6. Stress-strain relationships at 500 °C; Thermomechanical rolled steels

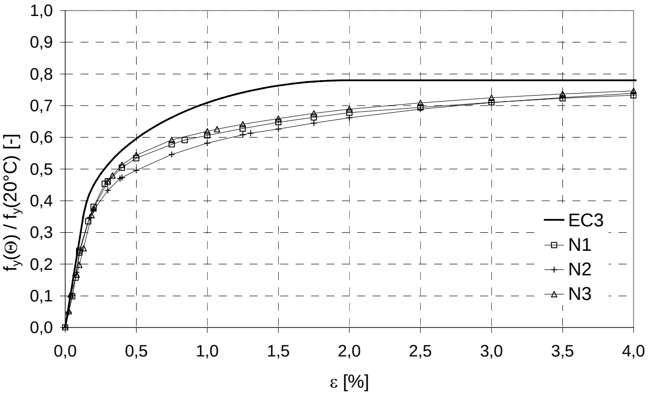

Figure 7. Stress-strain relationships at 500 °C; Normalized rolled steels

It can be seen clearly that the thermomechanical rolled steels show a better high temperature performance than the normalized ones. However, nearly none of the tested materials reaches the specifications of Eurocode 3 Part 1-2. This statement is valid for the whole tested temperature range up to 800 °C. Comparing just the S460M steels, the material M2 performs the best. Compared to M1, M3 and M4, it has the highest total content of niobium, vanadium und titanium. These elements are important for the development of the fine grain microstructure. Especially the content of vanadium is much higher than in the other three steels. This shows that a high content of certain alloying elements like niobium, vanadium und titanium has, in combination with the thermomechanical rolling process, a positive influence on the high temperature performance of structural S460 steel.

Remarkable is the very good high temperature performance of the tested steel for pressure purposes due to a high content of molybdenum (0.36 %, see Table 1). This element increases the creep resistance of the steel by solid solution strengthening.

Based on the weakest thermomechanical and normalized rolled steel, the test results were described for both delivery conditions by mathematical functions. The stress-strain relationships can be described by an elliptical curve and straight lines as used in the Eurocode 3 Part 1-2, by a power function as proposed by Ramberg & Osgood (1943) or by an equation proposed by Richard & Abbott (1975), as shown by Poh (1997). Figures 8 and 9 show the test results approximated to an elliptical curve and straight lines. The curves according to EC3 Part 1-2 are also shown for the purpose of comparison.

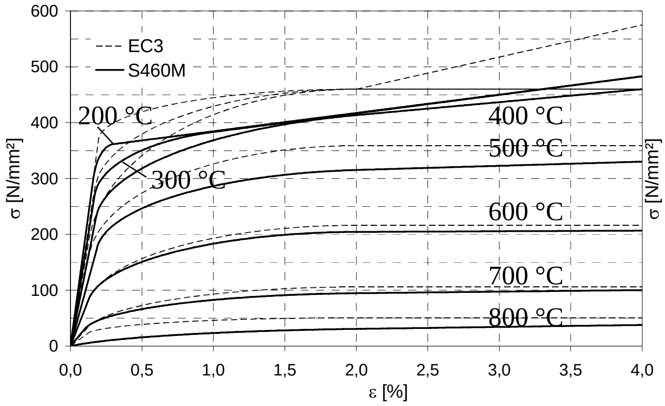

Figure 8. Stress-strain relationships 200 - 800 °C; Thermomechanical rolled steels

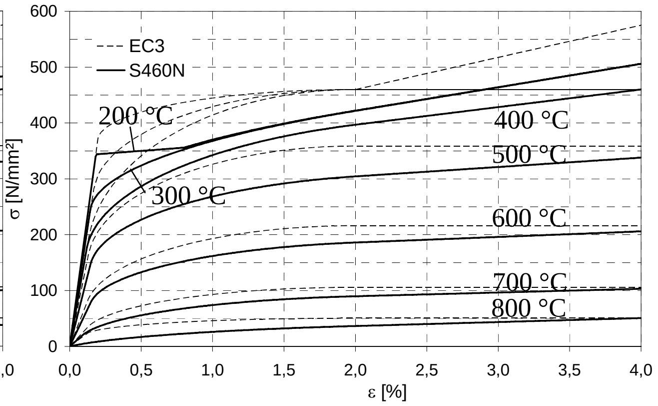

Figure 9. Stress-strain relationships 200 - 800 °C; Normalized rolled steels

It is obvious that the stress-strain relations according to EC3 Part 1-2 considerably overestimate the high temperature performance of S460 as shown by the test results. The consequence is an overestimation of the bearing capacity of structural members made of S460 steel in fire design according to Eurocode 3 Part 1-2. This point requires a further examination in the form of nonlinear limit load calculations of flexural members and especially of columns to assess the emerging safety risk.

3.2 *Steady-state tests at elevated temperatures*

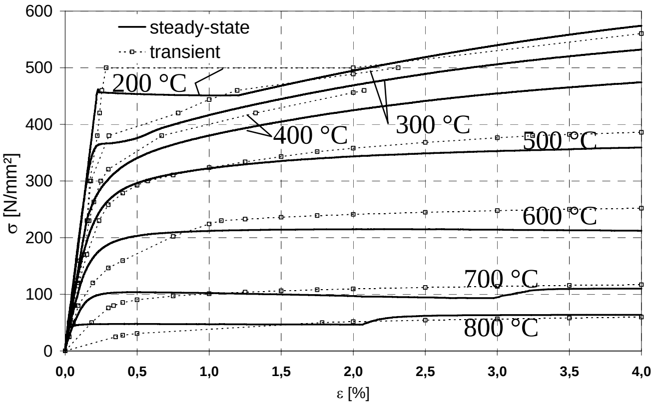

Figure 10. Comparison of the test results steady / transient state, material M4, temperature 200 °C - 800 °C

In Figure 10 the results of the steady state tests are compared to the stress-strain relations derived from the transient state tests for temperatures from 200 °C up to 800 °C. The steady state tests were performed at strain rates between 0.002 - 0.005 /min. After reaching a strain of about 4 % (700 °C: 3 %, 800 °C: 2 %) the strain rate was raised for the determination of the tensile strength and maintained constant until rupture. The steady state tests confirm the results of the transient state tests insofar as the comparison between the results shows a distinctive regularity. For all temperature levels, the stress $R_{t2,0}$ at a strain of 2% that was determined in the steady state tests is lower than in the transient state tests. Noticeable is the highly deferring curve progression in the range of small strain values at temperatures above 500 °C. This demonstrates the influence of the creep strain which is included in the results of the transient state tests. However, the extremely high initial modulus of elasticity measured in the steady state test at a temperature of 800 °C may not be realistic, but a deficiency in the strain measurement at the very beginning of the test.

3.3 *Transient state tests with different heating rates*

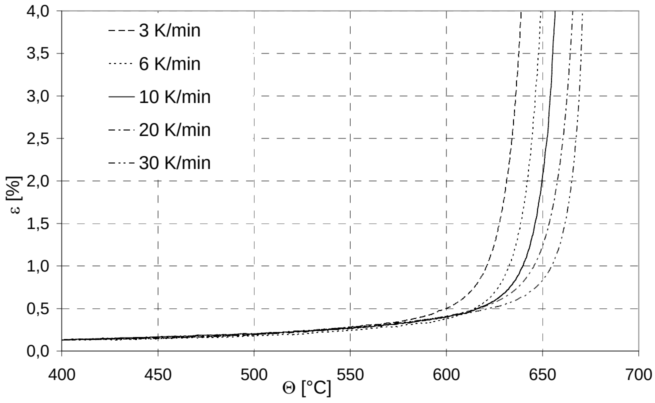

Figure 11. Temperature-strain curves with variation of the heating rate, $\sigma = 170$ N/mm², material M1

Figure 11 shows the results of transient state tests with a constant loading of 170 N/mm² and different heating rates. With increasing heating rates smaller strain values and higher failure temperatures can be observed. The reason for that is the smaller amount of creep strain included in the test results at high heating rates.

The evaluation of these test results is carried out using the concept of temperature-compensated time θ; see Dorn (1954), Harmathy (1967) and Skowronski (2004). The objective is the quantification and analytical description of the creep strain as a function of time, stress and temperature without the necessity of performing separate steady state creep tests.

The temperature-compensated time θ is defined:

$$\theta = \int_0^t e^{-\frac{\Delta H}{RT}} dt \qquad (1)$$

where

ΔH	Activation energy of creep [J/mol]
R	Gas constant [J/mol K]
t	Time [h]
T	Temperature [K]

The creep strain ε_k is calculated according to the following expression:

$$\varepsilon_k = B \cdot \sigma^m \cdot \theta^n \qquad (2)$$

where

B	material constant [$(\text{N/mm}^2)^{1/m}\text{h}^{1/n}$]
σ	stress [N/mm²]

By means of a two-step regression procedure, the exponents n and m as well as the material constant B can be determined, using the differences between the measured temperature-strain curves at different heating rates. Skowronski declares a value of 1/3 for the exponent n. Cho & Findley (1984) indicated a dependence of n on the temperature. Analyses of the test data also show that a constant value of n is not appropriate to describe the measured strain differences between the different temperature-strain curves properly, because it does not comprise the state of tertiary creep. But if n is expressed as a function of θ and σ as

$$n = a(\sigma) \cdot \theta + \frac{1}{3} \qquad (3)$$

where

a	function of stress

good results are obtained, because the resulting ε_k-θ-relationship describes all states of creep including the tertiary creep phase.

After the determination of all constants, an analytical expression is available to calculate the creep strain. For a defined heating process, leading to a certain maximum temperature, the expression θ has a constant value because it does not depend on stress. This means that the formula for the creep strain occurring during this heating process is transformed into a function only depending on stress. This permits the elimination of the time-dependent strain proportions from the stress-strain relationships obtained in the transient state tests. Furthermore, the stress-strain relations can be adapted to any heating process that a structural member might be subjected to in the course of a fire.

4 SUMMARY AND OUTLOOK

The transient state tests carried out at seven commercial high strength fine-grained structural S460 steels show that the thermomechanical rolled steels have a better high temperature performance than the normalized rolled materials. Nevertheless, nearly all of tested materials do not reach the specifications of Eurocode 3 Part 1-2. This can lead to a safety risk if fire design of structural members made of S460 steel is done according to Eurocode 3 Part 1-2. In comparison to the transient state tests, the steady state testing procedure results in stress-strain relationships with a steeper initial gradient which demonstrates the influence of creep strain included in the transient test results.

The evaluation of the transient state tests with different heating rates makes the assessment of the included time-dependent strain possible and will permit the consideration of the creep strain arising in any heating process in the constitutive equations.

Further examination is necessary to establish recommendations concerning suitable alloying elements and quantities or fabrication processes which could improve the high temperature performance.

For this purpose, metallographic investigations are actually carried out at selected specimens that were subjected to certain combinations of thermal and mechanical loading during the testing procedure. They shall depict differences in the initial microstructures of the tested steels as well as the effect of the combined thermal and mechanical impact on the material in case of fire.

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