

# Effect of Elevated Temperatures on Behavior of Structural Steel 50CrMo4

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**Abstract.** In this paper an effect of different temperatures on mechanical properties and creep responses of 50CrMo4 steel were considered. Both mechanical properties and creep behavior were determined by uniaxial tests. Curves representing specimen elongations as well as reduction in specimen areas at elevated temperatures are also shown. Creep curves as the responses of the considered material subjected to uniaxial stresses at high temperatures are also demonstrated. The notch impact test was carried out using Charpy impact machine and fracture toughness was calculated. The experimentally obtained data may be of significant interest in structure design procedure.

**Keywords.** Elevated temperatures, Creep behaviour, 50CrMo4 steel.

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## 1 Introduction

Optimal design has become an indispensable tool in the computational repertoire of a structural designer [1]. There are many classes of problems in structural optimization. However, the designed structure has to be of enough safety, functionality and cost-effectiveness. Design procedure includes both stress and strain analysis as well as lifetime prediction according to service life conditions. The operating regime of the structure at some special environmental conditions may cause certain failure modes like: mechanical overload, fatigue, yielding, creep and others [2]. Some of engineering structures may be exposed during their service life to elevated temperature conditions, like fire exposure or similar what can cause creep behavior. Being defined as time-dependent inelastic strain under sustained load and elevated temperatures, creep may be said to be thermally activated process [3, 4]. Creep in general may be described

in terms of three different stages: I-instantaneous creep, II-steady-state creep and III-accelerating creep. Many efforts have been expended in an attempt to devise a good model for accurate prediction of long-term creep behavior based on short-time creep tests. Certain useful methods have been developed for approximating long-term creep behavior based on a series of short-time experiments, for example, abridged method, mechanical accelerating method, thermal acceleration method.

Sometimes it can be easy to quantify damage in laboratory creep procedure conducted at constant stress (load) and temperature, but components of machines in service hardly ever operate under constant conditions [5]. The strength of metals decreases with increasing temperature and the properties become much more time dependent. Based on experimental investigations, creep will occur in metal material subjected to a sustained load which is usually slightly below yield strength and at a temperature slightly above its recrystallization temperature. Generally, the minimum temperature required for creep deformation to occur is often deemed as approximately  $0.4 T_m$ , where  $T_m$  is the melting point for metals. So, creep as a permanent deformation of a material may be negligible in materials at room temperature if room temperature is under 40 % of their  $T_m$ . In a literature, many details can be found about considered material, especially about its possible applications but not enough data about its properties and behavior at elevated temperatures. That is the main reason for the experimental investigations presented in this paper. Accordingly, it is possible to find something about failure investigation and application of this steel to pump shafts in [6]. Also, an effect of laser beam radiation on fatigue crack propagation in AISI 4150 (50CrMo4) was considered in [7]. Simulation of forming processes, which requires accurate constitutive models describing material behavior at large strains, and which includes some data regarding 50CrMo4 steel, can be found in [8]. Some interesting data about the influence of high temperature regime on mechanical properties for stainless steel and high-strength low-alloy steel (HSLA) may be found in [9].

## 2 Material Under Consideration

The considered material was EN/DIN 50CrMo4 steel (AISI 4150, ASTM A505, Mat. No/W. Nr.: 1.7228) with the following composition in mass %: C (0.487), Cr (0.999), Mn (0.735), Si (0.257), Mo (0.185), S (0.0278), P (0.0178) and

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rest (97.29). This kind of steel is widely used in statically and dynamically stressed larger cross-sections structural components. It is applicable to aircraft and automotive industry, engines and machines as well as to components for driving gears, axles, rings, bushes, steering components, etc. Machinability of this steel is good. It may be welded by conventional methods. In hardened condition this process may affect the mechanical properties due to welding heat input. In that way, post-weld treatment may be needed.

## 2.1 Testing System

The testing system used in these experimental investigations consists of 400 kN materials testing machine, high temperature furnace 1173 K (900°C) and high temperature extensometer. Charpy pendulum impact machine was used for notch impact energy determination.

## 2.2 Specimens and Testing Procedures

The test specimens were prepared from 50CrMo4 steel rods. Their shapes as well as geometry are defined by appropriate standard.

Experimental uniaxial tensile tests were carried out at both room and elevated temperatures. The aim of these tests is to determine mechanical properties and to consider creep behavior. Mechanical properties at room temperature were determined according to the EN 10002-1 (ASTM E8) standard, while mechanical properties at elevated temperature were determined according to EN 10002-5 (ASTM E21) standard. Creep behavior was tested according to the ASTM E139 standard, given in [10]. The test determining notch impact energy was carried out according to ASTM E23-05 standard.

# 3 Results and Discussion

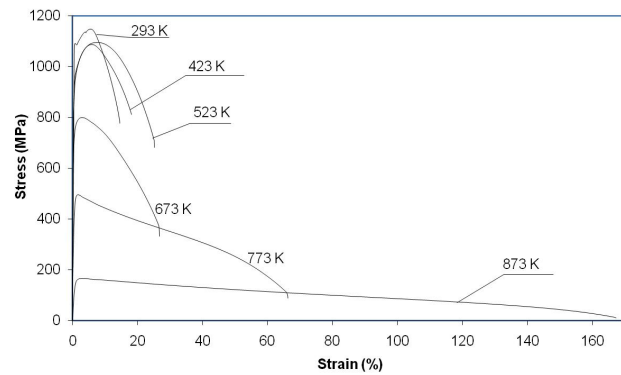
## 3.1 Engineering Stress-strain Diagrams

Engineering stress-strain diagrams for 50CrMo4 steel at both room and elevated temperatures are presented in Figure 1.

Numerical data of mechanical properties of 50CrMo4 steel at elevated temperatures are given in Table 1.

An effect of elevated temperature on mechanical properties, elongation and reduction in area is presented in Figure 2.

According to Figures 1 and 2a, as well as Table 1 it is possible gain insight in to changes of mechanical properties and elongation versus temperature. This steel has quite high ultimate tensile strength at room temperature. It decreases with temperature increasing. Also, 0.2 percent offset yield strength is quite high at room temperature. The shapes representing both of mechanical properties are very



**Figure 1.** Behavior of 50CrMo4 steel at elevated temperatures.

| Temperature<br>K; (°C) | $\sigma_{0.2}$<br>MPa | $\sigma_m$<br>MPa |
|------------------------|-----------------------|-------------------|
| 293; (20)              | 1090.2                | 1146.9            |
| 423; (150)             | 921.8                 | 1086.7            |
| 523; (250)             | 862.3                 | 1095.7            |
| 673; (400)             | 693.9                 | 799.7             |
| 773; (500)             | 437.2                 | 495.2             |
| 873; (600)             | 113.8                 | 165.6             |

**Table 1.** Mechanical properties of 50CrMo4 steel at elevated  $\sigma_m$  – ultimate tensile strength,  $\sigma_{0.2}$  – 0.2 percent offset yield strength.

similar. Because both of mentioned strengths have enough high values in wide temperature range, this steel may be very useful in structural design.

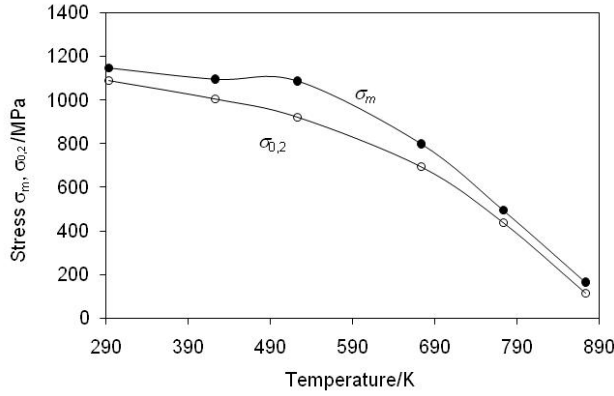
## 3.2 Material Creep Response

Several creep tests were carried out and the appropriate creep curves are presented. Creep temperatures and stress levels are given in Table 2. The related creep responses are presented in Figures 3–5.

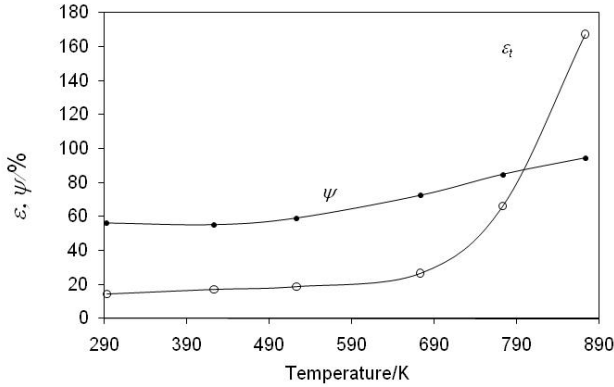
According to experimentally obtained results is visible that this material is not creep resistant even at low stress levels independent of temperature level.

| Constant temperature T<br>K; (°C) | Constant stress level $\sigma$<br>MPa |
|-----------------------------------|---------------------------------------|
| 673; (400)                        | 174; 312                              |
| 773; (500)                        | 44; 109                               |
| 873; (600)                        | 11; 22                                |

**Table 2.** Creep processes: temperatures and stresses.

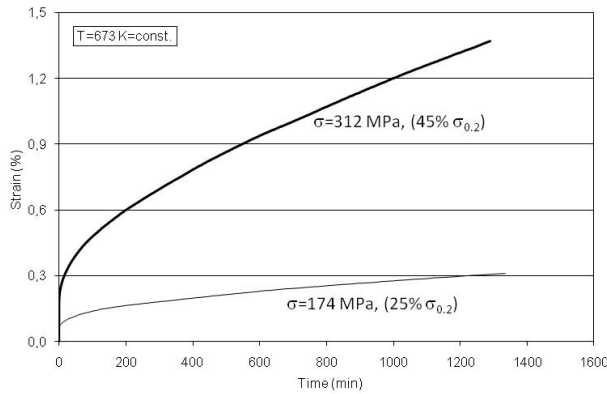


a)

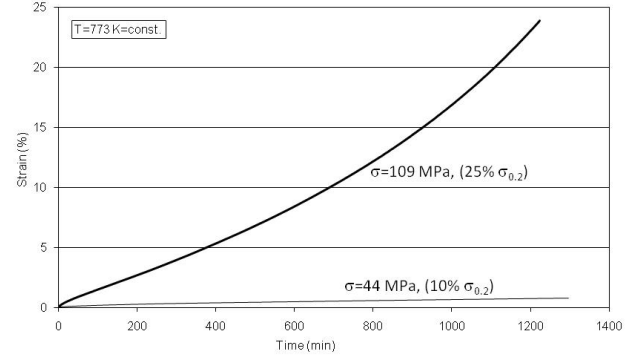


b)

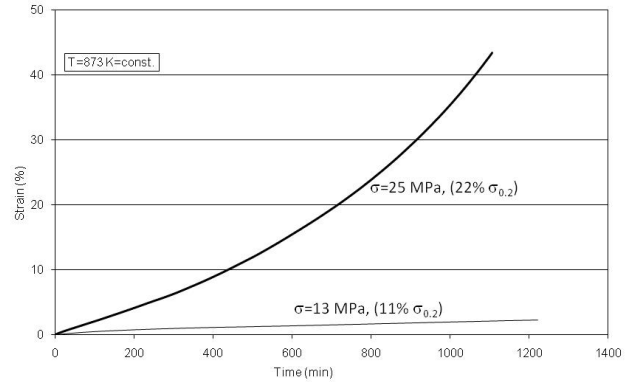
**Figure 2.** The effect of elevated temperatures on mechanical properties, elongation and reduction in area of 50CrMo4 steel. a) Mechanical properties. b) Elongation and reduction in area.



**Figure 3.** Creep behavior of 50CrMo4 steel at temperature of 673 K (400°C).



**Figure 4.** Creep behavior of 50CrMo4 steel at temperature of 773 K (500°C).



**Figure 5.** Creep behavior of 50CrMo4 steel at temperature of 873 K (600°C).

### 3.3 Creep Behavior Modeling

Many solutions for creep response modeling exist. Some of known analytical equations can be found in [3]. In this paper modeling of material creep behavior is based on well known Burger's rheological model [11]. It is a model where both Maxwell and a Kelvin models are connected in series. This rheological model is suitable for simulation of primary and secondary creep stages.

For the mentioned rheological model using stress as well as strain equilibrium equations, the following equation representing material strain behavior was obtained [9, 11]:

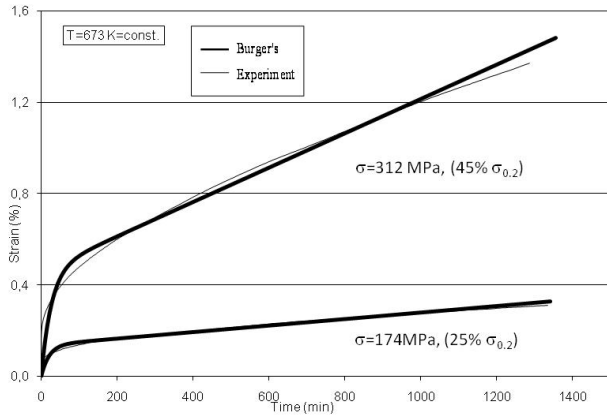
$$\varepsilon = \sigma \left[ \frac{1}{E_1} + \frac{1}{E_2} \left( 1 - e^{(-E_2/\eta_1)t} \right) + \frac{t}{\eta_2} \right]. \quad (1)$$

The material parameters  $E_2$ ,  $\eta_1$ ,  $\eta_2$  are interpolated regarding to experimentally obtained creep curves and are presented in Table 3 for the temperature  $T = 673$  K (400°C).

In Figure 6 a comparison between experimentally obtained creep curves and creep curves modeled by the Burger's rheological model is presented. These comparisons are related to the creep behavior at the temperature of 673 K (400°C).

| Temperature<br>K; (°C) | $\sigma$<br>(MPa) | $E_1$<br>(GPa) | $E_2$ (Pa), $\eta_1$ (Pa min)<br>$\eta_2$ (Pa min)                                                                                   |
|------------------------|-------------------|----------------|--------------------------------------------------------------------------------------------------------------------------------------|
| 673; (400)             | 174–312           | 201            | $E_2 = 1.008 \cdot 10^9 - 2.15 \sigma$<br>$\eta_1 = 1.87 \cdot 10^{10} - 30.9 \sigma$<br>$\eta_2 = 1.12 \cdot 10^{12} - 2911 \sigma$ |

**Table 3.** Burger's model parameters for 50CrMo4 steel for the temperatures of 673 K (400°C),  $\varepsilon = f(\sigma, t)$ .



**Figure 6.** Creep curves comparison: experiment and Burger's model.

### 3.4 Fracture Toughness Assessment

In ASTM E 399-90 standard, some standard tests related to measure fracture toughness  $K_{Ic}$  are described. As noted in [12], the stress concentration in front of a crack is often sufficient to initiate yielding here. This plastic deformation then accounts for most of the fracture work.

Besides fracture toughness, as the most useful material property in design against fracture, there are also other tests which provide a measure of fracture resistance. One of such test is the widely used Charpy impact test which is conducting by the Charpy pendulum impact machine. On the basis of notch impact energy, impact toughness  $K$  may be calculated. Standard tests related to fracture toughness are appropriate to provide a measure of fracture resistance, but sometimes may be useful to make an assessment of this resistance using a very simple method. In order to avoid complicated standard test concerning fracture toughness determination, similarly to equation presented in [13], the following relationship between fracture toughness  $K_{Ic}$  (MPa  $\sqrt{m}$ ), modulus of elasticity  $E$  (MPa), impact toughness  $K$  (J/mm<sup>2</sup>) and Poisson's ratio  $\nu$  is proposed in [14]:

$$K_{Ic}^2 = (1/f)(EK)(1 + \nu). \quad (2)$$

The aim was to calculate an average value of  $K_{Ic}$  using data obtained by very simple Charpy test. Impact toughness  $K$  was calculated as:

$$K = CVN/A. \quad (3)$$

In equation (3),  $CVN$  is experimentally obtained Charpy-V-Notch impact energy (J), and  $A$  (mm<sup>2</sup>) is cross-sectional area of impact specimen at the place of notch. Experimentally obtained data used in this procedure are related to the temperature of 294 K (21°C). In present case, 2V notch was used. For used material the value for Poisson ratio of  $\nu = 0.3$  was adopted. According to average experimentally obtained data for notch impact energy  $CVN$  and modulus of elasticity  $E$ , as well as for used specimen:

$$CVN = 69 \text{ J}, \quad A = 80 \text{ mm}^2, \quad E = 203.900 \text{ MPa},$$

and if factor  $f = 15$  is adopted, the following values were calculated:

$$K = 0.8625 \text{ J/mm}^2 \quad \text{and} \quad K_{Ic} = 123 \text{ MPa}\sqrt{m}.$$

Now, according to average value of  $CVN$  impact energy of 69 J, the following formula [14, 15] can be suitable for fracture toughness calculation:

$$K_{Ic} = 8.47 \cdot (CVN)^{0.63}. \quad (4)$$

After calculation according to this formula, the following result for fracture toughness is obtained:

$$K_{Ic} = 122 \text{ MPa}\sqrt{m}.$$

According to obtained results using equations (2) and (4), good accordance is visible.

## 4 Conclusions

The behavior of 50CrMo4 steel at different environmental conditions was considered. As this steel is widely used in engineering practice, the experimentally obtained data may be of interest for designer of structural components made of this kind of steel and exposed to the similar environmental conditions in their service life. Both of the considered mechanical properties, e.g., ultimate tensile strength and 0.2 percent offset yield strength, at room temperature are quite high. In general, it can be said that these mechanical properties decrease while temperature range increases. Actually, their values decrease quite fast after temperatures above 763 K (400°C). Accordingly, that may be the reason for restricted applications of this material to structure design of structural components that operate at such environmental

conditions. When creep behavior is under consideration, it can be said that this steel is not enough creep resistant even at low temperatures and low stress levels. Perhaps at very low stress levels and at quite low temperatures this type of steel might be used in such environmental conditions for a very short time. According to the figure representing creep behavior simulation, it is shown that the used rheological model is suitable for creep modeling for the first and second creep stages, but it is not appropriate for modeling of accelerating creep stage. Also, a practical engineering calculation for fracture toughness is presented according to the proposed formula as well as according to the equation known from literature.

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