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EXPERIMENTAL DETERMINATION OF MATERIAL MECHANICAL PROPERTIES AND MODELING OF MATERIAL BEHAVIOUR IN SPECIAL ENVIRONMENTAL CONDITIONS

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Abstract. Modern design of the structure is based on the known material properties and high computer capacity. In this paper, constructional steel (42CrMo4 / AISI 4140 / 1.7225) and stainless steel (X46Cr13 / AISI 420 / 1.4034) have been experimentally tested. By means of experimental tests, their mechanical properties creep and fatigue behaviour were determined. All the mechanical properties are presented in the form of the curves representing temperature dependence. Mechanical tests related to mechanical properties include ultimate tensile strength, yield strength and modulus of elasticity. From the other hand, by uniaxial creep tests performed at different temperatures and stress levels material creep resistance has been determined. Short-time creep modelling is also presented. Fatigue limit (endurance limit) was determined by high cycle tensile tests at stress ratio of $\boldsymbol{R = 0.25}$. As fatigue life model is used stress-life model ($\boldsymbol{\sigma - N \ \rightarrow S - N}$, $\boldsymbol{Wohler\ curve}$), where the ordinate (y-axis) covers maximal uniaxial stresses while apcisa (x-axis) covers number of cycles to failure. The mentioned stress-life model consists of two region and that fatigue finite life region and fatigue infinite life region, or, it can be said that, an inclined line and a horizontal line represent it. The so-called fatigue limit is defined by modified staircase method. As the results of the performed experimental investigations may be mentioned as follows. Tested materials have quite high ultimate tensile strength ($\boldsymbol{20°C/1.7225/735\ MPa}$; $\boldsymbol{20°C/1.4034\ /782\ MPa}$) and yield strength ($\boldsymbol{20°C/1.7225/593\ MPa}$; $\boldsymbol{20°\ /1.4034\ /657\ MPa}$) while fatigue limit is of amount ($\boldsymbol{1.7225/532\ MPa}$; $\boldsymbol{1.4034\ /682\ MPa}$).

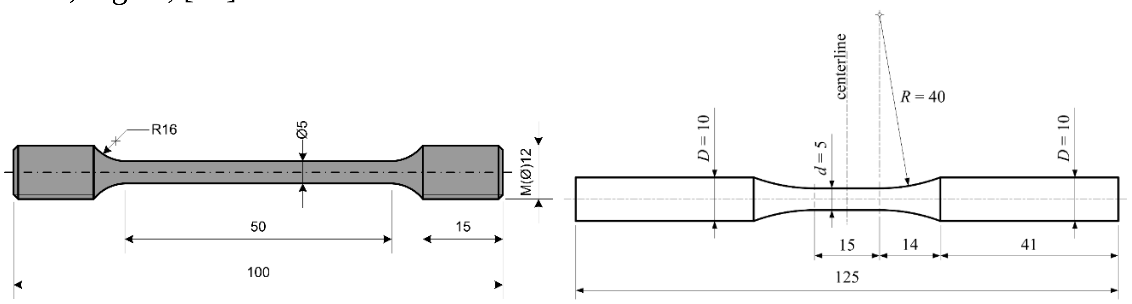
1 INTRODUCTION

Well-known material behaviour data in certain environmental conditions and finite element analysis carried out using high-capacity computers provide a modern and reliable structural design. The finite element procedure (FEP) is an important and very powerful tool in engineering analysis of the structure [1-2]. Consequently, the choice of the material should be made in accordance with the expected material behaviour during its service life. In any case, the possible failures that can arise during design, manufacture, maintenance or service life need to be avoid [3]. However, various failures may occur during structure history. Analysis of failure is a new established discipline dealing with the determination of the origin and form of expression of the particular failure. In this sense, an answer why and how a certain engineering component has failed can be obtained. As a common causes of failures usually are numbered: improper material, unforeseen operating conditions, design errors, misuse, manufacturing defects, inadequate control [4]. From the other hand in engineering practice many different failures can arise such that creep, fracture, fatigue, force induced elastic deformation, yielding, etc., [5]. In this paper, besides the mechanical properties, creep and fatigue of the mentioned materials were investigated. Creep is an inelastic strain that increases with time in material exposed to elevated temperatures at constant stress, or usually, creep can be defined as time-dependent behaviour during which deformation is constantly increasing while the stress is kept constant [6]. Regarding the creep strains, in engineering practice usually is stated that only 1-2% of creep strains is admissible. In addition, it is stated that creep is appreciable at temperature above 0.4 $T_{m,}$ where T_m is the melting temperature [7]. As far as fatigue or fracture is concerned, these failures are very important for the design of the structure. Namely, so - called fatigue limit (endurance limit) is always lower than static strength. In the following part, some of recent published papers dealing with the investigated materials are mentioned. The influence of high temperatures on the fatigue strength, typical for diesel engine components, was considered in Ref. [8]. The microstructure banding of the alloyed steels 4340, 42CrMo4 and 20NC11 is estimated using the approach of the ASTM E 1268 standard and presented in Ref. [9]. Uniaxial fatigue properties of 42CrMo4 steel, produced by closed die hot forging and then heat treated by conventional quenching and tempering treatment, are studied in the Ref. [10]. Also, some of material properties and material behaviour of 42CrMo4 were considered in Ref. [11]. Effect of surface modification on corrosion resistance of uncoated and DLC coated stainless steel surface was studded in Ref. [12]. Influence of solution annealing temperature and cooling medium on microstructure, and some properties of X46Cr13 steel were studded in Ref. [13]. In addition, mechanical behaviour of X46C13 steel was investigated in Ref. [14]. The main intention of this paper is to make some comparisons between these materials with very similar contents of carbon, but different contents of other constituents.

2 DATA RELATED TO CONSIDERED MATERIAL, SPECIMENS AND EQUIPMENT

Materials under consideration were chromium-molibdenum – manganese low-alloy 42CrMo4 steel and chromium martensitic stainless steel X46Cr13. Both of them were delivered as annealed and cold drawn 16 mm-round bars. First of them is designated as: EN/DIN 42CrMo4 (1.7225); AISI 4140, and its chemical composition in mass (%) is: C (0.42), Cr (1.07), Si (0.24), Mn (0.84), Mo (0.22), S (0.003), P (0.007), and Rest (97.2). Applications of this steel are in statically and dynamically stressed engineering components (gears, crankshafts). The other mentioned material is commonly recognized as high hardenability material in conjunction with good corrosion resistance. It is also well suited for the production of roller bearings, cutting tools, etc. This material may be used in mechanical, civil and industrial engineering, means for transport, etc. Its chemical composition in mass (%) is: C (0.442), Si (0.375), Mn (0.381), P (0,0121), S (0.0192), Cr (13.05); Rest (85.7207).

Specimens used in tensile testing (stress-strain diagrams and creep behaviour) were manufactured in accordance with ASTM Standard, ASTM: E 8M-15a, [15], Fig 1a, while specimens used in fatigue testing are manufactured in accordance with ISO 12107:2012 (2012) standard, Fig 1b, [16].



a) b)

Figure 1: Geometry of the specimen used in these investigations. a) Uniaxial testing. b) Fatigue testing.

Standard used in tensile testing (stress-strain procedure at room temperature) was ASTM: E 8M-15a, while that used at high temperatures was ASTM: E21-09. Creep tests were carried out in accordance with ASTM: E 139-11 standard. Fatigue tensile testing were carried out according to ISO 2017 standard. Also, all mentioned ASTM standards can be found in Annual Book of ASTM Standards (2015).

Equipment: Material-testing machine (Zwick / Roell) of 400 kN capacity was used in tensile testing (stress-strain diagrams as well as creep tests). Macro-extensometer was used in tensile testing at room temperature while high temperature extensometer was used in testing at elevated temperatures. Dynamic tensile testing machine (Servopulser) was used in fatigue tensile testing.

3 RESEARCH RESULTS

3.1 Engineering stress-strain diagrams

Engineering design is better when the knowledge about the material is bigger, especially that, that relate to behaviour in similar conditions. Using experimental investigations performed at different temperatures so-called mechanical properties of the material can be obtained. Namely, from the stress-strain diagrams temperature dependency of the material properties are visible. In this sense, in Fig. 2 engineering stress- strain diagrams for both of considered materials are presented.

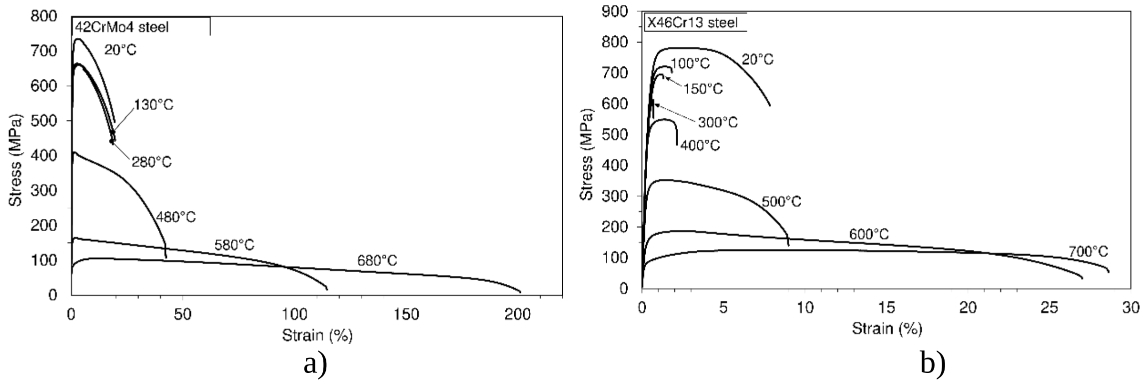


Figure 2: Engineering stress-strain diagrams. a) Steel 42CrMo4. b) Steel X46Cr13.

On the basis of engineering stress-strain diagrams is visible that ultimate tensile strength for both materials does not differ so much. From the other hand, strains of 42CrMo4 steel are much larger.

3.2 Creep behaviour

To have an insight into creep behaviour of investigated material, several short-time creep tests were performed. In Fig. 3 some of creep tests are presented.

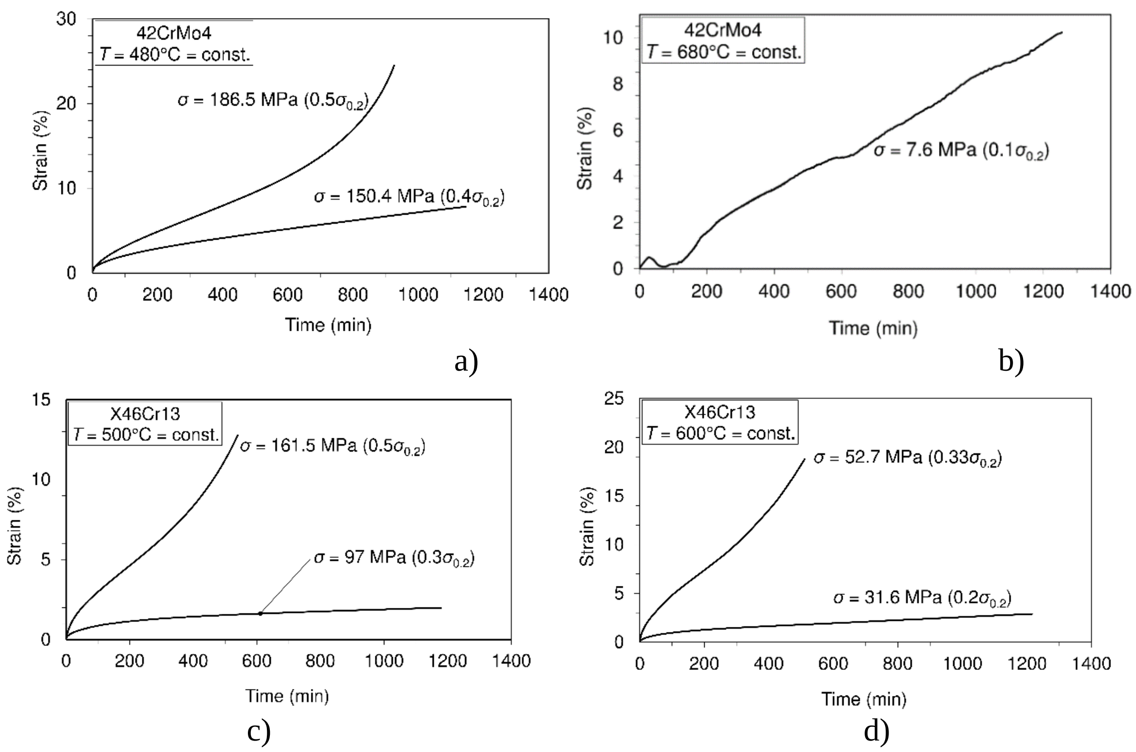


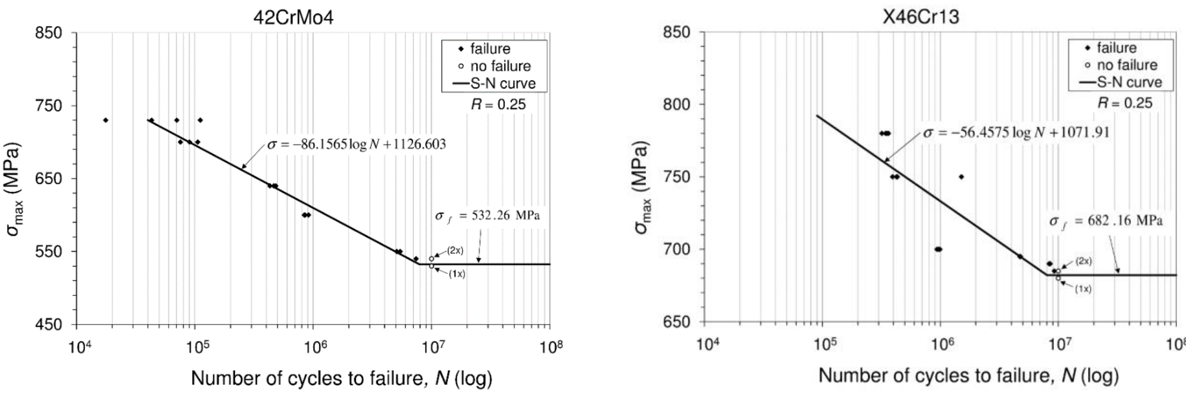
Figure 3: Short-time creep tests. a) Steel 42CrMo4 at temperature of 480°C. b) Steel 42CrMo4 at temperature of 680°C. c) Steel X46Cr13 at temperature of 500°C. d) Steel X46Cr13 at temperature of 600°C

Based on results shown in Fig.3 it is visible that material 42CrM04 should not be treated as creep resistant at temperature of 480°C although stress level is 0.4 of yield strength. From the other hand, steel x46Cr13 may be treated as creep resistant at temperatures of 500°C and stress level lower than 0.3 of yield strength, and at temperature of 600°C and stress level lower than 0.2 of yield strength. Under yield strength here is considered the yield strength relates to considered temperature.

3.3 Fatigue tests and fatigue limit

Many of structures are exposed to dynamic loadings. Fatigue as one of possible mechanical failure due to dynamic loading need to be analysed, and it may result in fracture of considered element. Repeated loads induce cyclic stresses and as result of them microscopic damage and macroscopic crack can be accumulated. Usually, fatigue is defined as the process of the accumulation of damage due to cyclic loading [17]. In this investigation, the specimens were subjected to tensile stresses at prescribed stress ratio and the cyclic loading processes were carried out in accordance with the sinusoidal law. Each fatigue test generates one point in *S-N* curve, where *S* is maximum axial stress and *N* is the number of the cycles to failure. When regardless of the number of cycles test specimen remains unbroken at the prescribed test conditions, this stress limit is called fatigue limit (endurance limit), [18, 19].

The fatigue limit (endurance limit, fatigue strength in the infinite fatigue life range), can be, for example, estimated in accordance with the modified staircase method, Fig. 4, presented by horizontal line. Specimens were tested under decreasing stresses regime. All of data needed for this method usually are presented in tables. Using this method, infinite and finite ranges are visible from Fig.4. In this case the designations related to specimens are as follows: specimens failed (♦), no - failed (○) for the appropriate stress levels at a certain number of cycles. Finally, as it is visible in Fig 4, obtained fatigue limits related to considered materials are as follows: 42CrMo4 steel / 532 MPa; X46Cr13 steel / 682 MPa.



a) b)

Figure 4: Fatigue tests and fatigue limit calculation. a) 42CrMo4 steel. b) X46Cr13 steel.

4 CONCLUSION

Investigations related to mechanical properties, creep behaviour and fatigue testing were carried out for two different steels, 42CrMo4 and X46Cr13. First of them was constructional steel, chromium-molibdenum – manganese low-alloy 42CrMo4 steel, and second one was chromium - martensitic stainless steel X46Cr13. In accordance with experimental results it can be said that strength of the materials does not differ so much, but elongations are quite different. As for creep behaviour, it is visible that steel 42CrMo4 at high temperatures may not be treated as creep resistant, while steel X46Cr13 may be treated as creep resistant if applied stress level is quite low, or better to said, lower that 0.3 of yield strength at considered temperature. Finally, it is visible that fatigue limit of the steel X46Cr13 is significantly higher than that for 42CrMo4 steel.

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