Comparison of the mechanical behavior of materials subjected to specific operating conditions

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Abstract. The materials for making the construction elements are selected according to the required conditions and the available material properties. In this sense mechanical properties and material behavior of the materials such as 42CrMo4 steel, X46Cr13 steel and X6CrNiTi18-10 steel were investigated. Mechanical properties of the mentioned materials are shown in the form of engineering stress-strain diagrams, creep behavior is presented in the form of creep curves while uniaxial fatigue of these materials are given using life diagrams. These materials differ in chemical composition, their strength properties differ within 20\% while their fatigue limits are significantly different.

1. Introduction
Design of the considered element must be optimal. This means that it is necessary to select a material corresponding to the required operating conditions. During the service life of the structure many failures can appear [1-3]. Some of them may arise as a consequence of operating conditions (structural loading, corrosion, etc.) and some of them may arise as assembly errors, improper maintenance, manufacturing defects, design errors, etc. In any case it is needed to determine why and how an engineering component has failed. Since creep and fatigue are possible failures, they are subject of this research. It is known that creep phenomenon is usually defined as time-dependent behavior where strain continuously increases while the stress (load) is kept constant [4]. Creep is usually appreciable at temperature above 40\% of the melting temperature of the considered material [5]. In these investigations, some materials were subjected to creep at different stress levels and different temperatures. From the other hand, these materials were also subjected to uniaxial fatigue at stress ratio R = 0.25. More data about considered materials can be found in literature, and some of the published papers are mentioned here, [6-7, 8-9, 10-11]. Some data related to fatigue resistance of 42CrMo4 steel are presented in Ref. [12]. Further, Ref. [13] focuses on the lifetime reduction of cyclically loaded X46Cr13 steel constantly exposed to highly corrosive CO2-saturated hot thermal water at 60\°C. The damage of the material and the microhardness variations of X6CrNiTi18-10 were analyzed at different cavitation conditions in a cavitation chamber, Ref. [14]. The main intention of this research was to obtain mechanical properties at different temperatures of these materials as well as consider their creep resistance and fatigue limit.

2. Considered materials, equipment, specimens, standards
Tested materials were, table 1: 42CrMo4 steel (chromium-molybdenum – manganese low-alloy constructional steel, 16 mm, soft annealed and cold drawn), applications: statically and dynamically...
stressed machine components (gears, crankshafts, etc.); X46Cr13 steel (chromium martensitic stainless steel, 16 mm annealed and cold drawn round steel), applications: in manufacturing of pump parts, machined metal parts, shaft, gears, tie rods, screws; X6CrNiTi18-10 steel (18 mm soft annealed austenitic stainless steel round bar, applications are as follows: automotive industry, chemical industry (chemical processing equipment), building and construction industries, food and beverage industries and aviation and aerospace industries.

Table 1. Tested materials: Chemical compositions (only some elements are shown)

| Material          | Chemical composition: some of the elements |
|-------------------|-------------------------------------------|
| 42CrMo4; 1.7225; AISI 4140 | C 0.42, Cr 1.07, Si 0.24, Mn 0.84, Mo 0.22, Ni - |
| X46Cr13; 1.4034; AISI 420 | C 0.442, Cr 13.05, Si 0.375, Mn 0.381, Mo 0.049, Ni - |
| X6CrNiTi18-10; 1.4541; AISI 321 | C 0.0176, Cr 16.95, Si 0.436, Mn 1.44, Mo 0.241, Ni 9.236 |

Equipment used: materials testing machine (Zwick/Roell) of 400 kN, macro-extensometer, high temperature extensometer, furnace (900°C), dynamic testing machine (Servopulser), (±50kN). Specimens for tensile testing related to stress-strain diagrams and tensile creep behavior were manufactured in accordance with ASTM Standard, ASTM: E 8M-15a, and for fatigue axial testing in accordance with ASTM: E 466-15 standard. Standard used in tensile testing related to 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 has been carried out according to ISO 2017 standard. Also, all mentioned ASTM standards can be found in Annual Book of ASTM Standards (2015), [15].

3. Experimental results

3.1 Determination of engineering stress-strain diagrams

Engineering stress-strain diagrams were obtained on the basis of tensile tests which were performed at different temperatures, figure 1.
Based on these diagrams mechanical properties (ultimate tensile strength, yield strength, modulus of elasticity) as well as total elongation and contraction in area of the specimen of considered steels were determined. As it is visible, steel X46Cr13 has the highest ultimate tensile strength [6, 8, 10].

3.2. Short-time creep tests
Short-time creep tests show the behavior of the considered material during considered time period. This behavior of the material is very important property that defines the possibility of use of the material at higher temperature range. As it is known only 1-2% of creep strains are allowed in engineering practice. Consideration and knowledge of the creep behavior of material is of importance for material that can be exposed to high temperature in short time such as fire or other hazard environmental conditions. In figure 2 creep behavior of considered materials is shown.

Creep resistance of considered materials can be assessed based on the performed short-time creep tests, [6, 8, 10]. Based on known creep curves sometimes is of interest to model creep behavior using analytical formulas or rheological models. These procedures are more useful since experimental investigations consume much time and money.
3.3 Fatigue testing

Fracture of an engineering element is usually defined as the process of damage accumulation due to cyclic loading during its service life [16]. In this investigation uniaxial cyclic loading was considered. Tests were carried out at stress ratio \( R = 0.25 \) at all of examined materials and at \( R = -1 \) at steel X46Cr13. Tests were performed on unnotched specimens in accordance with the ISO 12107:2012 (2012) standard, [17]. As the results of the fatigue tests, experimentally obtained data are placed in a coordinate system, figure 3. On the ordinate (\( \sigma_{\text{max}} / \text{MPa} \)) data related to the maximum stresses is plotted, while on the abscissa (N) data related to the number of the cycles to failure is plotted. In this way, so called \( S – N \) diagram (stress versus number of cycles to failure), or diagram known as Wohler curve or fatigue life diagram can be created, [6, 8, 10]. Fatigue limit (endurance limit) was calculated by modified staircase method.

![Fatigue test graphs](image)

**Figure 3.** Stress versus number of the cycles to failure: \( S – N \) curves.

Based on the obtained results it is visible that the lowest fatigue limit has material X6CrNiTi18-10, when consideration is taken for stress ratio \( R = 0.25 \).
4. Conclusion
Mechanical properties, creep resistance and fatigue limit were determined for considered materials based on experimental investigations. These data can be of interest for designers who are involved in structural design using considered materials. Based on these investigations it is visible that material X6Cr13 has the highest ultimate tensile strength at room temperature, material X6CrNiTi18-10 may be treated as most creep resistant, while material X6Cr13 has the highest fatigue limit. Some other investigations related to Charpy impact energy, fracture toughness as well as fatigue limit at elevated temperature can be of interest.

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