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# Analysis of the mechanical response of materials used in design for highly stressed components

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**Abstract.** In this paper both the mechanical properties and responses of materials usually used in engineering for design and manufacture of highly stressed components were considered. Between the materials used for the aforementioned purposes are considered the following steel alloys: 30CrNiMo8, 20MnCr5, 51CrV4. Investigated mechanical properties of the materials were ultimate tensile strength, yield strength and modulus of elasticity, while in the area of mechanical responses were explored / tested creep behaviour and fatigue of the considered materials. In general, all of the responses are presented in the form of stress-strain curves, creep curves and S-N curves (maximum applied stress versus the number of the cycles to failure). Mechanical properties were tested at different temperatures, creep behaviour was investigated at different temperatures when material was subjected to stresses at prescribed percentage of yield strength while fatigue of the considered materials was investigated on smooth unnotched specimen for prescribed maximum uniaxial stress and for prescribed stress ratio. In addition, all of obtained data were analysed and compared regarding the type of used materials.

## 1. Introduction

Different types of materials are used in different environmental conditions. This means that material must be chosen in accordance with the purpose of the structure, the environmental operating conditions and with the choice of the process by which it is to be shaped or joined [1]. Under structure, it is understood any type of construction or machine. In the considered case, used material must be able to take high stresses, dynamic loads, and must be creep resistant. On the basis of this, follows, for example, that material can be exposed to high stresses, high temperatures, creep and fatigue. Regarding the quality and reliability of the structure, taking into consideration the entire structure life from design through manufacture and exploitation, several key problems must be analysed. These problems are: purpose for which structure is intended to be used, environmental operating conditions, choice of material, lifetime prediction, safety, common causes of failures, possible (common) failure modes, analyses of how and why structural component has failed, etc. Causes of the failures and appropriate failure modes are interconnected. In engineering practice, structure is usually designed and manufactured in order to guarantee that it does not contain any failure. However, this does not have to be the correct approach. Common causes of failures are [2- 3]: inadequate choose of material, design errors (used material, the size and shape of an engineering component, properties), manufacturing defects, structural loading, temperature effects, misuse (the structure is subjected to conditions for which it was not designed), assembly errors, improper maintenance, unforeseen operating conditions, inadequate control, etc. These causes may be divided into pre-existing causes and that appearing in



service life. The same applies to failure modes [4]. Commonly observed failures mode in engineering practice are [5]: yielding, creep, fatigue, wear, corrosion, impact, buckling, etc. Any of particular mechanical failure has its cause of origin and the form of expression (mode of representation), i.e., failure mode. In this sense the cause can provide the answer why an engineering component has failed while the failure mode enables the answer how an engineering component has failed. In addition, it is useful to mention that science categories are involved in this problematic. In this sense, materials science primarily concerned with the basic knowledge of materials while materials engineering concerned with the use of the knowledge of materials. In accordance with the considered problems within this paper, i.e., design of highly stressed engineering components, the following subjects related to the applied materials were explored and analysed: mechanical properties, creep and fatigue of material. Designer who deals with material selection must be familiar with all of mentioned subjects. Some details of investigated responses of considered materials can be found in the literature. In this sense, in Ref. [6], effects of welding parameters related to 30CrNiMo8 steel were investigated, while, related to the same material, an analysis the relationship between cutting forces and tool wear during turning is presented in Ref. [7]. As far as 20MnCr5 steel is concerned, it is suggested to review papers published in Refs. [8-9]. In Ref. [8] material structure changes developing in the bore of gears made of a material of 20MnCr5 is considered, while in Ref. [9] dependence of material properties versus temperature are investigated. In addition, in Ref. [10] the microstructural features of 51CrV4 alloy, used as spring steel component, and its fatigue behavior was investigated. In Ref. [11] some of mechanical properties related to 51CrV4 steel and its responses are investigated. Three considered materials are selected for testing with respect to their use in high-stressed engineering elements, as above mentioned.

## 2. Data related to the tests

Chemical compositions of investigated materials are shown in table 1. All of tested materials can be used in applications for highly stressed engineering components. The equipment used in testing procedures were testing machine Zwick/Roell (400 kN), macro-extensometer, high temperature extensometer (900°C), dynamic testing machine ( $\pm 50$  kN). Testing procedures were performed in accordance with the standards contained in [12]: ASTM: E8M-15a (tensile testing at room temperature), ASTM: E21-09 (tensile testing at high temperatures), ASTM: E 139-11 (creep testing) as well as ISO standard 12017:2012 (tensile fatigue testing), [13].

**Table 1.** Tested materials: Chemical compositions (some elements only), mass %

Material / round bar (mm)	Chemical composition (some elements only), mass %					
	C	Cr	Si	Ni	Mn	Mo
<b>30CrNiMo8</b> (1.6580/AISI 4340) /20	0.29	2.07	0.31	1.89	0.41	0.24
<b>20MnCr5</b> (1.7147/AISI 5120) /18	0.22	1.11	0.29	0.08	1.23	0.01
<b>51CrV4</b> (1.8159/AISI 6150) /20	0.45	1.09	0.32	0.22	0.92	0.005

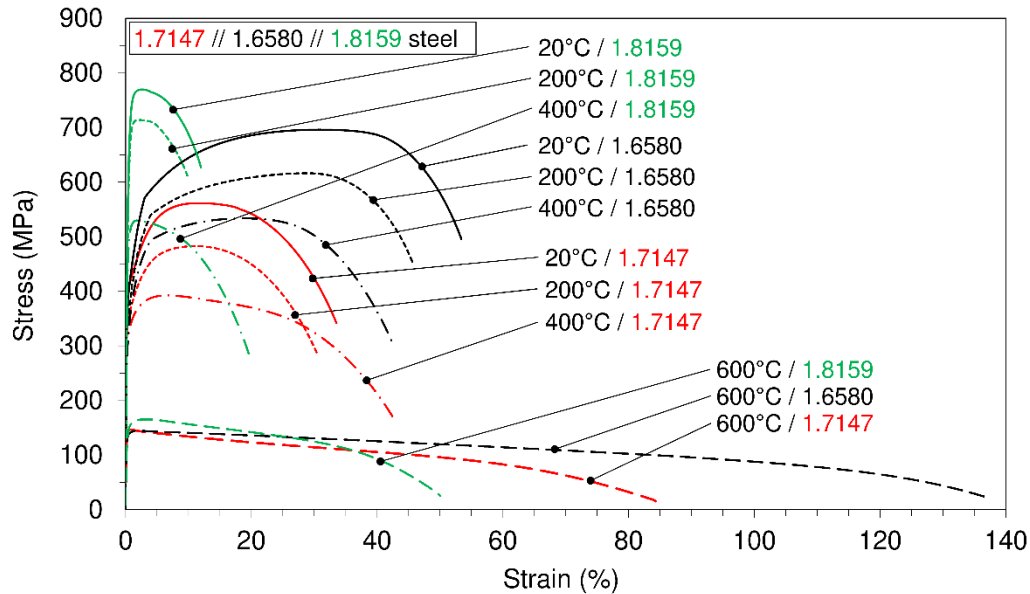
Delivered state of the material and its description:

30CrNiMo8 (annealed, low alloy); 20MnCr5 (annealed, low-carbon, low chromium); 51CrV4 (annealed, chromium-vanadium). All of tested specimens were manufactured from round bars according to the appropriate standards. In this sense, specimens used in the procedure of mechanical properties determination were manufactured in accordance with ASTM standards [12], while those used in fatigue testing (smooth unnotched specimen) in accordance with ISO standard [13]. In each type of test, 3-5 specimens were tested. The results presented mostly refer to the first test. All tests were performed as uniaxial tests, and at fatigue testing procedure was conducted as stress-controlled test. With respect to the geometry of the specimen no stress concentration factor was considered, and also, no multiaxial stress state can be addressed since no multiaxial loading was considered.

### 3. Results of research and analysis

#### 3.1 Determination of mechanical properties based on engineering stress-strain diagrams

Engineering stress-strain diagrams at different temperatures for tested materials are shown in figure 1.

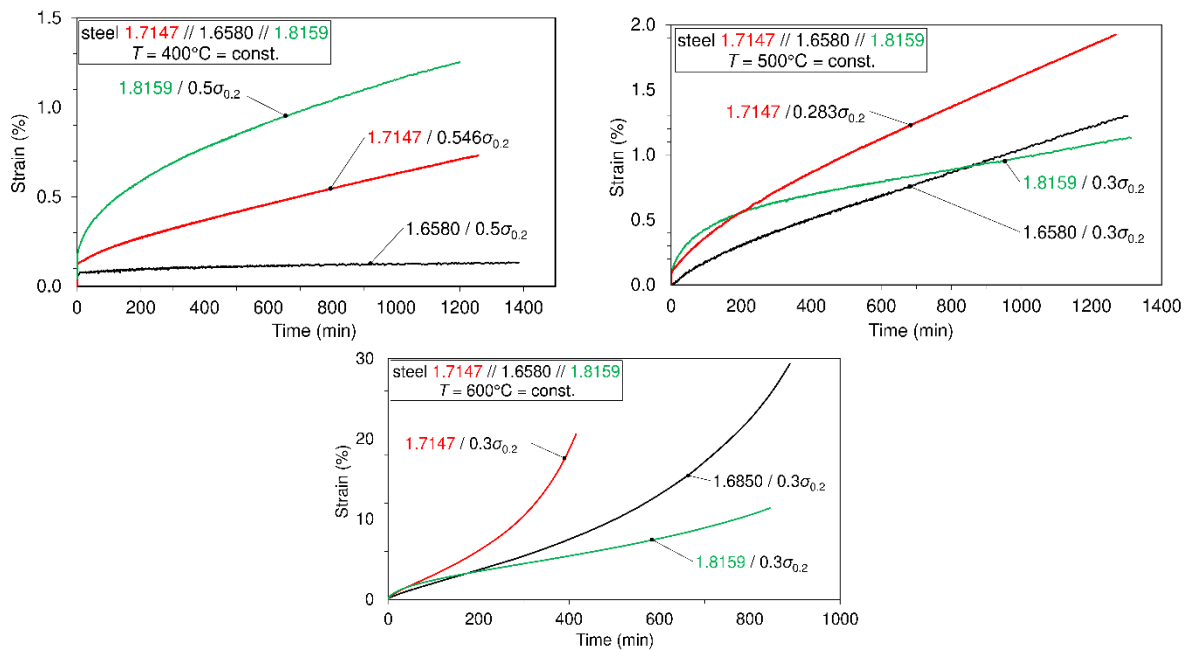


**Figure 1.** Engineering stress-strain diagrams at different temperatures: 1.8159 (51CrV4), 1.6580 (30CrNiMo8), 1.7147 (20MnCr5).

Mechanical properties as well as elongations and contractions can be derived on the basis of above presented diagrams. As it is visible 1.8159 steel has the highest values of the mechanical properties and the lowest elongation at the same time.

#### 3.2. Creep test results

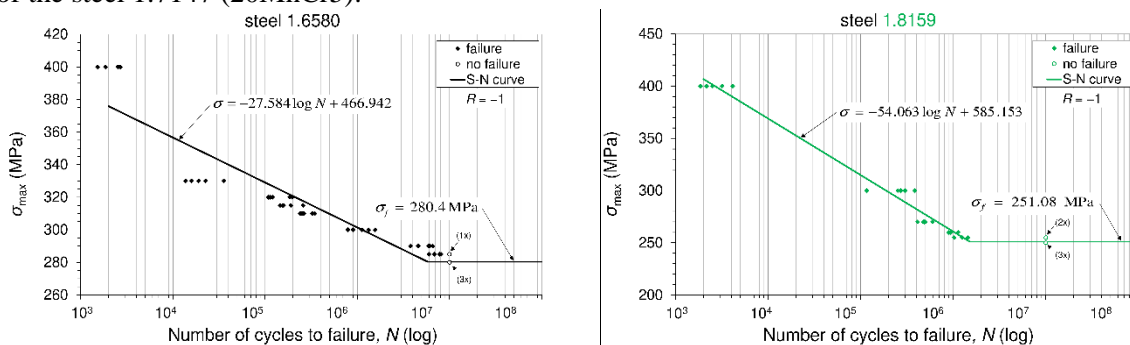
Short-time creep tests performed at different temperatures and different stress levels were considered. These tests show the mechanical behavior of the material during considered time, i.e., resistance of material to creep. Creep is usually defined as time dependent process showing continuously material strain increase while the stress (load) is kept constant [14]. It is appreciable at temperature above 0.4 of melting temperature [15] and in engineering practice it is usually allowed within the limits (1-2) %. For each of the tested materials creep behavior is presented in figure 2. All of materials were tested at the same temperatures and very similar stress levels regarding the percentage of their yield strength. As it is visible, at temperatures of 400°C steel 1.8159 has the parabolic shape for the longest period. In accordance with this, at higher temperatures and at new selected stress levels, this type of steel changes its shape of creep curve the slowest. From this point of view, it is apparent which material can be treated as the most resistant to creep.



**Figure 2.** Creep behavior of the tested materials at different temperatures and selected stress levels: 30CrNiMo8 (1.6580), 20MnCr5 (1.7147), 51CrV4 (1.8159)

### 3.3 Fatigue limit determination based on fatigue testing

Fatigue is one of very often encountered failure modes in dynamically stressed machine parts. Experience testifies that fracture of machine parts are often due to fatigue during regular operating conditions [16]. Based on fatigue tests performed on the specimens subjected to uniaxial cyclic loading at stress ratio  $R = -1$ , for some of tested materials, using ISO 12107:2012 (2012) standard, fatigue limit (endurance limit) was determined. Results of the fatigue tests are presented in figure 3 where on the ordinate ( $\sigma_{max}/\text{MPa}$ ) 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. This is so called S – N diagram (Wohler curve or fatigue life diagram). It is visible that steel 1.8159 (51CrV4) has higher fatigue limit than steel 1.6580 (30CrNiMo8). There was not enough test specimens to test the fatigue of the steel 1.7147 (20MnCr5).



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

## 4. Conclusion

The most important properties for all of investigated materials were determined. In this sense, at room temperature, steel 51CrV4 has the highest both ultimate tensile strength and yield strength (770 MPa, 642 MPa), while 30CrNiMo8 has (696 MPa, 583 MPa) and 20MnCr5 has (561 MPa, 397 MPa). Steel 51CrV4 can also be considered as the most effective regarding the creep resistance. In accordance

with experimental results steel 30CrNiMo8 (1.6580) exhibits the best fatigue limit. However, all of considered steels are suitable for use in design for highly stressed engineering components.

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