Comparison of Some Structural and Stainless Steels Based on the Mechanical Properties and Resistance to Creep

Josip Brnic, Goran Vukelic and Sanjin Krscanski

Abstract Knowledge of the properties of materials and their behavior in certain environmental conditions is one of the most important factors in the procedure of materials selection. In accordance with this fact, this paper presents and analyzes the experimental results relating to two structural (1.0044, 1.7228) and two stainless steel (1.4305, 1.4122) materials. Stress-strain diagrams as well as creep curves related to short-time creep are presented. According to the mentioned diagrams, the ultimate tensile strength, yield strength and modulus of elasticity are determined. On the other hand, based on material creep curves, some conclusions regarding to creep resistance may be given. Also some data related to Charpy impact energy is shown as well as fracture toughness assessment based on impact energy is made. Based on experimental results it can be said that all of the investigated materials have quite high tensile strength and yield strength. Also, these materials may be treated as creep resistant at temperature of 400 °C if the stress level does not exceed 50 % of the yield strength at this temperature.

Keywords Structural and stainless steels · Mechanical properties · Creep · Impact energy

J. Brnic (✉) · S. Krscanski
Faculty of Engineering, University of Rijeka, Vukovarska 58, Rijeka, Croatia
e-mail: brnic@riteh.hr

S. Krscanski
e-mail: sanjin.krscanski@riteh.hr

G. Vukelic
Faculty of Maritime Studies, University of Rijeka, Studentska ulica 2, Rijeka, Croatia
e-mail: gvukelic@pfri.hr

A. Öchsner and H. Altenbach (eds.), *Mechanical and Materials Engineering of Modern Structure and Component Design*, Advanced Structured Materials 70,
DOI 10.1007/978-3-319-19443-1_15

1 Introduction

The material for the design of structure is usually selected in accordance with purpose of the structure. The structure can, for example, be designed as a repository for gas under pressure, for movement of a load, for working at elevated temperatures, etc. However, the material properties of the designed structure must meet the conditions in which the structure will operate. Properties of the material are linked to the material chemical composition, processing path and material microstructure. Properties that depend on microstructure are called structure-sensitive properties. Among these properties can be counted mechanical properties like yield strength of the material, hardness, toughness, fatigue resistance, ductility. Processing is a way to develop and control microstructure, for example, hot rolling or something similar. A material should meet some of the requirements such as: high tensile strength, high creep resistance, fatigue strength, ductility, high temperature strength, heat resistance, resistance to high temperature corrosion, etc. In that way, the designer of the structure must be familiar with the knowledge of the material properties, e.g. he has to assess the material behavior under certain environmental conditions. Design philosophy includes material selection as well as production costs and both of these processes require optimization procedures [1, 2]. In general, optimization may be designated as making the best of things. In this case the term “best” refers to making the structure, for example, as light as possible, e.g., to minimize weight, or to make it as stiff as possible, etc. On the other hand, the stress analysis of the structure in the design process is commonly performed using the Finite Element Method [3]. It can be said that an engineering structure is usually designed, manufactured, maintained/controlled in order to guarantee that it does not contain any failures and that it can serve for the purpose for which it is intended. At room temperature and in the absence of adverse effects, a properly designed structure can support its static design load for an unlimited time [4]. Otherwise, at a sustained load of a certain level at elevated temperatures inelastic strains may occur in the material that increase with time. This phenomenon is known as creep [5]. Structure lifetime predictions and its safety during service life are key questions regarding its quality and reliability. Above implies that material availability, suitability for service conditions as well as the cost of the material should be considered. However, in engineering practice, a lot of failures may occur. These failures may be defined as any change in the size, shape or material properties of a structure that renders it incapable of satisfactorily performing its intended function. It is necessary to know why and how some engineering component has failed. In that way the main points related to the structural failure need to be mentioned and that cause of the origin of failure as well as mode of the failure manifestation. Usually, some failure causes worthy to be mentioned are: pre-existing defects or defects that initiate from imperfections, structural loading, corrosion, misuse (structure subjected to the conditions for which it was not designed), design errors, assembly error, improper maintenance, unforeseen operating conditions, yielding, creep, buckling, etc. The main attention in this research is paid to the comparison the material properties and creep resistance of selected structural and stainless steels [6–9]. Creep is usually defined as time-dependent inelastic strain under sustained load and elevated temperatures, creep may be said to be thermally activated process. Creep process at metals can be represented by creep curve consisting of three different stages and that primary (transient) stage, secondary (steady-state) stage and tertiary (accelerating) stage. Only a few percent (1–2) of creep strains is allowable in engineering practice. Dislocation climb, vacancy diffusion and grain boundary sliding are usually numbered as mechanisms of creep [10]. In addition, some data related to the minimum yield strength, tensile strength and elongation at room temperature for hot-rolled S275JR steel can be found in Ref. [11]. A study dealing with compression tests of $50CrMo_4$ steel to characterize its behavior at strains up to 150 % at appropriate strain rates are presented in [12]. Appling high temperature tension tests ductile damage evolution and fracture of a resulfurised stainless steel AISI 303 (1.4305) were analyzed in [13]. A study dealing with corrosion behavior of pipe steels used in Carbon Capture and Storage-technique (CCS) can be found in Ref. [14].

2 Data Related to Research

Materials under consideration were structural steels (1.0044/S275JR/ASTM A529; 1.7228/50CrMo4/AISI 4150) and stainless steels (1.4305/X10CrNiS18-9/AISI 303; 1.4122/X39CrMo17-1/AISI 420RM). Material 1.0044 was delivered as hot rolled bar and its applications are in many areas of engineering. Material 1.7228 can be used in statically and dynamically stressed larger cross-sections of structural components (aircraft and automotive industry, engines and machines). Material 1.4305 was delivered as a cold drown bar. It is primarily used in applications when corrosion or oxidation poses a problem. In addition material 1.4122 can be used in manufacturing of pump shafts, boat shafts for use in fresh water, then in polymer processing, compressor parts, etc. Test equipment in these investigations included: 400 kN material testing machine, the macroextensometer, a furnace (900 °C), high temperature extensometer and a Charpy impact machine. Specimens were machined from appropriate 18 mm steel rods. Material testing was performed in accordance with standards: uniaxial tests at room temperature were conducted in accordance with the standard ASTM: E8 M-11, while those at elevated temperatures in accordance with the ASTM: E21-09 standard. Creep tests were performed in accordance with ASTM: E139-11 standard, and Charpy impact tests were performed in accordance with ASTM: E23-07ae1 standard. All of the mentioned standards can be found in Ref. [15].

3 Research Results

3.1 Mechanical Properties

To compare the mechanical properties of the considered materials uniaxial tests were carried out. Using thus obtained engineering stress-strain diagrams at room and elevated temperatures (see Figs. 1, 2 and 3), it is possible to determine tensile strength, yield strength and the elastic modulus of the considered materials.

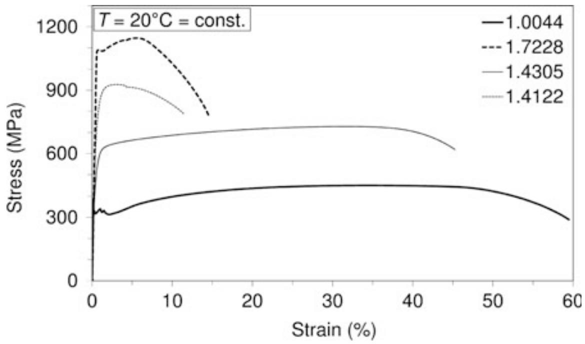

Fig. 1 Engineering stress-strain diagrams at room temperature for steels: 1.0044, 1.7228, 1.4305, 1.4122

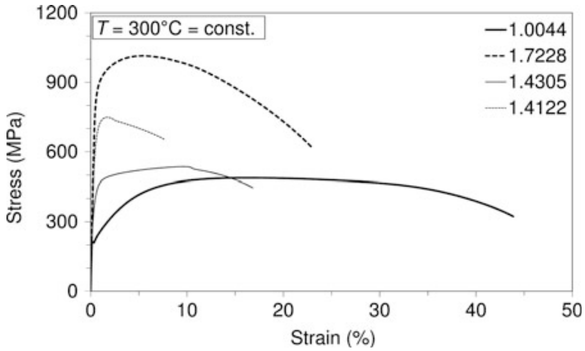

Fig. 2 Engineering stress-strain diagrams at temperature of 300 °C for steels: 1.0044, 1.7228, 1.4305, 1.4122

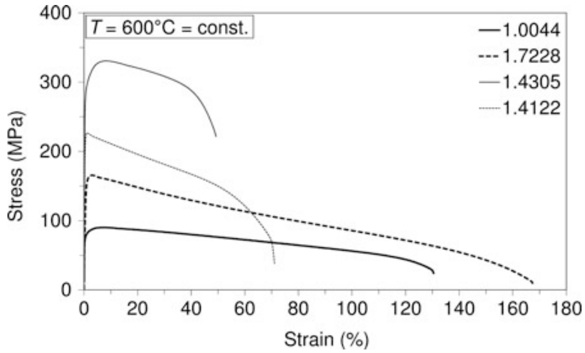

Fig. 3 Engineering stress-strain diagrams at temperature of 600 °C for steels: 1.0044, 1.7228, 1.4305, 1.4122

Based on the experimental results it is visible that all the materials at room temperature have a quite high ultimate tensile strength. The following data related to ultimate tensile strength, yield strength and modulus of elasticity at room temperature are as follows: (1.0044/452 MPa/323 MPa/211 GPa; 1.7228/1147 MPa/1090 MPa/204 GPa; 1.4305/728 MPa/467 MPa/187 GPa; 1.4122/927 MPa/746 MPa/208 GPa). Also it is visible that the lowest value of tensile strength at all test temperatures is the one of steel at 1.0044, while at the room temperature and at temperature of 300 °C steel 1.7228 has the highest ultimate tensile strength. At all of considered materials, ultimate tensile strength and yield strength decrease with temperature increase.

3.2 Short-Time Creep Tests

Several short time creep tests were carried out at selected stress levels and selected temperatures. At selected creep process, stress level is chosen to correspond to approximately the same percent of yield strength of the material under consideration that it has at the temperature of creep process. Creep tests were conducted at temperatures of 400, 500 and 600 °C. Creep curves are presented in Figs. 4, 5 and 6. As it can be seen on the basis of experiments, at a temperature of 400 °C, material 1.7228 tends to greater deformations. It should be noted, that this material was subjected to a higher level of stress at this temperature. As for creep at temperatures of 500 °C, it is evident that the materials 1.0044 and 1.4305 indicate a higher creep resistance. Regarding the creep process at 600 °C, it can be said that none of tested materials may be treated as creep resistant.

3.3 Assessment of Material Fracture Toughness Based on Experimental Impact Energy

As it is known, the yield strength of the material is a measure in structural design against plastic deformation while fracture toughness may serve as a measure against

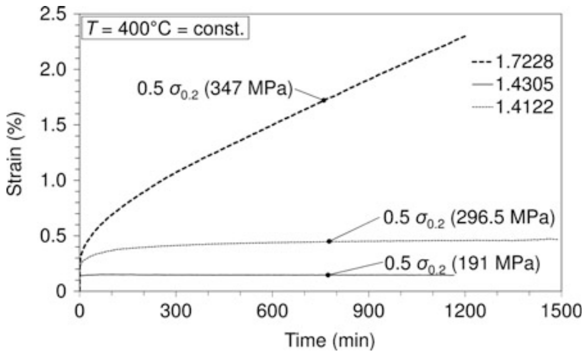

Fig. 4 Short-time creep process at temperature of 400 °C

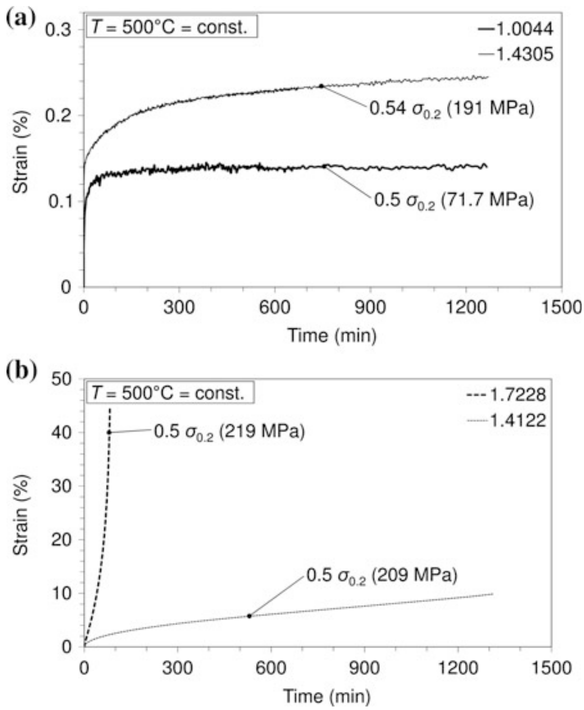

Fig. 5 Short-time creep process at temperature of 500 °C

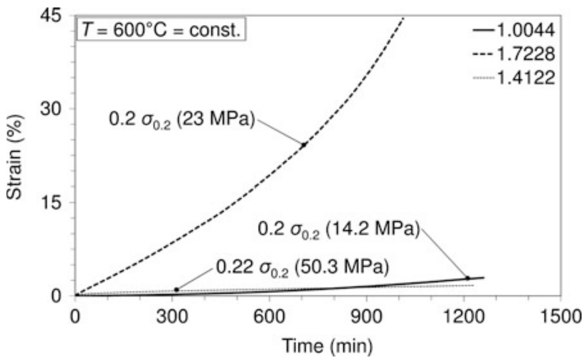

Fig. 6 Short-time creep process at temperature of 600 °C

fracture. However, the critical value of stress impact factor (SIF) is known as plane strain fracture toughness (K_{Ic}). This case implies that the fracture toughness of the material does not change with increasing thickness of the specimen. In general, the fracture toughness of the material is usually tested in laboratory conditions. Also, it can be said, that during this examination some problems may arise. On the other hand, it is also not advisable to use the results directly in engineering practice. To avoid some difficulties in experimental investigations, and for simplicity, the Charpy impact method can be used for impact energy determination. Based on the

Table 1 Charpy impact energy and fracture toughness calculation

Material: steel	Specimen 2 V-notch; temperature 20 °C	
	CVN (J)	K_{Ic} (Eq. 1) $(MPa\sqrt{m})$
1.0044	210	245.9
1.7228	69	122
1.4305	46	94.5
1.4122	16	48.6

impact energy, an assessment of fracture toughness can be made. Using, for example, the Roberts-Newton formula that is valid regardless of temperature, fracture toughness can be calculated as follows [16]:

$$K_{Ic} = 8.47(CVN)^{0.63}. \quad (1)$$

In addition, in Table 1 some data is presented related to Charpy impact energy.

4 Conclusion

The research results presented in this paper can be useful for designers of structures that can be made of considered materials. On the basis of presented engineering stress-strain diagrams it is visible that all of the considered materials have enough high mechanical properties at room temperature but these properties decrease with an increase in temperature. Also, it is visible that material 1.7228 has the highest mechanical properties at room temperature. Regarding creep resistance, it may be said that at a temperature of 400 °C, materials 1.4305 and 1.4122 can be treated as creep resistant, while at temperature of 500 °C materials 1.0044 and 1.4305 may be treated in the same way. At the temperature of 600 °C practically none of considered materials is creep resistant. The highest value of Charpy impact energy at room temperature was measured for the case of material to be 1.0044.

Acknowledgment Research presented in this paper has been financially supported by Croatian Science Foundation under the project 6876 and by the University of Rijeka under the project 13.09.1.1.01.

References

1. Papalambros PY, Wilde DJ (2000) Principles of optimal design, 2nd edn. Cambridge University Press, Cambridge
2. Rao SS (2009) Engineering optimization, 4th edn. Wiley, New Jersey
3. Borst R, Crisfield MA, Remmers JJC, Verhoosel CL (2012) Nonlinear finite element analysis of solids and structures, 2nd edn. Wiley, Chichester

4. Boresi AP, Schmidt RJ (2003) Advanced mechanics of materials, 6th edn. Wiley, New York
5. Collins A (1993) Failure of materials in mechanical design, 2nd edn. Wiley, New York
6. Brnic J, Turkalj G, Niu J et al (2013) Analysis of experimental data on the behavior of steel S275JR—reliability of modern design. Mater Design 47:497–504
7. Brnic J, Canadija M, Turkalj G et al (2010) 50CrMo4 Steel-determination of mechanical properties at lowered and elevated temperatures, creep behavior and fracture toughness calculation. J Eng Mater-T ASME 132(2):021004–1–021004-6
8. Brnic J, Turkalj G, Canadija M et al (2012) Responses of austenitic stainless steel american iron and steel institute (AISI) 303 (1.4305) subjected to different environmental conditions. J Test Eval 40(2):319–328
9. Brnic J, Turkalj G, Lanc D et al (2013) Testing and analysis of X39CrMo17-1 steel properties. Constr Build Mater 44:293–301
10. Raghavan V (2004) Materials science and engineering. Prentice-Hall of India, New Delhi
11. Simões da Silva L, Rebelo C, Nethercot D et al (2009) Statistical evaluation of the lateral–torsional buckling resistance of steel I-beams, part 2: variability of steel properties. J Constr Steel Res 65(4):832–849
12. Diot S, Gavrus A, Guines D et al (2003) Identification of a steel compression behaviour: from quasi static approach to dynamic one. Mec Ind 4–5:519–524
13. Tinet H, Klöcker H, Le Coze J (2004) Damage analysis during hot deformation of a resulfurised stainless steel. Acta Mater 52(13):3825–3842
14. Pfennig A, Kranzmann A (2011) Reliability of pipe steels with different amounts of C and Cr during onshore carbon dioxide injection. Int J Greenh Gas Con 54:757–769
15. ASTM International (2012) Annual book of ASTM standards—metal test methods and analytical procedures vol. 03.01. ASTM International, Baltimore
16. Roberts R, Newton C (1981) Interpretive report on small scale test correlation with K_{Ic}. Dana Weld Res Council Bull 265:1–16