Steel and Composite Structures, *Vol. 17*, *No. 5* (*2014*) *549-560*
DOI: http://dx.doi.org/10.12989/scs.2014.17.5.549

Mechanical testing of the behavior of steel 1.7147 at different temperatures

Josip Brnic *, Goran Turkalj and Marko Canadija

Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia

(*Received December 24, 2013, Revised February 03, 2014, Accepted March 24, 2014*)

Abstract. The paper provides the test results and analysis on the behavior of steel 1.7147 at different temperatures. Mechanical uniaxial tests were used to determine mechanical properties, resistance to creep and Charpy impact tests to determine impact energy. Test results are presented in the form of engineering stress-strain diagrams, creep curves as well as numerical data related to impact energy. The results show that the tensile strength has the highest value at room temperature, and the same goes for the yield strength as well as for modulus of elasticity. After room temperature both of mentioned properties decrease with temperature increasing. Some of creep curves were modeled using rheological models and analytical equation. Based on Charpy impact energy an assessment of fracture toughness was made.

Keywords: 1.7147 steel; material properties; creep; creep modeling; fracture toughness calculation

1. Introduction

Structures and machines are being designed for a specific purpose. In recent time, design process is based on the high capacity computers where structure analysis is performed using finite element method. Optimization of the structure is an integral part of the design process. Optimization is the process of obtaining the best result (solution) under given circumstances, Rao (2009). For example, in design procedure optimization is a mean to reach the best structure design which can guarantee the minimum weight of the structure while satisfying the prevailing constraints. In this sense engineers must have an understanding of the theory and techniques as well as manufacturing possibilities, Belegundu and Chandrpatla (2011). In any case a structure should be designed and manufactured in such a way that undesirable failure don not occur during its service life, Shijve (2009). However, some of structures or some of the machines are working in specific conditions. In this respect it is necessary to take into account the assessment of the service life of these structures. Specifically, it is important to know the possible reasons for the occurrence of failures and the way in which these failures can be manifested. Namely, particular failure has its cause of origin and the mode of manifestation. From other words it is very important for designer as well as for manufacturer and for customer, to be familiar with the fact why and how some engineering element has failed. This analysis may lead to the realization of preventive

*Corresponding author, Professor, E-mail: brnic@riteh.hr

http://www.techno-press.org/?journal=scs&subpage=8 ISSN: 1229-9367 (Print), 1598-6233 (Online)

action to avoid the appearance of failures. Failure may occur due to many reasons. In general, fracture of an element, i.e., separation of an element into two parts, occurs by propagation of one or several cracks. A discipline that deals with the problems of fracture is fracture mechanics, and it is driven to prevent failure of engineering components, Gross and Seeling (2011). In engineering practice a list of commonly observed failure modes can be encountered. At the mentioned list the following failures can be found: yielding, fatigue, creep, corrosion, etc., Collins (1993). Yielding failure occurs when the plastic deformation becomes large enough to interfere with the ability of the element to perform its intended function. Fatigue failure defines phenomenon when an element can be suddenly separated into two or more parts as a result of application of load. Creep, however, results in a large deformation of an engineering element which is subjected to high level of stress at elevated temperature, and the element appears to be unable to perform its intended function. Creep may be defined as time-dependent inelastic strain under sustain load and elevated temperature, Boresi and Schmidt (2003). Usually, creep is represented by creep curve consisted of three stages, and that, primary stage, secondary stage and tertiary stage. In engineering practice the most allowable strains may be those which belong to the secondary stage of creep, and they must not exceed 1-2%, Raghavan (2004). Main reason of the research, whose results are reported in this paper, is to provide information on the behavior of this material at high temperatures to all concerned, particularly to designers of the structure. This work provides insight into the data that characterize this material in special circumstances and which data are not available from the available literature. In literature can be found some data related to the material under consideration. So, in Martins *et al*. (2011) is presented a study of the influence of oil formulation on the protection against gear micropitting as well as on gear efficiency. Gears were made of 1.7147 steel. Further, very high cycle fatigue (VHCF) was studied, Bomas *et al*. (2012), using notched and fracture mechanics specimens which were machined from the steel SAE 5120 (1.7147 steel). According to the requirements for controlled tribological performance of gear contacts, a study was presented in Ahlroos *et al*. (2009). Some tests were carried out on the twin disc, made of 1.7147 (20MnCr5) steel. Some investigations related to splined shafts used in truck diesel engine, because of their possible fracture, were made and results are presented in Yu *et al*. (2012). The failed shafts were made of 1.7147 steel. Also, in Conrado *et al*. (2011) multiaxial fatigue criteria, was considered on rolling–sliding line contact problems taking into account both mechanical and thermal contact loads. One of considered materials was 1.7147 steel. As it was mentioned, the knowledge of both material properties and material behavior at certain environmental conditions is of great importance for designers of the structure. In this sense, it can be useful to have an insight in Brnic *et al*. (2010a, b, 2011a, b, 2012, 2013), Pepelnjak *et al*. (2005), Klobcar *et al*. (2012) and Milutinovic *et al*. (2012).

2. Preparation for experimental researches

2.1 Considered material

Material under consideration was steel 1.7147, usually called special structural steel, delivered as annealed. Chemical composition of this steel in mass (%) is given in Table 1. It may be characterized by good corrosion resistance, high hardness, toughness and strength. Its application is in engineering, particularly in production of highly stressed parts, like crankshaft, or other structural elements used in engineering.

Table 1 Chemical composition of considered steel

Chemical composition of steel 1.7147 (Mass (%))														
C	Mn	Cr	Si	Ni	Cu	Nb	S	P	Ti	W	Mo	V	Al	Rest
0.22	1.23	1.11	0.29	0.08	0.06	0.03	0.025	0.021	0.02	0.02	0.01	0.01	0.01	96.864

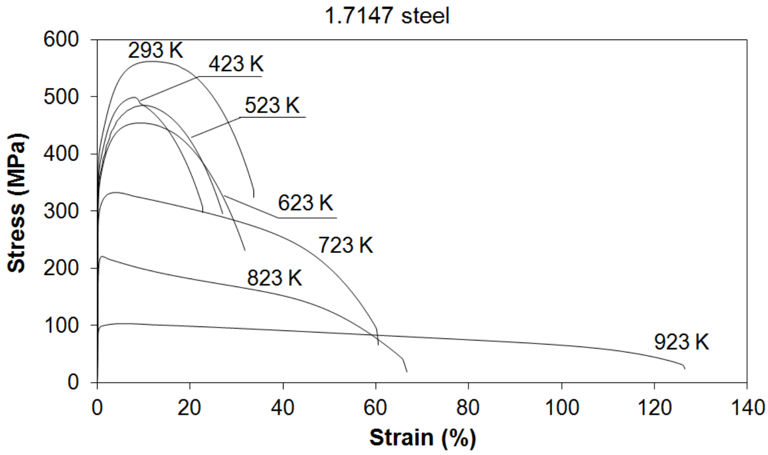


Fig. 1 Engineering stress-strain diagrams for steel 1.7147

2.2 Testing equipment, specimens and standards

Material testing machine capacity of 400kN was used in all of tensile tests, i.e., in tensile testing of mechanical properties and creep tests. Furnace (1173 K) and high temperature extensometer were used when testing at elevated temperatures was performed. Charpy impact machine was used in determination of fracture impact energy. Tensile tests related to room temperature were carried out according to ASTM: E8M-11 standard, while those related to elevated temperatures were carried out according to ASTM: E21-09. Creep tests were carried out according to ASTM: E139-11standard, Charpy impact tests were carriebd out according to ASTM: E23-07ae1 standard while preparation of metallographic specimens was conducted according to ASTM E3-11 standard. All of mentioned standards can be found in Annual Book of ASTM Standards (2012).

3. Experimental results

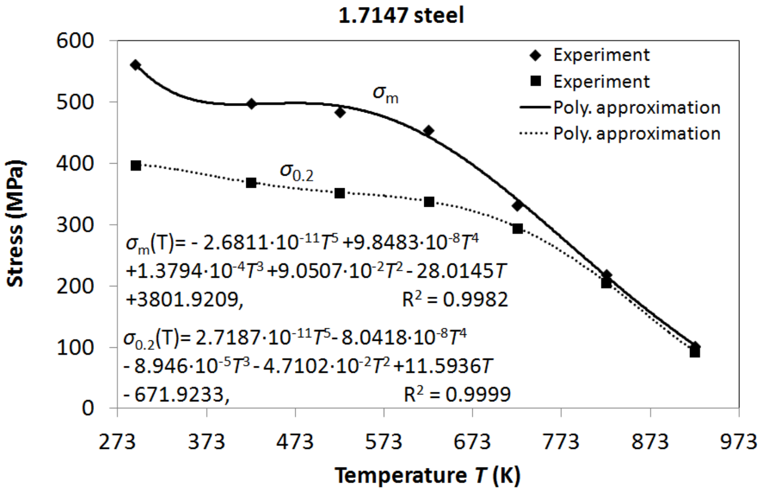
3.1 Material properties and their temperature dependence

Tensile tests for several temperatures were carried out. Engineering stress-strain diagrams are presented in Fig. 1.

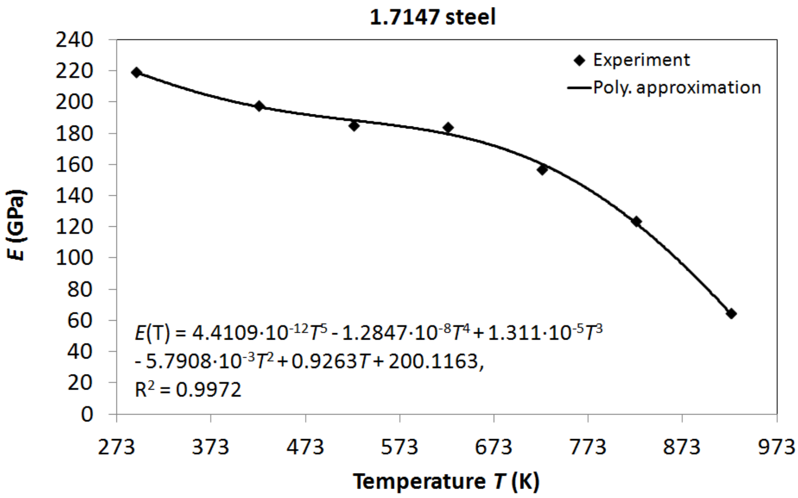
Temperature dependence of material properties is shown in Fig. 2.

Since the experimental studies and monitoring of real processes in engineering practice can be very expensive, there is an interest in a particular process or material response how to predict it, i.e., to predict the performance of a specific process. For this reason, a real process is to be simulated. Also, an analysis between a real and simulated process can be made. This analysis determines the accuracy with which the simulated process can replace the real process. A coefficient, called the coefficient of determination (R^2) is established, which is a measure of accordance of real (measured) and simulated (modeled, approximated, predicted) values. The R^2 is a statistic that gives information about how fit a model is, Draper and Smith (1998). In accordance with this, in Fig. 2, a set of measured values and their polynomial approximations is presented.

Based on Fig. 1, Fig. 2 and Table 2, it is visible that ultimate tensile strength and 0.2 offset yield strength as well as modulus of elasticity decreases with temperature increase. Also, it is

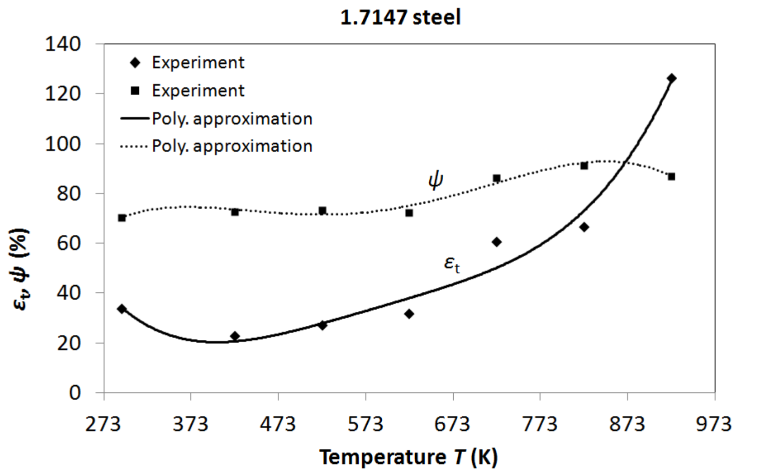


(a) Mechanical properties versus temperature



(b) Modulus of elasticity versus temperature

Fig. 2 Material properties versus temperature for steel 1.7147
(σ_m – ultimate tensile strength; $\sigma_{0.2}$ – 0.2 offset yield strength; E – modulus of elasticity;
ε_t – total strain, strain at break; ψ – reduction in cross-sectional area of the specimen)



$\varepsilon_t(T) = 4.0293 \cdot 10^{-9}T^4 - 9.3961 \cdot 10^{-6}T^3 + 8.2377 \cdot 10^{-3}T^2 - 3.1152T + 446.5191$, $R^2 = 0.9759$

$\psi(T) = 8.1529 \cdot 10^{-13}T^5 - 5.4008 \cdot 10^{-9}T^4 + 9.7061 \cdot 10^{-6}T^3 - 7.2219 \cdot 10^{-3}T^2 - 2.3756T - 211.8381$, $R^2 = 0.9632$

(c) Total strain and reduction in area versus temperature

Fig. 2 Continued

Table 2 Tensile creep tests related to steel 1.7147 – temperature and stress levels

Material Steel 1.7147	Constant temperature (K)		
	723	823	923
Constant stress level σ (MPa)	$\sigma = 0.25\sigma_{0.2} = 73.8$	$\sigma = 0.25\sigma_{0.2} = 51.6$	$\sigma = 0.1\sigma_{0.2} = 9.3$
	$\sigma = 0.35\sigma_{0.2} = 103$	$\sigma = 0.35\sigma_{0.2} = 72.4$	
	$\sigma = 0.5\sigma_{0.2} = 147.5$	$\sigma = 0.5\sigma_{0.2} = 103.2$	

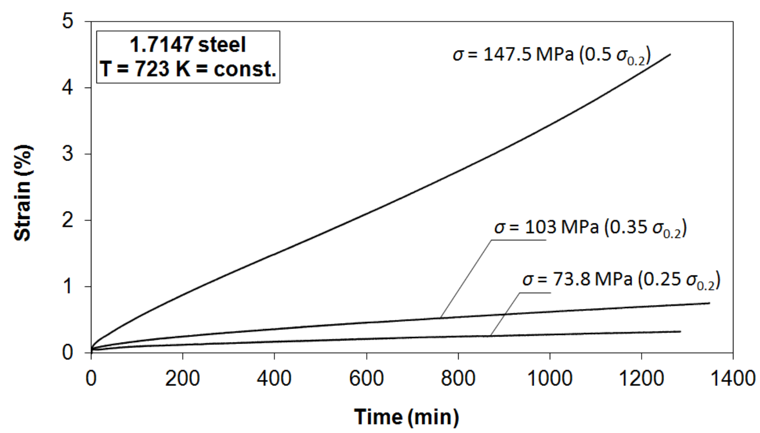


Fig. 3 Creep behavior of steel 1.7147 at temperature of 723K

visible that this steel has high strength at room temperature which makes it eligible for use in the manufacture of highly stressed engineering elements.

3.2 Short-time creep tests results and simulation

For any material is important to know how it behaves when it is exposed to elevated temperatures. To obtain information about the behavior of this steel in high temperature conditions, several tensile creep tests were carried out. Both temperature and stress levels of performed tests are given in Table 2, while appropriate creep curves are presented in Figs. 3-5.

Conduction of experiments is sometimes very expensive. Instead of an experiment simulation may be very useful to simulate material behavior for a specific load at a specific temperature. Simulation of creep behavior may be done using some known formula or by rheological models. In this paper, simulation is performed using two known rheological models and that, Burgers model and Standard Linear Solid (SLS) model, as well as using a formula which was proposed by authors of this paper.

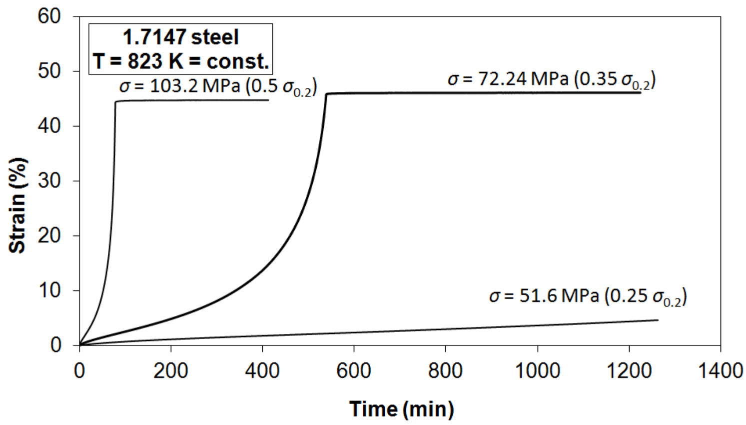


Fig. 4 Creep behavior of steel 1.7147 at temperature of 823K

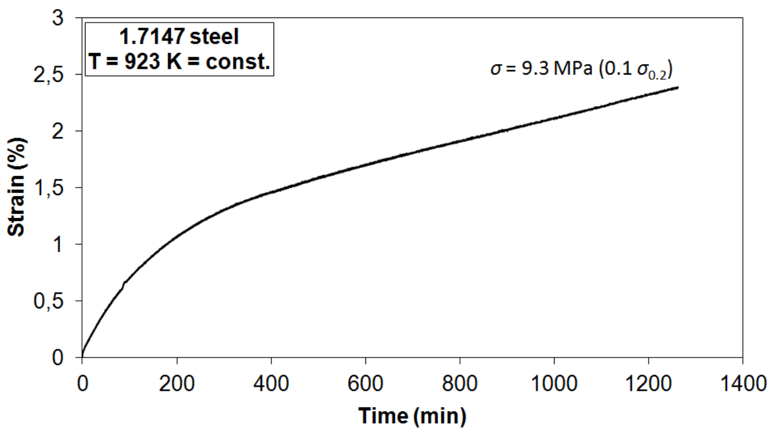


Fig. 5 Creep behavior of steel 1.7147 at temperature of 923K

For the Burgers model the following equation is valid, Brnic *et al*. (2010a)

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

In Eq. (1) there are: σ – stress, ε – strain, E_1 – modulus of elasticity, t – time, and E_2, η_1, η_2 are material parameters.

The Burgers model may be suitable for modeling both primary and secondary parts of the creep process (curve) but not for the tertiary part of the creep curve. The quality of the simulation using Burgers model depends on the stress range and of the shape of primary creep stage. The simulation will not be of appropriate quality if stress range is wide and shape of the primary creep range is markedly parabolic.

For the SLS model the following equation is valid, Plaseied and Fatemi (2008)

$$\varepsilon(t) = \frac{\sigma}{E_1} + \sigma\left(\frac{1}{E_1 + E_2} - \frac{1}{E_1}\right)\cdot e^{-\frac{E_1 E_2 t}{(E_1+E_2)\eta}} \tag{2}$$

In Eq. (2) there are: σ – stress, ε – strain, t – time, and E_1, E_2, and η are material parameters.

SLS model is quite suitable for creep modeling when primary creep stage is parabolic.

Table 3 Data for modeling selected creep curves of steel 1.7147

Material	steel 1.7147			
Constant temperature T(K)	723		823	923
Constant stress level σ (MPa)	$\sigma = 0.25\ \sigma_{0.2} = 73.8$	$\sigma = 0.35\ \sigma_{0.2} = 103$	$\sigma = 0.25\ \sigma_{0.2} = 51.6$	$\sigma = 0.1\ \sigma_{0.2} = 9.3$
Time (min)	1250	1250	1250	1250
Burgers model Eq. (1)	$E_1 = 157$ GPa $E_2 = 8.6054\cdot10^8$ Pa $\eta_1 = 1.66067\cdot10^8$ Pa min $\eta_2 = 3.72236\cdot10^{11}$ Pa min	$E_1 = 157$ GPa $E_2 = 5.45524\cdot10^8$ Pa $\eta_1 = 3.54228\cdot10^{10}$ Pa min $\eta_2 = 2.38064\cdot10^{11}$ Pa min	$E_1 = 124$ GPa $E_2 = 9.47156\cdot10^7$ Pa $\eta_1 = 4.33181\cdot10^9$ Pa min $\eta_2 = 1.62619\cdot10^{10}$ Pa min	$E_1 = 65$ GPa $E_2 = 8.46542\cdot10^6$ Pa $\eta_1 = 1.07276\cdot10^9$ Pa min $\eta_2 = 9.09395\cdot10^9$ Pa min
SLS model Eq. (2)	$E_1 = 1.72156\cdot10^8$ Pa $E_2 = 9.88685\cdot10^8$ Pa $\eta = 1.64526\cdot10^{11}$ Pa min	$E_1 = 9.99047\cdot10^7$ Pa $E_2 = 9.52449\cdot10^8$ Pa $\eta = 1.08673\cdot10^{11}$ Pa min	$E_1 = 1.9659\cdot10^6$ Pa $E_2 = 1.26889\cdot10^8$ Pa $\eta = 1.39786\cdot10^{10}$ Pa min	$E_1 = 3.98775\cdot10^6$ Pa $E_2 = 3.38663\cdot10^7$ Pa $\eta = 1.62744\cdot10^9$ Pa min
Eq. (3) Parameters: D, p, r	Valid for temperature range $723 \le T \le 923$(K), $t \le 1250$ min For: $T = 723$ (K), $\sigma \le 0.35\ \sigma_{0.2}$; $T = 823$ (K), $\sigma \le 0.25\ \sigma_{0.2}$; (if $T\uparrow$; $\sigma\downarrow$) $T = 923$ (K), $\sigma \le 0.15\ \sigma_{0.2}$; $D = -2.1808\cdot10^{-9}\cdot T^4 + 5.209115\cdot10^{-6}\cdot T^3 - 4.585625\cdot10^{-3}\cdot T^2 + 1.764786\cdot T - 249.738$ $p = -3.738153\cdot10^{-8}\cdot T^4 + 9.630173\cdot10^{-5}\cdot T^3 - 8.968636\cdot10^{-2}\cdot T^2 + 36.04507\cdot T - 5299.098$ $r = 2.8239\cdot10^{-9}\cdot T^4 - 6.210586\cdot10^{-6}\cdot T^3 + 5.068501\cdot10^{-3}\cdot T^2 - 1.81896\cdot T + 242.8445$			

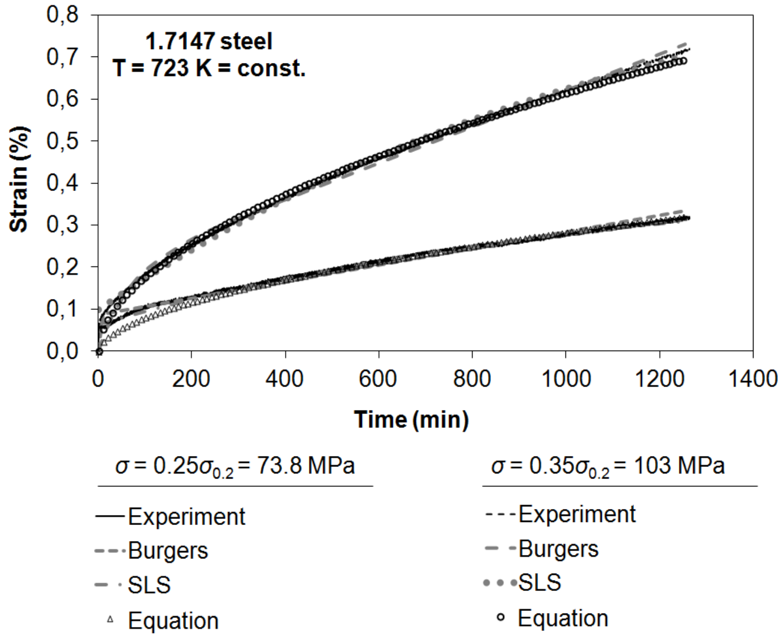


Fig. 6 Experimental creep curve and modelled curves for steel 1.7147 at temperature of $T = 723$ K

Also, the following equation can be proposed for creep simulation, Brnic *et al*. (2013)

$$\varepsilon(t) = D^{-T}\sigma^{p}t^{r} \tag{3}$$

where: σ and ε are stress and strain, while D, p, and r are material's parameters. T is temperature.

In Table 3 necessary data for modeling of selected creep curves are given and in Figs. 6-8 modeled creep curves are shown.

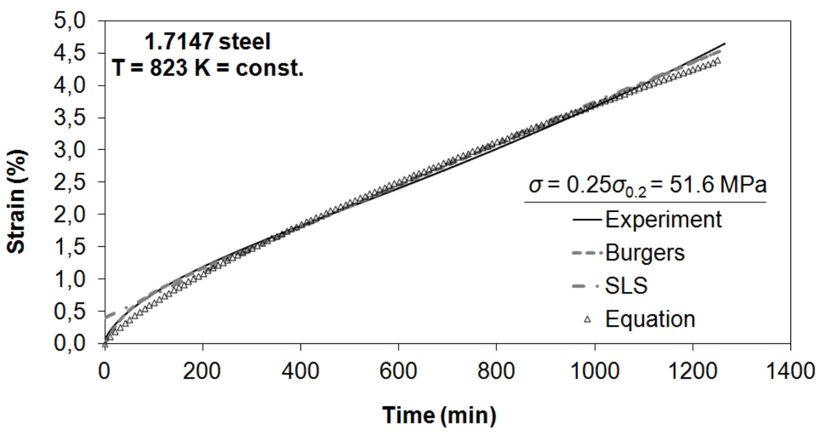


Fig. 7 Experimental creep curve and modelled curve for steel 1.7147

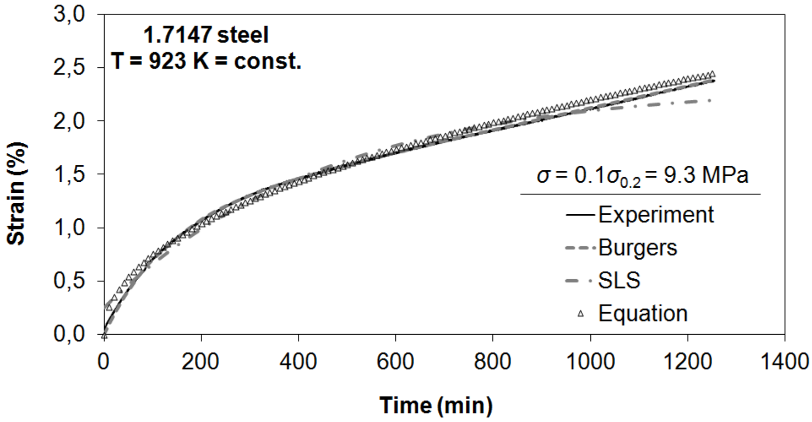
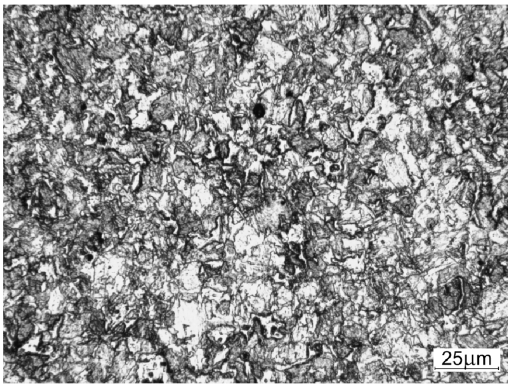
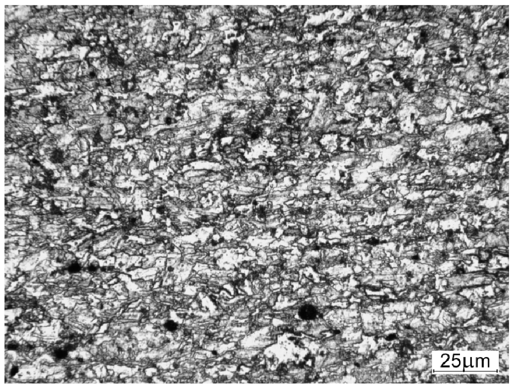


Fig. 8 Experimental creep curve and modelled curve for steel 1.7147 at temperature of T = 923 K



(a) As – received material, considered in this work



(b) After creep process conducted at 723 (K) / 147.5 MPa / 1200 min

Fig. 9 Optical micrograph of steel 1.7147, 4% nital

at temperature of $T = 823$ K.

Experimentally obtained results, presented in Figs. 3-5, show that steel 1.7147 is creep resistant till temperature of 723 (K) if stress level is less than 0.35 $\sigma_{0.2}$. When temperature increases then this material becomes less resistant to creep although stress level is low. As for the simulation of creep, it is possible to say that all the models that are used quite well simulate creep curves.

3.3 Microstructure of considered material

Two specimens were selected to get an insight in microstructure of this steel. Fig. 9(a) presents an optical micrograph of as-received material (one specimen). Fig. 9(b) presents an optical micrograph of this steel after its use in creep process (second specimen) conducted at temperature of 723 (K) / 147.5 MPa /1200 min. It is evident that it is a mixture of relatively small ferrite and granular cementite. Regarding the creep conducted at 450°C and given stress level, no significant changes at 450°C in the crystal grains can be visible, except a certain elongation in the direction of

Table 4 Fracture toughness calculation

Material: steel 1.7147				Charpy test; 2V notch	
Temperature (K)	Modulus of elasticity E (GPa)	Poisson ratio ν	Area A (mm^2)	CVN (J)	Fracture toughness (MPa $\sqrt{m}$) Eq. (4)
293	170	0.3	80	195	234.7
313	208	0.3	80	210	246
363	206	0.3	80	224	256
373	205	0.3	80	230	260

pull.

3.4 Engineering calculation of fracture toughness

Fracture toughness is one of the most important properties in design of structure against fracture. It can be measured by a number of standard tests, for example by ASTM standards in Anderson (1995), and it is a measure of material resistance to fracture. Although these experiments provides insight in material resistance to fracture, at the same time manufacture of specimens may be quite complicated. Also, specimens are made from disposable material not from structure in service. However, to avoid mentioned problems another tests may be applied to assess material resistance to fracture. One of possible tests is Charpy impact energy test using which fracture impact energy can be determined, and based on it, fracture toughness can be calculated. Of course, this test has some disadvantages, namely, specimen is small compared with real structure, and notch in this specimen is quite blunt compared with a sharp crack used in fracture mechanics tests. In spite of the possible disadvantages of these tests, for simplicity, they usually used to make an engineering assessment of fracture toughness. Some correlations between the results obtained by the Charpy tests and those made according to other prescribed standard tests have been reviewed in Roberts and Newton (1981) and Shekhter *et al*. (2002). In investigations related to considered material (1.7147) in this paper, several Charpy impact tests were carried out and the following results were obtained, Table 4. Fracture toughness calculation was made according to the Roberts – Newton formula

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

Eq. (4) may be used independent of temperature level. In this equation, CVN is Charpy V – notch impact energy. In Table 4, “A” is cross-sectional area of the specimen at the place of notch.

4. Conclusions

Material properties related to steel 1.7147 at different temperatures were determined. Creep behavior of this steel is also investigated. Using Charpy impact tests fracture toughness was calculated. As it is seen, all of material properties decrease with temperature increases. According to tests conducted, it can be said that this steel may be treated as creep resistant only at temperature of 723 K and that at stress level which is less than 35% of 0.2 offset yield strength. Strength of this material is quite high and accordingly this steel may be used in design of structures that are highly stressed. In this paper, modeling of creep behavior is also presented. It is shown that all of used models may be treated as satisfying.

Acknowledgments

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. The authors would like to express their gratitude to staff of Material Testing Laboratory of Department of Materials at the Faculty of Engineering Rijeka for their investigation in testing of material chemical composition, and to staff of Material Testing Laboratory of School of Materials Science, Henan Polytechnic University, for microstructure examination.

References

Ahlroos, T., Ronkainen, H., Helle, A., Parikka, R., Virta, J. and Varjus, S. (2009), "Twin disc micropitting tests", *Tribol. Int.*, **42**(10), 1460-1466.

Anderson, T.L. (1995), *Fracture Mechanics*, CRC Press, New York.

Annual Book of ASTM Standards (2012), *Metal Test Methods and Analytical Procedures*, Vol. 03.01, ASTM International, Baltimore, MD, USA.

Belegundu, A.D. and Chandrpatla, T.R. (2011), *Optimization Concept and Application in Engineering*, Cambridge University Press, New York, USA.

Bomas, H., Burkart, K. and Zoch, H.W. (2012), "VHCF behaviour of case-hardened specimens made of two grades of steel SAE 5120 differing in microstructure", *Int. J. Fatigue*, **60**, 63-73.

Boresi, A.P. and Schmidt, R.J. (2003), *Advanced Mechanics of Materials*, John Wiley & Sons, USA.

Brnic, J., Canadija, M., Turkalj, G. and Lanc, D. (2010a), "50CrMo4 steel-determination of mechanical properties at lowered and elevated temperatures, creep behavior and fracture toughness calculation", *J. Eng. Mater. Techn.*, **132**(2), 021004.

Brnic, J., Canadija, M., Turkalj, G. and Lanc, D. (2010b), "Structural steel ASTM A709-behavior at uniaxial tests conducted at lowered and elevated temperatures, short-time creep response, and fracture toughness calculation", *J. Eng. Mech.*, **136**(9), 1083-1089.

Brnic, J., Turkalj, G., Canadija, M. and Lanc, D. (2011a), "AISI 316Ti (1.4571) steel – Mechanical, creep and fracture properties versus temperature", *J. Construct. Steel Res.*, **67**(12), 1948-1952.

Brnic, J., Turkalj, G., Canadija, M., Lanc, D. and Krscanski, S. (2011b), "Martensitic stainless steel AISI 420 – Mechanical properties, creep and fracture toughness", *Mech. Time-depend. Mater.*, **15**(4), 341-352.

Brnic, J., Turkalj, G., Vukelić, G. and Brcic, M. (2012), "Analysis of the dependence of material properties on temperature – Steel 1.4122" , *High Temp. Mater. Proc.*, **31**(3), 259-266.

Brnic, J., Turkalj, G., Niu, J., Canadija, M. and Lanc, D. (2013), "Analysis of experimental data on the behavior of steel S275JR – Reliability of modern design", *Mater. Des.*, **47**, 497-504.

Collins, J.A. (1993), *Failure of Materials in Mechanical Design*, John Wiley & Sons, New York, USA.

Conrado, E., Foletti, S., Gorla, C. and Papadopoulos, I.V. (2011), "Use of multiaxial fatigue criteria and shakedown theorems in thermo-elastic rolling–sliding contact problems", *Wear*, **270**(5-6), 344-354.

Draper, N.R. and Smith, H. (1998), *Applied Regression Analysis*, Wiley– Interscience Publications, USA.

Gross, D. and Seeling, T. (2011), *Fracture Mechanics*, Springer - Verlag, Berlin, Germany.

Klobcar, D., Kosec, L., Kosec, B. and Tusek, J. (2012), "Thermo fatigue cracking of die casting dies", *Eng. Fail. Anal.*, **20,** 43-53.

Martins, R.C., Seabra, J.H.O. and Ruis-Moron, L.F. (2011), "Influence of oil formulation on gear micropitting and power loss performance", *Proceedings of the Institution of Mechanical Engineers*, *Part J*: *J. Eng. Tribol*., **225**(6), 429-439.

Milutinovic, M., Movrin, D. and Pepelnjak, T. (2012), **"**Theoretical and experimental investigation of cold hobbing processes in cases of cone-like punch manufacturing**",** *Int. J. Adv. Manuf. Tech*., **58**(9-12), 895-906.

Pepelnjak, T., Petek, A. and Kuzman, K. (2005), "Analysis of the forming limit diagram in digital environment", *Adv. Mater. Res*., **6-8**, 697-704.

Plaseied, A. and Fatemi, A. (2008), "Deformation response and constitutive modeling of vinyl ester polymer including strain rate and temperature effects", *J. Mater. Sci*., **43**(4), 1191-1199.

Raghavan, V. (2004), *Materials Science and Engineering*, Prentice- Hall of India, New Delhi, India.

Rao, S.S. (2009), *Engineering Optimization*, John Wiley & Sons, NJ, USa.

Roberts, R. and Newton, C. (1981), *Interpretive Report on Small Scale Test Correlation with KIc Data*, Welding Research Council Bulletin, **Volume 265**, 1-18.

Shekhter, A., Kim, S., Carr, D.G., Crocker, A.B.L. and Ringer, S.P. (2002), "Assessment of temper embrittlement in an ex-service 1Cr–1Mo–0.25V power generating rotor by Charpy V-notch testing; KIc fracture toughness and small punch test", *Int. J. Press. Vessels Pip*., **79**(8-10), 611-615.

Shijve, J. (2009), *Fatigue of Structures and Materials*, Springer Science & Business Media, Delft, Netherlands.

Yu, Z.W., Xu, X.L., Yang, Z. and Li, Y.Y. (2012), "Case internal oxidation and intergranular fracture of carburized splined-shaft", *Eng. Fail. Anal*., **22**, 141-151.

CC