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Short-time creep, fatigue and mechanical properties of 42CrMo4 - Low alloy structural steel

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Abstract. The proper selection of materials for the intended use of the structural member is of particular interest. The paper deals with determining both the mechanical properties at different temperatures and the behavior in tensile creep as well as fatigue testing of tensile stressed specimens made of low alloy 42CrMo4 steel delivered as annealed and cold drawn. This steel is usually used in engineering practice in design of statically and dynamically stressed components. Displayed engineering stress - strain diagrams indicate the mechanical properties, creep curves indicate the material creep behavior while experimental investigations of fatigue may ensure the fatigue limit determination for considered stress ratio. Also, hardness testing provides an insight into material resistance to plastic deformation. Experimentally obtained results regarding material properties were: tensile strength (735 MPa / 20°C, 105 MPa / 680°C), yield strength (593 MPa / 20°C, 76 MPa /680°C). Fatigue limit in the amount of 532.26 MPa, as maximum stress at stress ratio R = 0.25 at ambient temperature was calculated on the basis of experimentally obtained results. Regarding the creep resistance it is visible that this steel can be treated as creep resistant at high temperatures (including 580°C) when applied stress is of low level (till 0.2 of yield stress).

Keywords: 42CrMo4 steel; mechanical properties; short-time creep; fatigue; fatigue limit

1. Introduction

Modern design is based on the results of experimental investigations, numerical structural analysis and high capacitive computers. First, experimental investigations provide the data using which the designer may assess the behavior of the structure in similar environmental conditions. Further, finite element method provides very powerful tool for structural modeling as well as stress and strain analyses. Finally, modelling and analysis need to be supported by high capacitive computers. Namely, considered structure may be treated as a deformable body and its geometry as well as its deformation under applied loads can be modelled by finite element method. Finite element procedure is a reliability procedure that can be used in computer –aided design, Bathe (1996). The structure will change its size and shape as a result of loads that are applied to it or as a result of temperature changes, Craig (2011). Design and manufacturing of the structure are performed in that way that considered structure fulfil all the requirements in its service life. In addition, the structure is designed and manufactured with the assumption that it does not contain

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any failure in the material or any other mechanical failure. However, during structural service life or let to say, during structure history, some of mechanical failures can occur. Any of the particular failure has its cause of origin and the form of its expression. In engineering practice, a special discipline was established to analyze the structural failures and that is called analysis of failures. In this sense, an answer why and how a certain engineering component has failed can be obtained. The causes of the failures usually are specified and the modes of their expression give the answer how the component has failed. As a common causes of failures usually are numbered: design errors, improper material, unforeseen operating conditions, misuse, manufacturing defects, inadequate control, Brooks and Choudhury (2002) and Farahmand *et al.* (1997). On the other hand, different failure modes exist in engineering practice and they can be listed as: force induced elastic deformation, creep, fracture, yielding, fatigue, corrosion, buckling, etc., Collins (1993). Above mentioned design errors may include: the size and /or the shape of a component, used material, etc., while the misuse describes that the structure was used in the conditions for which it is not designed. Creep and fatigue as a possible and very common failures in engineering practice were experimentally investigated for the steel 42CrMo4 and these investigations are presented in this paper. Creep as an inelastic strain that increases with the time is also usually defined as time-dependent behavior during which deformation increases while the stress (load) is kept constant. Creep, as one of possible failure modes was experimentally studied in these investigations. The phenomenon that arises in material in the form of inelastic strain that increases with time is known as creep. Also, an established definition of creep is that this is time-dependent behavior during which deformation continues to increase while the stress (load) is kept constant, Findley *et al.* (1989). Regarding the creep behavior, in the literature can be found the statement that in engineering practice usually it is admissible 1-2% creep strains as well as that creep is appreciable at temperature above 0.4 T_m, where T_m is melting temperature, Raghavan (2004). In any case the knowledge about the material behavior under life conditions in advance is very useful for design procedure. The motivation for these experimental investigations was to obtain data that are interesting and useful for the design process. Also, it is very useful to be familiar with the data about material properties previously the design process. In this sense, some information is given about material behavior of different materials usually used in engineering practice. In this way in the following references can be found as follows: in Brnic *et al.* (2013), properties of S275JR steel are investigated, in Brnic *et al.* (2009), properties and creep behavior of toll materials are investigated, in Brnic *et al.* (2011), behavior of 316Ti steel is investigated. Further, in Herakovič and Bevk (2010), behavior of material used in valve design is investigated, in Brnic *et al.* (2010a), ASTM A709 material is examined, in Šturm *et al.* (2011), influence of alloying elements in Al-Si alloy on the remelting process is investigated, in Brnic *et al.* (2015), steel X15CrNiSi25-20 is investigated. Cold hobbing process in cases of cone-like punch manufacturing is described in Milutinovic *et al.* (2012) numerical simulation in optimization of product and forming process is described in Pepelnjak *et al.* (2001), and material properties and creep behavior of 50CrMo4 steel is investigated in Brnic *et al.* (2010b). Also, structural steel 1.7147 was investigated and results can be found in Brnic *et al.* (2014a).

1.1 Some of the latest researches related to 42CrMo4 steel

In the following part of this paper briefly are presented some known data regarding the behavior of 42CrMo4 steel. In Černy and Sis (2014) the results of an experimental investigation of 42CrMo4 steel fatigue resistance is presented. The structure and fatigue behavior of an ion nitrided

42CrMo4 steel were considered and compared with a quenched and tempered structure in Terres *et al*. (2010), where fatigue limit was tested by three-point bending tests at stress ratio R = 0.1. Further, in Terres *et al*. (2012), bending fatigue resistance of the nitrided steel improvement by shot-peening was considered. In addition, for this high strength low-alloy steel (42CrMo4), experimental determination of fatigue crack growth parameters was considered in Göncza *et al*. (2010). Investigations relating to the mechanical properties and short-time creep of soft annealed 42CrMo4 steel are presented in Brnic *et al*. (2014b). It is evident that properties presented in mentioned reference are different from those obtained in this study. Namely, now under consideration as received material is annealed and cold drawn 42CrMo4 steel. The influence of two different coolant agents on the mechanical properties of the round hot rolled bars were considered in Stanczyk and Figlus (2014). An illustration of the application of infrared thermography measurement for the investigation of fatigue behavior in high-cycle fatigue range of 42CrMo4 steel is presented in Krewerth *et al*. (2013).

2. Material under consideration, geometry of specimens, used equipment and standards

Material: under consideration was chromium-molibdenum – manganese low-alloy 42CrMo4 steel. It was delivered as soft annealed and cold drawn 16 mm round bar. This steel is designated as: EN/DIN 42CrMo4 (1.7225); AISI 4140; BS 708M40, GOST 35KHM, etc. Chemical composition of this steel, 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). Its applications may be found in many fields of engineering where good torsional strength and good fatigue strength are requested. To this areas belong statically and dynamically stressed machine components (gears, crankshafts, etc.).

Specimens: for tensile testing related to stress-strain diagrams and tensile creep behavior were manufactured in accordance with ASTM Standard, ASTM: E 8M-15a.

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, Charpy tests were carried out in accordance with ASTM: E23-12c standard, hardness tests were carried out using ASTM: E 10-14 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: used in this investigations is as follows. Material testing machine (Zwick / Roell) of 400 kN capacity was used in tensile testing for stress-strain diagrams determination as well as in 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, Charpy impact machine in impact energy testing and universal hardness testing machine was used in material hardness testing.

3. Experimental results

3.1 Engineering stress-strain diagrams - mechanical properties

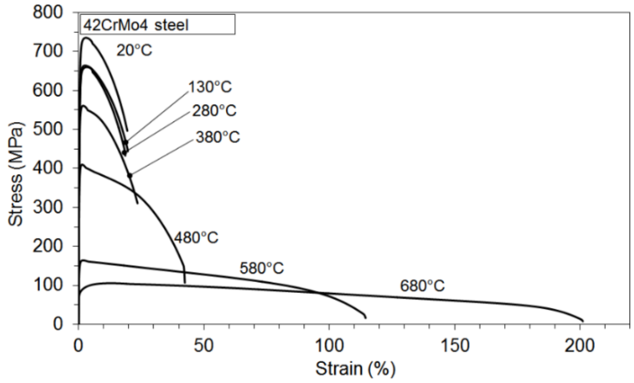


Fig. 1 Engineering stress-strain diagrams: 42CrMo4 steel

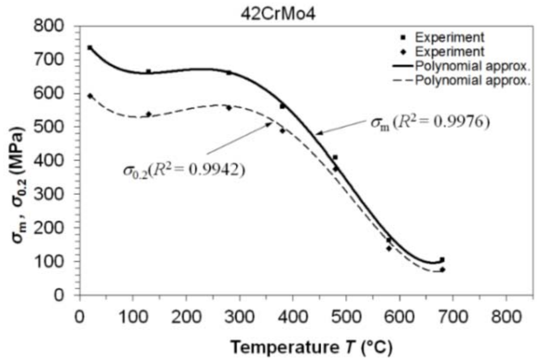
Table 1 Mechanical properties: steel 42CrMo4 (first test)

Temperature (°C)	σ_m (MPa)	$\sigma_{0.2}$ (MPa)	E (GPa)	ε_t (%)	ψ (%)
20	735	593	202	19.5	58
130	664	538	190	19.7	60
280	660	557	180	18.64	60
380	560	489	170	23.5	65
480	409	376	117	42.4	78
580	164	139	90	114.5	92
680	105	76	75	201	95

As it was previously said, the knowledge of material mechanical properties at defined temperature is of importance for structural design that is intended to be used at similar conditions. In this sense tensile tests were carried out at different temperatures and that in such a way that for each temperature level several tests were performed. Since that differences between stress-strain diagrams in their shapes were negligible, in Fig. 1 are presented stress-strain diagrams obtained on the basis of first test for each of the temperature. In Table 1 numerical values of the mechanical properties are given.

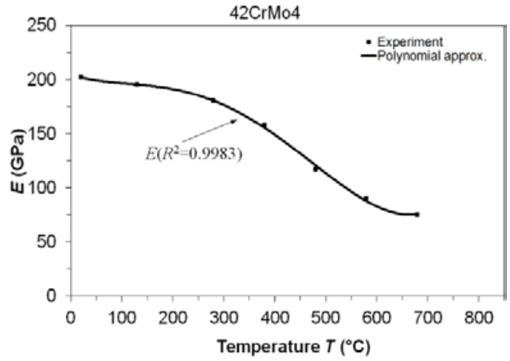
3.1.1 Measured data and polynomial approximations: *mechanical properties and modulus of elasticity versus temperature*

In engineering practice two processes can be distinguished and that real processes and simulated / modeled processes. In the case of this investigation as real process may be taken tensile experiment at any of considered temperatures. Each of this tensile test gives the data related to tensile strength, yield strength, etc. When the results of all the tests related to considered property are assembled, the experimentally obtained results in such a way form the set of the discrete points. If someone wants to connect these points by certain curve, then this curve will be described by certain polynomial that will describe the change of discussed property versus temperature with less or more accuracy. However, an analysis may establish the accuracy with which the simulated / modeled curve can replace the real data. In this sense, a coefficient called the



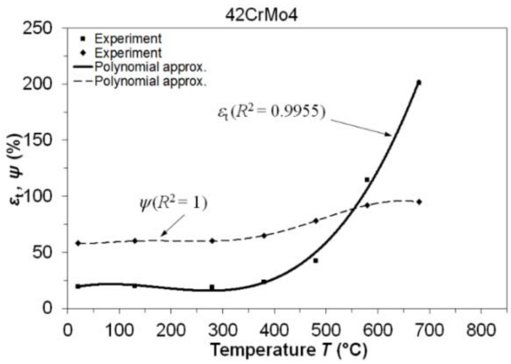
$$\sigma_m(T) = 3.29246 \cdot 10^{-8} T^4 - 4.46229 \cdot 10^{-5} T^3 + 1.7316 \cdot 10^{-2} T^2 - 2.4912 \cdot T + 779.641$$
$$\sigma_{0.2}(T) = 3.02935 \cdot 10^{-8} T^4 - 4.2207 \cdot 10^{-5} T^3 + 1.69423 \cdot 10^{-2} T^2 - 2.36018 T + 635.89$$

(a)



$$E(T) = 3.40712 \cdot 10^{-9} T^4 - 3.99391 \cdot 10^{-6} T^3 + 1.08399 \cdot 10^{-3} T^2 - 1.51298 \cdot 10^{-1} T + 204.489$$

(b)



$$\varepsilon_t(T) = 1.64097 \cdot 10^{-6} T^3 - 8.77166 \cdot 10^{-4} T^2 + 1.10852 \cdot 10^{-1} T + 17.5207$$
$$\psi(T) = 1.43022 \cdot 10^{-14} T^6 - 3.29499 \cdot 10^{-11} T^5 + 2.68528 \cdot 10^{-8} T^4 - 9.27046 \cdot 10^{-6} T^3 +$$
$$+ 1.35629 \cdot 10^{-3} T^2 - 5.99687 \cdot 10^{-2} T + 58.7268$$

(c)

Fig. 2 Measured data and polynomial approximations coefficient of determination (R^2) is established and it is treated as a measure of accordance of real (measured) and simulated (modeled, approximated, predicted) values. This coefficient is a statistic that gives information about how fit a model is Draper and Smith (1998). In Fig. 2 a set of experimental results related to ultimate tensile strength, yield strength and modulus of elasticity and their polynomial approximations is presented.

On the basis of experimentally obtained engineering stress-strain diagrams the changes of the material properties versus temperature are visible. Temperature dependency of these properties are shown in Fig. 2. All of properties decrease with temperature increases. However, it can be said that ultimate tensile strength as well as yield strength at high temperatures, including 480°C, may be treated as satisfactory for high temperature applications.

3.2 Short - time tensile creep tests and creep modeling

As it is known metallic materials subjected to constant stress continue to increase their deformations with time. This knowledge is also very important since the achieved level of creep strains after a period of time can prevent the function of the element for which it is designed. In this investigation short-time creep behavior of tested material is considered. In Figs. 3-5 some of performed creep tests are presented.

Since that experimental investigations of material creep behavior consume quite a lot of time and money, modeling of creep behavior based on known data from similar previously performed

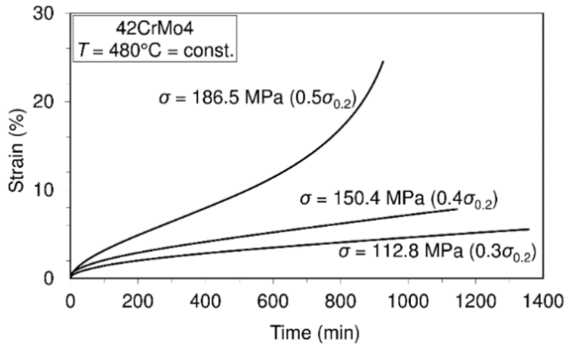


Fig. 3 Creep behavior of 42CrMo4 steel at 480°C

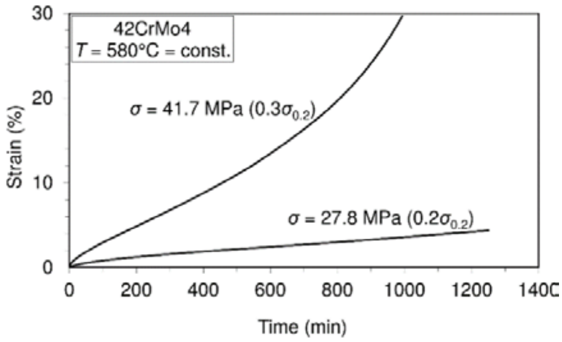


Fig. 4 Creep behavior of 42CrMo4 steel at 580°C

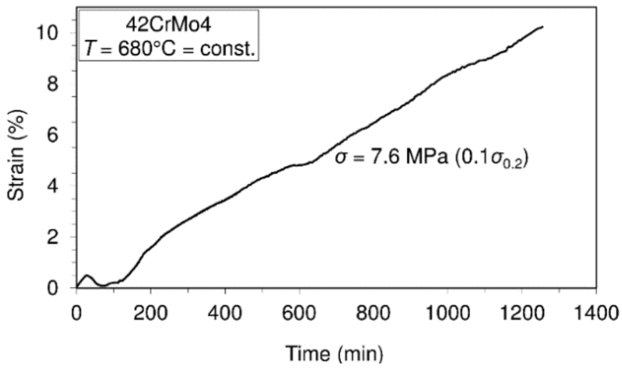


Fig. 5 Creep behavior of 42CrMo4 steel at 680°C

tests is welcome. Creep behavior modeling can be based on rheological models or on known formulas. Here, modeling will be performed using the formula, Brnic *et al*. (2013, 2014c, d)

$$\varepsilon(t) = D^{-T}\sigma^{p}t^{r}. \tag{1}$$

In Eq. (1) there are: σ – stress, t – time, T – temperature and D, p and r are parameters which need to be determined. In creep behaviour modelling, in general, three cases can be used and that

$$\varepsilon\ (t) = \varepsilon\ (\sigma, T, t) \tag{2a}$$

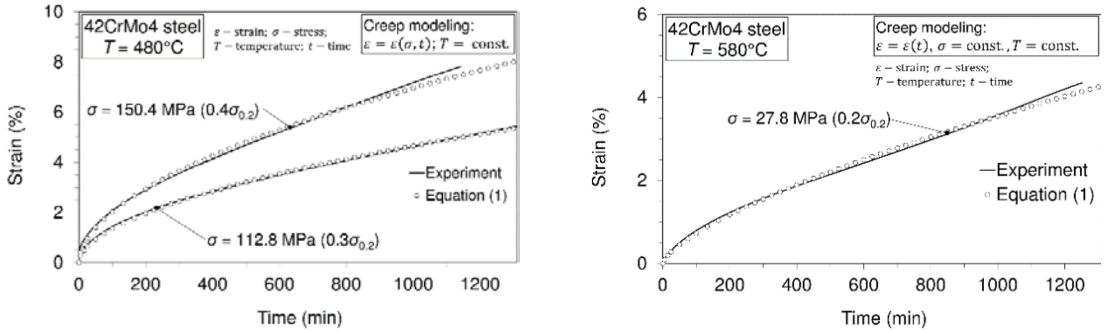
$$\varepsilon\ (t) = \varepsilon\ (\sigma, t), \qquad T = const \tag{2b}$$

$$\varepsilon\ (t) = \varepsilon\ (\ t), \qquad T = const, \qquad \sigma = const \tag{2c}$$

As it is visible, Eq. (2a) is the most general case since the modeling can be done for a certain range of stress within a certain range of temperatures. Here, creep modeling was made by Eq. (1). For the temperature of 480°C the model (2b) was applied while for the temperature of 580°C the model (2c) was applied. Data related to creep modeling is presented in Table 2 while modeled creep curves are presented in Fig. 6.

Table 2 Creep modeling data: 42CrMo4 steel

Model	Temperature (°C)	480	580
	Time (min)	1300	1300
	σ (MPa)	(0.3 – 0.4) $\sigma_{0.2}$	$<$ 0.2 $\sigma_{0.2}$
		112.8 -150.4	27.8
Analytical formula (1) $\varepsilon(t) = D^{-T}\sigma^{p}t^{r}.$	D	1.06027	1.20451
	p	1.3986	6.09303
	r	0.53511	0.68808



(a) Creep modeling at temperature of 480°C (b) Creep modeling at temperature of 580°C

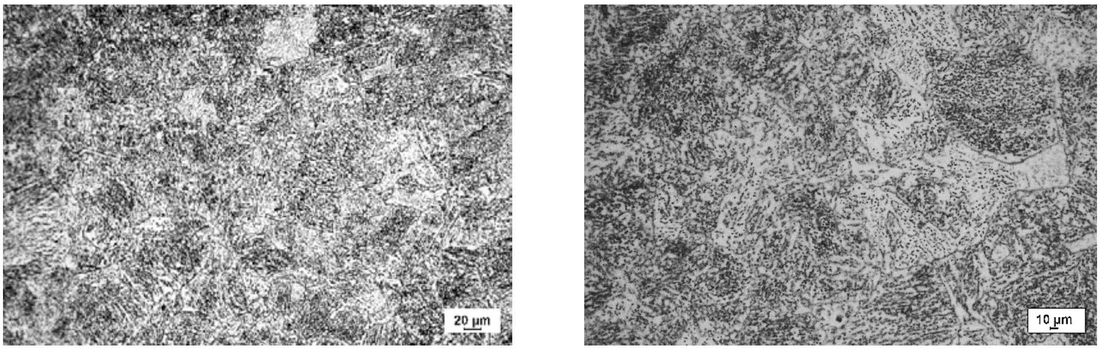
Fig. 6 Steel 42CrMo4: Creep modeling

3.3 Hardness testing

Material properties that depend on microstructure are called structure - sensitive properties. To this group of properties can be counted, for example, yield strength and hardness. Since that processing is a mean to develop (and control) microstructure, hot or cold rolling is of importanceand they have a significant influence on mentioned material properties. Hardness testing provides a relevant material mechanical property and usually it is defined as resistance of material against its deformation. In engineering practice various mechanical (and other) tests are used to determine material properties and on this way its suitability for a considered application. As one of most important material property is hardness. Namely, during manufacturing, factors such as loads, pressures and temperatures affect the performance of manufactured member (part). Due to complex specimen geometry in testing of some properties, based on linear correlation between hardness and tensile strength for considered metallic material, hardness testing is often used as an appropriate approach of establishing that engineering component will survive and can be able to perform its function. For the considered material in this investigation, Brinell method was used to define material hardness. As usually result related to hardness is reported, in this case, result is: 232 HB, 2.5 / 187.5 kgf (1,8 kN), where hardness of the material is 232 HB, while the diameter of the indenter is 2.5 mm and the test force is 187.5 kgf. Result of 232 HB for this constructional steel can be compared with that related to the austenitic stainless steel AISI 303 (1.4305) where tested hardness was obtained in the amount of 239 HB, Brnic *et al*. (2012), using the same testing method.

3.4 Basic analysis of microstructure

As it was previously said, the properties of steels are linked to the chemical composition, processing path and resulting microstructure of the material. For considered steel, most properties depend on microstructure and they are called structural-sensitive properties. On the other hand, mentioned processing (for example- hot or cold rolling, etc.) is a means to develop and control microstructure. In this investigation basic consideration was made related to material microstructure. In this sense, microstructure of the cross-sections of two specimens were analyzed. One specimen represented material as it is received, and the other represented the material that was previously subjected to creep. Creep process was carried out at 480°C / 150.4 MPa / 1200 min.



(a) As - received material, longitudinal section of the specimen, 500 x

(b) Material of the specimen previously subjected to creep: 480°C /150.4 MPa / 1200 min, cross-section of the specimen, 1000 x

Fig. 7 Steel 42CrMo4: optical micrographs, 4% nital

Microstructure analysis shows that this steel, in general, consists of thin pearlitic microstructure and a few ferrite and fairly small particles of cementite in the case of as received material, Fig. 7(a). For the microstructure of the specimen previously subjected to creep, no noticeable changes were observed, but the grain size, slightly increased, Fig. 7(b).

3.5 Fatigue testing of tensile stressed specimens

3.5.1 Introduction to fatigue testing

In past times structures and machines were designed in a very simple way where modern computers and technologies as well as numerical analyses have not been involved. However, achieved results were acceptable for that time. Despite of the progress there is still a large number of failures which reduces both the quality and safety of products. Design criteria must pay the attention also to the cyclic loading. Fatigue design criteria related to the durability of the structure, include time range from infinite life to damage tolerance, depending on the application. As fatigue life models may be mentioned: stress-life (σ-N $\rightarrow$ S-N) model, deformation-life (ε-N) model and model related to the crack propagation rate (da / dN – ΔK). Stress – life curve is usually constructed depends on stress ratio and it relates to possible applied load. Each fatigue test generates one point in stress – life system, i.e., to each fatigue stress corresponds an appropriate number of cycles to the failure. Based on the recorded points in stress-cycles system a stress-life curve can be constructed in fatigue finite life region. Further step is define the so called fatigue limit (endurance limit) that is fatigue strength and corresponds to the infinite fatigue life. As the number of the cycles at infinite fatigue life (infinite fatigue region), the amount of 10 million cycles for steel alloys is usually accepted. However, if finite fatigue life and infinite fatigue life are modeled as straight lines based on experimentally obtained points in stress-life system, then this stress-life diagram contains one inclined and one horizontal line. The mentioned horizontal line belongs to the infinite fatigue life. Fatigue is a failure due to repeated loading and it is common a cause of fracture that can occur at a stress level that is much lower than fracture stress corresponding to a monotonic tensile load. Usually fatigue is defined as the process of demage accumulation due to cyclic loading as reported in Pollak (2005). In this investigation fatigue is considered as cyclic tensile stressed procedure performed on unnotched (smooth) specimens,

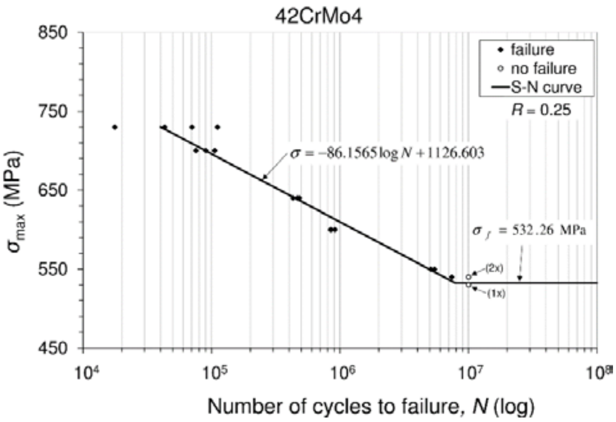


Fig. 8 Fatigue tests data and approximated S - N curve in finite and infinite fatigue regions at room temperature and stress ratio of R = 0.25

although other types of loading may also be considered. In addition, this (tensile) loading is usually modeled as sinusoidal loading. Diagram stress-life (S-N curve, Wohler curve) that contains results of fatigue tests is usually constracted in such a way that on the abscissa is plotted number of cycles to the failure, in log scale, while on the ordinate is placed maximum stress (or mean stress or stress amplitude) in linear or in log scale. Geometry of the specimen as well as fatigue testing procedure are defined by standards (ASTM standard, ISO standard). Fatigue limit (practically horizontal line for materials with clearly defined fatigue limit) in infinite fatigue region is associated with the number of the cycles when specimen remains unbroken, and usually, as previously said, for steel aloys this number may be addopted as 10 million of cycles.

3.5.2 Fatigue limit

Material subjected to fatigue tests was 42CrMo4 steel, soft annealed and cold drawn as received. Fatigue tests of cyclic tensile stressed specimens were carried out in accordance with ISO 12107:2012 standard (2012) at prescribed stress ratio of R = 0.25, at room temperature. On the basis of fatigue tests $W\ddot{o}hler$ curve (or usually designated as "S – N" curve, stress-life curve) is constructed. From this diagram fatigue limit (endurance limit) can be established. In Fig. 8 is presented a set of experimentally obtained data related to stress versus number of cycles to failure and it is approximated by "S – N" curve ("$W\ddot{o}hler$" curve) for stress ratio of R = 0.25.

On the basis of this diagram an approximated fatigue curve (line) is visible. Further task is define the fatigue limit. In this sense the so called staircase method is used. Fatigue tests in infinite

Table 3 Data for modified staircase method related to failed ♦) and no-failed (○) specimens obtained from fatigue tests in infinite fatigue region

Stress σ_i MPa	Number of specimen 1	2	3	4	5	6	7
550			♦				♦
540		♦		○		○	
530	○				○		

Table 4 Data analysis for Modified staircase method

Stress σ_i (MPa)	Level of stress i	f_i	if_i	i^2f_i
550	2	2	4	8
540	1	1	1	1
530	0	0	0	0
Σ		3	5	9

Table 5 *A*, *B*, *C* and *D* constants calculated in accordance with ISO standard

Formula	Material: X6CrNiTi18-10
$A = \sum i \cdot f_i$	5
$B = \sum i^2 \cdot f_i$	9
$C = \sum f_i$	3
$D = \frac{B \cdot C - A^2}{C^2}$	0.22

fatigue region were carried out. Obtained data from these tests show whether specimen has failed (♦) or no-failed (○) and these data are used as data for modified staircase method, Table 3.

In further procedure these modified staircase method data are analyzed, Table 4, and constants *A*, *B*, *C* and *D* are determined, Table 5.

Determination of fatigue limit (endurance limit) is defined in accordance with ISO standard

$$\sigma_{f(P,1-\alpha)} = \bar{\mu}_y - k_{(P,1-\alpha,dof)} \cdot \bar{\sigma}_y, \tag{3}$$

- The mean fatigue strength is

$$\bar{\mu}_y = \sigma_0 + d\left(\frac{A}{C} - \frac{1}{2}\right) \tag{4}$$

Taking that d is stress step.

- The coefficient for the one sided tolerance limit for a normal distribution

$$k_{(P,1-\alpha,\nu)}. \tag{5}$$

- The estimated standard deviation of the fatigue strength

$$\bar{\sigma}_y = 1.62 \cdot d(D + 0.029). \tag{6}$$

In accordance with the standard recommendation of $\nu = n - 1 = 6$, where n is the number of items in a considered group. Further, for a desired probability of P = 10% and a confidence level $(1-\alpha)$ = 90%, in accordance with the table B_1 (ISO), it is: $k_{(P,1-\alpha,\nu)} = k_{(0.1;0.9;6)} = 2.333$. In accordance with the Eqs. (4) and (6), it is

$$\bar{\mu}_y = \sigma_0 + d\left(\frac{A}{C} - \frac{1}{2}\right) = 530 + 10\left(\frac{5}{3} - \frac{1}{2}\right) = 541.67 \text{ MPa},$$

or, this can be obtained as (Table 5)

$$\bar{\mu}_y = (530 + 540 + 550 + 540 + 530 + 540 + 550) \,/\, 7 = 540 \text{ MPa},$$

which amount is quite similar as previously obtained.

$$\bar{\sigma}_y = 1.62 \cdot d(D + 0.029) = 1.62 \cdot 10\,(0.22 + 0.029) = 4.0338 \text{ MPa}$$

Finally, fatigue limit is

$$\sigma_{f\,(0.1;0.9;6)} = \bar{\mu}_y - k_{(P,1-\alpha,\nu)} \cdot \bar{\sigma}_y = 541.67 - 2.333 \cdot 4.0338 = 532.26 \text{ Mpa}.$$

It should be noted that fatigue limit is a calculated value that is obtained on the basis of experimental investigations and it represents the maximum stress that can be applied at atress ratio of R = 0.25.

4. Conclusions

Experimentally obtained results and their analysis in this investigation can be very useful for designers of the structures. Ultimate tensile strength of 735 MPa and yield strength of 593 MPa at room temperature show that this steel may be subjected to high stress. This indicate, as previously was said in Chapter 2, that the considered steel can be designed for applications that are highly statically and dynamically stressed. Even at high temperatures (up to 480°C) the mechanical properties of this steel are of high levels. Also, calculated fatigue limit (532.26 MPa) of tensile stressed specimens made of 42CrMo4 steel that is delivered as annealed and cold drawn bar, for prescribed stress ratio (R = 0.25), indicates that this steel can be used in applications with dominant cyclic loading. Regarding the creep it can be said that this material can be considered as resistant to creep at the temperatures of 480^0C and 580^0C if applied stress at both temperatures does not exceed 0.2 of yield strength.

Acknowledgments

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