Wenfei Shen, Chi Zhang, Liwen Zhang*, Yang Yang and Zhi Zhu

Stress Relaxation Behaviour and Creep Constitutive Equations of SA302Gr.C Low-Alloy Steel

<https://doi.org/10.1515/htmp-2017-0090>

Received June 25, 2017; accepted November 27, 2017

Abstract: In order to study the stress relaxation behaviour of SA302Gr.C low-alloy steel, the stress relaxation experiments were performed at the temperatures of 400, 500 and 620 °C with the constant strain of 0.5%. Based on the experimental stress relaxation curves, the relationship between creep strain rate and stress were derived and the creep strain rate–stress curves at different temperatures were obtained. Then, the creep constitutive equations at different conditions were developed and the constants in the equations were determined. In order to verify the developed creep constitutive equations, the finite-element (FE) model of stress relaxation of SA302Gr.C low-alloy steel was established with the FE software MSC.Marc. The comparison results show that the simulated stress relaxation curves agree with the experimental ones, which illustrates that the developed creep constitutive equations are appropriate for the tested steel.

Keywords: SA302Gr.C low alloy steel, stress relaxation experiment, creep constitutive equations, FE simulation

1 Introduction

SA302Gr.C is a typical low-alloy steel which has been widely used in the boiler and pressure vessels due to its excellent properties, such as higher strength at medium temperature, good plasticity and toughness, resistance to hot shortness and heat checking [1–3].

The boiler and pressure vessels are large welded structures, which are filled with corrosive gases or liquids. Usually, they work in severe environments with high temperature and high pressure. Therefore, high

quality of boiler and pressure vessels is necessary to resist the severe environment. In recent decades, with the size and capacity of boiler and pressure vessels continuously increasing, requirements of quality of the pressure vessels are more stringent [4].

In large welded structure, the residual stress is high in weld zone after welding, which has an important influence on the assembling and dimensional stability of the pressure vessels and also results in stress corrosion. Consequently, it is necessary to relieve the residual stress in the boiler and pressure vessels. Relief annealing is often used as a kind of local postweld heat treatment (PWHT) method to relieve the residual stress in large weld structure. During the local PWHT process of the large weld structure, the stress relaxation takes place and the residual stress nearby the weld zone will be relieved [5–7]. Recently, numerical simulation technology has been widely applied to the study of PWHT process [7, 8]. Furthermore, in order to simulate the local PWHT process more accurately by finite-element (FE) method, the creep constitutive equations which describe the stress relaxation behaviour should be precisely developed. Therefore, the study of stress relaxation behaviour of materials has important theoretical value and practical significance. Recently, many studies about stress relaxation or creep behaviour of metallic materials were published [9–16], but few studies about the relaxation behaviour of SA302Gr.C steel were found.

In this paper, first, the stress relaxation experiments of SA302Gr.C steel were carried out. Then, the creep constitutive equations at different conditions were derived. Finally, the equations were verified by FE simulation, which indicates the equations can be used to the actual local PWHT process.

2 Experiments

SA302Gr.C is a typical low-alloy high-strength steel and the main strengthening chemical elements are Mn, Mo and Ni. The chemical composition of SA302Gr.C used in this investigation is shown in Table 1 and its mechanical

*Corresponding author: Liwen Zhang, School of Materials Science and Engineering, Dalian University of Technology, Dalian, China, E-mail: commat@mail.dlut.edu.cn

Wenfei Shen: E-mail: shenwf0716@163.com, Chi Zhang:

E-mail: zhangchi@dlut.edu.cn, Yang Yang:

E-mail: 549809972@qq.com, Zhi Zhu: E-mail: 1752830861@qq.com, School of Materials Science and Engineering, Dalian University of Technology, Dalian, China

Table 1: Chemical composition of SA302Gr.C (wt %).

C	Mn	P	S	Si	Mo	Ni
0.10	1.45	0.014	0.001	0.27	0.47	0.47

Table 2: Mechanical properties of SA302Gr.C.

Temperature (°C)	Tensile strength (MPa)	Yield strength (MPa)	Young's modulus (GPa)
26	585	455	200
400	545	410	170
500	545	405	149
600	515	380	121
700	270	205	100

properties are given in Table 2, which meet the requirement of ASME code [17]. The specimens for the stress relaxation experiments were prepared from forging blocks of SA302Gr.C steel. The geometry and dimensions of specimens are shown in Figure 1. The initial microstructure was observed as shown in Figure 2. The ferrite and perlite can be found in the specimen and the average grain size was measured as 28 μm .

The stress relaxation experiments were conducted on a RD-50 electronic creep testing machine. During the relief annealing process of pressure vessels, the long-term holding usually takes place in the temperature range of 400 °C to 620 °C. Therefore, the stress relaxation experiments at 400, 500 and 620 °C with the constant strain at 0.5 % were performed according to ASTM E328 [18]. During the process, the specimens were heated to the experiment temperatures with a heating rate of 10 °C/s and held for 1 h to eliminate the thermal gradient. Then, the specimens were subjected to an increasing load with a constant moving speed of 0.002 mm/s until the specific strain of 0.5 % was attained. Then, the stress in the specimens began to decrease automatically at constant temperature. The whole experiment duration is

Figure 2: The initial microstructures of the specimen.

7 h. The specimens after the stress relaxation experiments are shown in Figure 3.

3 Results and Analysis

3.1 Stress relaxation curves

Based on the experiments data (including time, moment, force, deformation, displacement and temperature), the initial stress and residual stress can be calculated from the force at initial time (the time when the specific initial strain 0.5 % is obtained) and force was determined under constant strain. Then, the relaxation (stress–time) curves of SA302Gr.C steel during stress relaxation at 400, 500 and 620 °C can be achieved as shown in Figure 4.

It can be found that there are so many undulant experimental data in the relaxation curves, which are interference for the actual experimental data. As a result, the data obtained from the stress relaxation experiments should be preprocessed by a routine at Fortran language based on a cubic exponential decay function [12].

Figure 1: Geometry and dimensions (mm) of stress relaxation specimen.

Figure 3: Specimens after stress relaxation experiments.

Figure 4: Experimental stress relaxation curves and fitted curves of SA302Gr.C at different temperatures.

$$\sigma = A_1 \exp(-(t - t_0)/\tau_1) + A_2 \exp(-(t - t_0)/\tau_2) + A_3 \exp(-(t - t_0)/\tau_3) + \sigma_0 \quad (1)$$

where σ is the transient stress; t is the stress relaxation time; t_0 is zero time; σ_0 is the stress relaxation limit; A_1 , A_2 , A_3 , τ_1 , τ_2 and τ_3 are constants which determine the fitted curves shape.

The fitted stress–time curves with the data achieved from Fortran routine at different temperatures are shown in Figure 4. It can be seen that the relaxation curves have similar regularity for change of stress and the whole relaxation process can be divided into three stages. During the first stage, the stress relaxes very fast, while stress relaxes slowly in the second stage. And after a long relaxation time, the stress reaches a limit which is called stress relaxation limit during the third stage.

Another parameter we should notice is stress relaxation rate which is the absolute value of slope of the residual stress–time curve. The stress relaxation rate and stress relaxation limit are two basic parameters which are used to describe the stress relaxation behaviour. If the additional stress is lower than the stress relaxation limit, the stress relaxation will not take place.

Though there are some references [19–23] about the deformation mechanism for the stress relaxation or creep process, it is still difficult to clearly understand the deformation mechanism for the stress relaxation. By using the stress exponent which is obtained from the relationship between $\log \dot{\epsilon}$ and $\log \sigma$, the deformation mechanism was qualitatively analysed in this research. For the specimen under 600 °C, when the stress is high, the stress exponent does not exist, called power law breakdown phenomenon. With the decreasing of stress, the deformation mechanism is from dislocation climb process to viscous slip process. For the specimens under 400 and 500 °C, when the stress is high, the specimen also shows the power law breakdown phenomenon. With the decreasing of stress, the stress relaxation occurs by dislocation viscous slip process.

3.2 Creep constitutive equations

Usually, when the stress relaxation experiments are carried out under conditions of constant strain, the elastic strain is gradually converted into the creep strain. The total constant strain is defined as shown in eq. (2).

$$\epsilon_t = \epsilon_e + \epsilon_c = \text{const} \quad (2)$$

where ϵ_t = total strain, ϵ_e = elastic strain, and ϵ_c = creep strain

Differentiating both sides of eq. (2) with time gives eq. (3). Because the change in the total strain is zero, $d\epsilon_t/dt = 0$. Then, eq. (4) can be obtained.

$$d\epsilon_e/dt + d\epsilon_c/dt = d\epsilon_t/dt = 0 \quad (3)$$

$$d\epsilon_e/dt = -d\epsilon_c/dt \quad (4)$$

The elastic strain is further defined by

$$\epsilon_e = \sigma/E \quad (5)$$

where σ = stress, and E = elastic modulus. Differentiating eq. (5) with time

$$d\epsilon_e/dt = 1/E(d\sigma/dt) \quad (6)$$

Therefore, the creep strain rate ($d\epsilon_c/dt$) is defined as follows:

$$\dot{\varepsilon}_c = d\varepsilon_c/dt = -1/E(d\sigma/dt) \quad (7)$$

$$\dot{\varepsilon}_c = -\dot{\sigma}/E \quad (8)$$

where $\dot{\varepsilon}_c$ = creep strain rate and $\dot{\sigma}$ = stress rate.

So, the creep strain rate can be obtained from the stress relaxation experimental curves by using eq. (8), and the creep strain rate–stress curves at different temperatures are shown in Figure 5.

Considering the creep during the PWHT process, the creep constitutive equations at constant temperature should be formulated. The most common expressions used to describe the relationship between steady state creep strain rate and stress are Norton power law (9) and exponential function (10) [24–26]:

$$\dot{\varepsilon}_c = A_1 \sigma^n \quad (9)$$

$$\dot{\varepsilon}_c = A_2 \exp(B\sigma) \quad (10)$$

where σ is the applied stress. A_1 , A_2 and B are constants of material which are dependence of temperature; n is the stress exponent.

In order to find an optimal creep constitution equation, the power law and exponential function were both used to fit the creep strain rate–stress curves. As shown in Figure 5, the creep curves at different temperatures have similar regularity for change of creep strain rate. During the fitted process, the curves were divided into three stages. The first stage and second stage were fitted with exponential function. Considering the regularity for

change of stress in the third stage, the quadratic polynomial was used to fit this stage. It was found that the power law and exponential function could fit the curves well.

Based on these analyses, eq. (11) was chosen to fit the creep strain curves at different temperatures. When the stress is less than σ_2 , exponential function is used as the fitted function. When the stress is greater than or equal to σ_2 , quadratic polynomial was used as the fitted function. Then, the creep curves were fitted using software Origin and the value of the parameters of fitted functions were achieved. Table 3 gives the material constants of constitutive equations and the value of σ_1 and σ_2 at 400, 500 and 620 °C.

Table 3: Material constants in creep constitutive equations.

Parameters	Temperature (°C)		
	620	500	400
A (s ⁻¹)	9.00787E-10	2.39776E-13	1.22974E-27
B (MPa ⁻¹)	0.06273	0.05226	0.13515
C (s ⁻¹)	4.06873E-10	5.66894E-14	2.8329E-35
D (MPa ⁻¹)	0.07050	0.05794	0.18940
E (s ⁻¹)	-1.84586E-5	-1.01827E-6	3.13374E-5
F (MPa ⁻¹ s ⁻¹)	1.63710E-7	-8.92802E-9	-1.96790E-7
G (MPa ⁻² s ⁻¹)	5.95483E-11	5.18726E-11	3.08912E-10
σ_1 (MPa)	100	240	320
σ_2 (MPa)	140	280	335

Figure 5: Creep strain rate–stress curves at different temperatures: (a) 620 °C; (b) 500 °C; (c) 400 °C.

$$\begin{cases} \dot{\epsilon}_c = A \exp(B\sigma), \sigma \leq \sigma_1 \\ \dot{\epsilon}_c = C \exp(D\sigma), \sigma_1 < \sigma < \sigma_2 \\ \dot{\epsilon}_c = E + F\sigma + G\sigma^2, \sigma \geq \sigma_2 \end{cases} \quad (11)$$

where A , B , C , D , E , F and G are material constants.

3.3 Verification of creep constitutive equations

In order to verify the developed creep constitutive equations, the FE model was established to simulate the stress relaxation processes. FE software MSC.Marc with the user-subroutine Crplaw [27] was used to perform stress relaxation. The creep constitutive equations at different temperatures were programmed with Fortran language into Crplaw and then the user-subroutine was invoked during the simulation process.

Taking the specimen under 620 °C as an example, the distribution of effective stress in the specimen during stress relaxation process is shown in Figure 6. It can be seen that the stress is homogeneous in the central part of specimen and the stress decreases with the time increasing. This is because that part of elastic strain in the specimen has transformed into creep strain, which can decrease the stress. The evolutions of different types of strain under 620 °C are shown in Figure 7. It is obvious that the creep strain increases with the time increasing, and the elastic strain decreases conversely. The total strain almost holds at a constant value and the plastic strain constantly keeps at zero.

Figure 6: The distributions of effective stress at different time under 620 °C.

Figure 7: The evolutions of different types of strain under 620 °C.

Figure 8 shows the simulated stress relaxation curves and the experimental curves at 400, 500 and 620 °C. It can be seen that the simulated stress relaxation curves obtained based on the creep constitutive equations established above are in good agreement with the experimental results. It is believed that the models constructed can be successfully used to describe the stress relaxation behaviour at experimental temperatures of SA302Gr.C.

4 Conclusion

In order to investigate the stress relaxation behaviour of SA302Gr.C, the stress relaxation experiments were performed at temperatures of 400, 500 and 620 °C with constant strain of 0.5%. The stress relaxation curves at different temperatures were obtained and the corresponding creep strain rate versus stress curves were gotten based on the data of creep strain rate which are calculated through the relationship between creep strain and stress which was derived previously.

By fitting the creep strain rate–stress curves with the exponential function, the creep constitutive equations at different temperatures were established and the parameters in the creep constitutive equations were calculated. An FE model was built to simulate the stress relaxation processes at different temperatures. The simulated curves have a good agreement with the experimental ones, which illustrates that these creep constitutive equations can be used to describe the stress relaxation behaviour of SA302Gr.C at different conditions.

Figure 8: Comparison between the simulated stress relaxation curves and the experimental curves at different temperatures: (a) 620 °C; (b) 500 °C; (c) 400 °C.

References

- [1] M. Nikic and Z. Xia, Proceeding of the ASME 2012 Pressure Vessels & Piping Conference (2012) PVP2012-78548:1–7.
- [2] Y. Z. W, Q. A. F, L. Q. S and W. X. H, Boiler Technol, 40 (2009) 57–66.
- [3] C. J. P, Y. Z. W, J. A. F, W. L. H and G. He, Boiler Technol, 40 (2009) 53–57.
- [4] Z. S. Luo and X. D. Xiao, Heat Treat Met, 28 (2003) 44–46.
- [5] Y. W. Qian and J. P. Zhao, Int J Pres Ves Pip, 154 (2017) 11–16.
- [6] K.-H. Lee, M. J. Jhung, M.-C. Kim and B.-S. Lee, Nucl Eng Tech, 46 (2014) 413–422.
- [7] H. Serizawa, S. Nakamura, H. Tanigawa, H. Ogiwara and H. Murakawa, J Nucl Mater, 442 (2013) 535–540.
- [8] M. R. Tchoquessi Diodjo, Y. Joliff, L. Belec, E. Aragon, F. X. Perrin, M. Bonnaudet and L. Lanarde, Prog Org Coat, 104 (2017) 152–160.
- [9] L. H. Zhan, Z. Y. Ma, J. Zhang, J. S. Tan, Z. Yang and H. Li, J Alloys Compd, 679 (2016) 316–323.
- [10] G. Krishna, J. Swaminathan, R. Nilima and R. N. Ghosh, Mater Sci Eng A, 684 (2017) 683–696.
- [11] Y. Z. Wang, J. X. Dong, M. C. Zhang and Z. H. Yao, Mater Sci Eng A, 678 (2016) 10–22.
- [12] Z. Zhu, L. W. Zhang, G. Y. Song, C. Q. Cheng and D. J. Wu, Rare Metal Mat Eng, 41 (2012) 697–700.
- [13] Z. Zhu, L. W. Zhang and S. D. Gu, Chin J Nonferrous Met, 22 (2012) 1063–1067.
- [14] X. J., S. G. Tian and X. M. Zhou, J Mater Eng Perform, 22 (2013) 2048–2055.
- [15] Y. C. Lin, Y. C. Xia, Y. Q. Jiang, H. M. Zhou and L. T. Li, Mater Sci Eng A, 565 (2013) 420–429.
- [16] Y. C. Lin, Y. C. Xia, X. S. Ma, Y. Q. Jiang and M. S. Chen, Mater Sci Eng A, 550 (2012) 125–130.
- [17] ASME SEC II A SA302/SA-302M, Specification for Pressure Vessel Plates, Alloy Steel, Manganese-Molybdenum and Manganese-Molybdenum-Nickel, New York, US, 01, Jul. (1998).
- [18] ASTM E328-02, Standard Test Methods for Stress Relaxation for Materials and Structures, Annual Book of ASTM Standards, West Conshohocken, US, (2008).
- [19] J. Warren, L. M. Hsiung and H. N. G. Wadley, Acta Metall Mater, 43 (1995) 2773–2787.
- [20] Y. Q. Jiang, Y. C. Lin, C. Phaniraj, Y. C. Xia and H. M. Zhou, High Temp Mater Processes, 32 (2013) 533–540.
- [21] T. S. Cao, Research and Application of Relationship between High-Temperature Stress Relaxation and Creep of Heat Resistant Steel, Dalian, Doctoral Dissertation (2016).
- [22] Y. C. Lin, Y. Q. Jiang, H. M. Zhou and G. Liu, J Mater Eng Perform, 16 (2014) 4350–4357.
- [23] B. Wilshire, Metall Mater Trans A, 33 (2002) 241–248.
- [24] J. S. Zhang, High Temperature Deformation and Fracture of Materials, Beijing, Science Press (2007).
- [25] O. Golan, A. Arbel, D. Eliezer and D. Moreno, Mater Sci Eng A, 216 (1996) 125–130.
- [26] S. R. Holdsworth, M. Askins, A. Baker, E. Gariboldi, S. Holmstrom and A. Klenk, Int J Pres Ves Pip, 85 (2008) 80.
- [27] MSC, Marc Volume D: User Subroutines and Special Routines, Version 2000, Los Angeles, MSC Software Corporation (2000).