International Journal of Pressure Vessels and Piping 117-118 (2014) 42–48

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

Effect of creep constitutive equation on simulated stress mitigation behavior of alloy steel pipe during post-weld heat treatment

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Keywords:
Alloy steel
PWHT
Norton's law
Norton-Bailey law
FEA

ABSTRACT

Post-weld heat treatment (PWHT) is usually conducted to reduce the residual stress and to improve the mechanical properties of the welded region. The thermal elasto-plastic creep analysis is used to estimate the mitigation of the residual stress in the welded region analytically. The stress mitigation is caused by effect of the creep relaxation behavior during PWHT. Thus, creep constitutive equation is used to estimate the residual stress mitigation. The material properties of Norton's law and the Norton-Bailey law for alloy steel pipe JIS STPA23 (equivalent to ASME SA335P11 seamless steel tubes) were experimentally investigated. Creep tests were conducted at 400, 500, 600, and 700 °C. Specimens were subjected to certain stresses, and creep strain was measured. The material properties of Norton's law and the Norton-Bailey law were calculated from the measured creep strain data. Five bead-on curved plate specimens were fabricated in order to verify the thermal elasto-plastic creep analysis done with these creep constitutive equations. The curved plate was made from a pipe cut in the hoop direction. The specimens were welded without filler metal by gas tungsten arc weld (GTAW) on both surfaces in the center of the curved plate. The residual stress in one specimen was measured without PWHT. The other specimens were measured under different PWHT conditions. The results of analysis with the two creep constitutive equations agreed well with the experimentally measured results. In addition, no differences in the creep constitutive equations were observed at high PWHT temperature. Accordingly, these analyses conducted with both types of creep constitutive equation were verified to be effective. The effect of creep constitutive equation on simulated stress mitigation behavior during PWHT has been clarified for analytically estimating residual stress in the welded region.

1. Introduction

Alloy steel pipe is used to fabricate the piping in power plants. Welding is normally used to join the pipes. Tensile residual stress typically occurs in the welded region, which reduces their fatigue strength and brittle fracture strength. Therefore, it is important to improve and estimate the residual stress status of the welded region in order to maintain high reliability of structures that include weld. Many studies have used thermal elasto-plastic analysis to estimate the residual stress distribution in the welded region [1,2]. The models for simulation of welding were investigated to simulate residual stress distributions and distortions in welded structures accurately. For example, the effect of the phase transformation on residual stress was investigated to improve the accuracy for simulated residual stress [3–5]. Stress-strain history during welding process was investigated to simulate cyclic stress-strain behavior from room temperature to melting temperature [6]. Post-weld heat treatment (PWHT) is a common method that can be applied in service to reduce tensile residual stress and to improve the mechanical properties of the welded region. The effect of PWHT on the hardness of material and microstructure are investigated [7]. Thermal elasto-plastic creep analysis is used to estimate the stress mitigation in the welded region after PWHT. The stress mitigation is an effect of the creep behavior during PWHT. The creep behavior is estimated using creep constitutive equation [8,9]. Many studies have used Norton's law or the Norton-Bailey law [10–12]. The residual stress after PWHT is simulated under the actual conditions in these studies. An actual structure is subjected to various influences during PWTH. However, few studies have investigated the effects of PWHT temperature and holding time on stress mitigation during PWHT. It is important to investigate these effects, when estimating

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0308-0161/$ – see front matter
http://dx.doi.org/10.1016/j.ijpvp.2013.10.008

Table 1
Chemical composition (mass%) of JIS STPA23.

Chemical composition (mass%)	C	Si	Mn	P	S	Cr	Mo
STPA23	≤0.15	0.50–1.00	0.30–0.60	≤0.030	≤0.030	1.00–1.50	0.45–0.65

Table 2
Thermal properties of the STPA23.

Temperature (°C)	Specific heat (J/kg K)	Thermal conductivity (J/s m K)	Thermal expansion ($\times 10^{-5}$K)	Density (kg/m^3)
25	452	36.5	1.18	7850
100	476	38.1	1.21	7850
200	512	37.5	1.27	7850
300	550	36.9	1.30	7850
400	602	36.0	1.36	7850
500	657	34.8	1.41	7850
600	748	33.2	1.44	7850
700	926	31.4	1.46	7850
800	772	28.9	1.36	7850
900	631	28.7	1.21	7850
1000	684	32.2	1.31	7850

the residual stress mitigation in an actual structure. Also, it is important to clarify the effect of creep constitutive equations on simulated stress mitigation behavior during PWHT.

This study was conducted in order to clarify the effect of creep constitutive equations on simulated stress mitigation behavior during PWHT. To do this, the residual stresses in the welded region before and after PWHT were experimentally and analytically estimated. The material properties of creep constitutive equations were calculated from the measured creep strain data. Thermal elasto-plastic creep analysis using Norton's law or the Norton-Bailey law was conducted to estimate the stress mitigation of welded specimens during PWHT. Additionally, the residual stress of the welded specimens was measured under different PWHT conditions in order to verify the thermal elasto-plastic creep analysis with these creep constitutive equations. The calculated stress distributions were then compared to the measured stress distributions to examine the validity of the analyses.

2. Material test of the STPA23 alloy steel pipe

Table 1 lists the chemical composition of the STPA23 alloy steel pipe (equivalent to ASME SA335P11 seamless steel tubes). This material is hot-rolled seamless pipe, which is fabricated from chromium-molybdenum steel. The initial heat treatments are normalizing at 910 °C with 6 min air cooling and tempering at 730 °C with 30 min air cooling. The material properties were experimentally measured to enable transient heat transfer analysis, thermal elasto-plastic analysis, and thermal elasto-plastic creep analysis to be conducted. Table 2 lists the thermal properties for the transient heat transfer analysis.

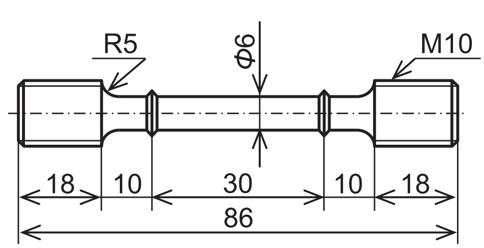

Fig. 1. Shape and dimensions of tensile test and creep test specimen.

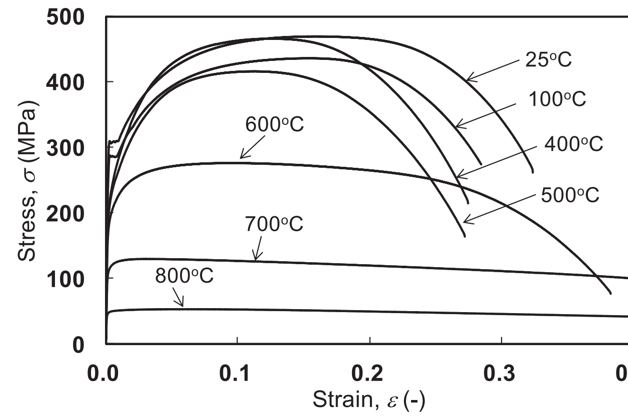

Fig. 2. Relations between stress and strain.

Table 3
Material properties of the STPA23.

Temperature (°C)	Young's modulus (GPa)	Poisson's ratio	Yield stress (MPa)	Tensile strength (MPa)	Elongation (%)
25	214	0.3	310	470	32.0
100	207	0.3	288	436	29.0
200	204	0.3	280	453	23.3
300	204	0.3	254	473	22.3
400	191	0.3	172	467	27.7
500	180	0.3	173	416	27.0
600	146	0.3	152	276	38.0
700	118	0.3	100	129	63.0
800	738	0.3	32	52	91.7

The shape and dimensions of the tensile test and the creep test specimens are shown in Fig. 1. These specimens used in the tests were extracted from the STPA23 alloy steel pipe in the longitudinal direction.

Uniaxial monotonic tensile tests were conducted to measure the stress-strain curves at temperatures from 25 °C to 800 °C. Fig. 2 plots the relation between stress and strain. The stress-strain curves were approximated from their multi-linear behavior. Table 3 lists the material properties for the thermal elasto-plastic analysis. The plasticity model was used based on the isotropic-hardening law. The material specification minimal values were satisfied.

Creep tests were done at temperatures of 400, 500, 600, and 700 °C to enable thermal elasto-plastic creep analyses to be conducted. Table 4 lists the conditions for the creep test. The material properties of Norton's law and the Norton-Bailey law for STPA23 were specified from the measured creep strain data. The uniaxial equivalent creep strain rate $\dot{\varepsilon}_{cr}$ of the steady-state creep region is calculated based on Norton's law (1) as follows.

$$\dot{\varepsilon}_{cr} = A\sigma^n \quad (1)$$

Table 4
Creep test conditions.

Temperature (°C)	Applied stress (MPa)
400	375, 400, 425, 450
500	200, 250, 300, 350
600	50, 100, 150, 200
700	15, 30, 50, 75