Numerical Simulation of the Shape Memory Alloy Pipe Joint

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***Abstract*-Based on the existing constitutive model of shape memory alloys (SMA), as well as on the state of stress distribution between the pipe and pipe joint, a simplified constitutive model for SMA can indeed fit the SMA pipe coupling structure. Using this constitutive model to simulate the stress distribution during the process of heating up, we can use the system to discuss the relationship between the radial compressive stress and various influencing factors.**

Keywords- Shape Memory Alloys; Constitutive Model; Radial Compressive Stress; Pipe Joint; Wall Thickness

I. INTRODUCTION

Serious corrosion problems have been existing in oil and gas pipelines, which lead to huge economic losses [1, 2]. The main reason resulting in the great part of corrosion existing in the joints of pipeline, is the original pipe connected by welding, on the one hand, needing high technical requirements, and on the other hand itself having a lot of disadvantages. NiTi shape memory alloys (NiTi SMA) have excellent shape memory properties, so they were applied earliest in military aircraft hydraulic pipeline connection. Now they have been widely used in aerospace and other fields of pipe connection. Iron base shape memory alloys (Fe SMA) have many advantages, such as high strength, high restored deformation and good property of corrosion resistance as well as their phase transition temperature Ms near the room temperature; in addition to the above advantages, the alloy of Fe SMA is easy to process and its price is cheaper than that of NiTi SMA. Due to these advantages, this alloy is widely used in pipeline connection in the field of petroleum, chemical industry and so on.

The Fe SMA pipeline joints are easy to keep at room temperature, due to their inverse phase transition temperatures above room temperature. Because the inner diameter of pipe joint is smaller than the outer diameter of connected pipe, so the joint diameter can be expanded in room temperature, then the joint can be set on the outside of the connected pipe completely. And then because of the increasing temperature, the heated pipe joint can also make the SMA joint induce the shape memory effects, the radius of the joint become narrower, at last the joint and pipeline connect together tightly [3, 4].

This paper, using the simplified constitutive model derived previously to simulate the structure of SMA fittings, is to study the effect of different factors of the fastening force (radial compressive stress) between SMA joint and pipeline.

II. A CONSTITUTIVE MODEL FOR SMAS

The article using the Brinson's model [5], and the martensite fraction ξ divided into two parts ξ_T and ξ_S, where ξ_T represents the fraction of material that is purely temperature-induced martensite with multiple variants and ξ_S denotes the fraction of the material that has been transformed, or oriented, by being stressed into a single martensite variant, the constitutive relation of SMA can be expressed as

$$\begin{aligned}\sigma-\sigma_0 &= D(\xi)\bar{\varepsilon}-D(\xi_0)\bar{\varepsilon}_0+\Omega(\xi)\xi_S \\ &-\Omega(\xi_0)\xi_{S0}+\Theta(T-T_0)\end{aligned} \tag{1}$$

Where σ is the second P-K stress, ε is the Green strain and D represent modulus of SMA, Ω is transformation tensor, Θ is thermal coefficient of expansion for SMA. (σ_o ε_o T_o ξ_o) represent the initial state if material.

A. Conversion to Detwinned Martensite

For T>Ms and

$$\begin{aligned}\xi_s &= \frac{1-\xi_{s0}}{2}\cos\left\{\frac{\pi}{\sigma_s^{cr}-\sigma_f^{cr}}\left(S-\sigma_f^{cr}-C_M\left(T-M_s\right)\right)\right\} \\ &+\frac{1+\xi_{s0}}{2}\end{aligned} \tag{2}$$

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$$\sigma_s^{cr} + C_M(T - M_s) < \sigma < \sigma_f^{cr} + C_M(T - M_s)$$

$$\xi_T = \xi_{T0} - \frac{\xi_{T0}}{1 - \xi_{s0}}(\xi_s - \xi_{s0}) \tag{3}$$

For T<Ms and $\sigma_s^{cr} < \sigma < \sigma_f^{cr}$

$$\xi_s = \frac{1 - \xi_{s0}}{2} \cos\left\{ \frac{\pi}{\sigma_s^{cr} - \sigma_f^{cr}} \left(S - \sigma_f^{cr} \right) \right\} + \frac{1 + \xi_{s0}}{2} \tag{4}$$

$$\xi_T = \xi_{T0} - \frac{\xi_{T0}}{1 - \xi_{s0}}(\xi_s - \xi_{s0}) + \Delta_{T\xi} \tag{5}$$

Where, if M_f<T<Ms and T<T_o

$$\Delta_{T\xi} = \frac{1 - \xi_{T0}}{2} \left[\cos\left(a_M \left(T - M_f \right) \right) + 1 \right] \tag{6}$$

else

$$T > A_s$$

$$\Delta_{T\xi} = 0$$

B. Conversion to Austenite

For $T > A_s$ and $C_A(T - A_f) < \sigma < C_A(T - A_s)$

$$\xi = \frac{\xi_0}{2} \left\{ \cos\left[a_A \left(T - A_s - \frac{S}{C_A} \right) \right] + 1 \right\} \tag{7}$$

$$\xi_s = \xi_{s0} - \frac{\xi_{s0}}{\xi_0}(\xi_0 - \xi) \tag{8}$$

$$\xi_T = \xi_{T0} - \frac{\xi_{T0}}{\xi_0}(\xi_0 - \xi) \tag{9}$$

Constant C_M and C_A are material properties of SMA. σ_s^{cr} and σ_f^{cr} representing critical stresses at the start and finish of the conversion of the martensitic variants.

III. STRESS STATE BETWEEN PIPELINE AND SMA PIPE JOINT

With the elastic-plastic theory, the stress state between pipeline and SMA joint can solve the thick wall cylinder problem and plane axisymmetric problem [6]. Because of the austenitic phase transformation, the connected pipe limits the shape recovery of SMA joint, so the SMA joint can produce restore stress. The recovery stress provides the hoop stress σ_θ in the pipe joint system. And then the radial compressive stress σ_r produced in the pipeline and SMA joint P_2, as well as the connected pipes thus producing fastening force P_2, the connected pipelines and SMA joint connect together tightly. The stress analysis of pipe coupling system is shown in Fig. 1.

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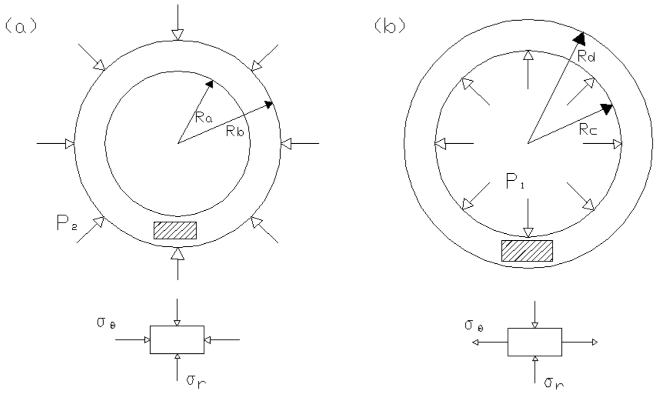

Fig. 1 Stress analysis of pipe coupling system

According to the Lamé formula, we can get the relationship between hoop stress $\sigma_{s\theta}$, radial stress σ_{sr} and fastening force P_2 in the connected pipelines just as follows [7]:

$$\sigma_{sr} = -\frac{R_b^2 P_2}{R_b^2 - R_a^2}\left(1 - \frac{R_a^2}{r^2}\right) \tag{10}$$

$$\sigma_{s\theta} = -\frac{R_b^2 P_2}{R_b^2 - R_a^2}\left(1 + \frac{R_a^2}{r^2}\right) \tag{11}$$

We can also get the relationship between hoop stress σ_θ, radial stress σ_r and fastening force P in the SMA pipelines just as follows:

$$\sigma_r = \frac{R_c^2 P_1}{R_d^2 - R_c^2}\left(1 - \frac{R_d^2}{r^2}\right) \tag{12}$$

$$\sigma_\theta = \frac{R_c^2 P_1}{R_d^2 - R_c^2}\left(1 + \frac{R_d^2}{r^2}\right) \tag{13}$$

From the above content, we can use the formula to deduce the expressions of radial stress and fastening force using hoop stress:

$$P_1 = \frac{\left(\frac{R_d^2}{R_c^2} - 1\right)}{1 + \frac{R_d^2}{r^2}}\sigma_\theta \tag{14}$$

$$\sigma_r = \frac{\left(1 - \frac{R_d^2}{r^2}\right)}{1 + \frac{R_d^2}{r^2}}\sigma_\theta \tag{15}$$

IV. NUMERICAL SIMULATION AND CALCULATION ANALYSIS

At initial state, the radius of SMA joint in parent phase is smaller than the radius of connected pipes. Firstly expanding the diameter under low temperature, during this process, we can make the twin martensite transformed into detwined martensite by external forces; with the heating SMA joint, the joint wants to restore the radius before expanded, yet the recovery is limited by the connected pipes, so the SMA joint produces large recovery forces. Write the MATLAB program according to the relevant transformation equations in the equation (1) and equation (14) and (15), to simulate the structure of SMA pipe coupling,

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analyze the relationships between fastening force and hole enlargement ratio, wall thickness of pipe and heating temperature.

The parameter of SMA is as follows: modulus of elasticity of 100% austenite D_a=67000 Mpa, martensite modulus elasticity D_m=26300 Mpa, transformation temperature M_f=-9°C, M_s=0°C, A_s=80°C, A_f=250°C, transformation constants C_M=8 MPa/°C, C_A =13.8 MPa/°C, σ_s^{cr} =100 Mpa, σ_f^{cr} =170 Mpa. The size of connected pipe are Ra=38 mm, Rb=42 mm respectively. Provided that the connected pipe is rigid, the radius is fixed.

Example 1: choose the expanding rate of SMA joint from 0.02 to 0.1, the thickness of SMA joint, and the outer radius of connected pipe are fixed. The results are shown in Fig. 2, from the curve, we can know that the radial pressure decreases with the increase of expanding rate of SMA joint.

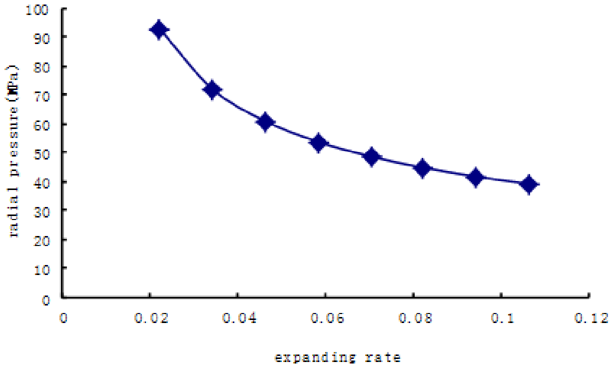

Fig. 2 Relationship between radial pressure and expanding rate

Example 2: choose the wall thickness of SMA joint from 2 mm to 16 mm, the expanding rate of SMA joint, and the outer radius of connected pipe are fixed. The results are shown in Fig. 3, from the curve, we can also make the conclusion that the radial pressure increases with the increase of wall thickness of SMA joint.

Example 3: choose outer radius of connected pipe from 36 mm to 52 mm, the expanding rate and wall thickness of SMA joint are fixed. The results are shown in Fig. 4, from the curve, we can get that the radial pressure decreases with the increase of radius of connected pipe.

V. CONCLUSIONS

In this paper, a constitutive law was made for SMAs, which use the existed constitutive model combined with the state of stress distribution between the pipe and SMA joint. It can be used to illustrate the behaviors of the thermodynamic performance of SMAs.

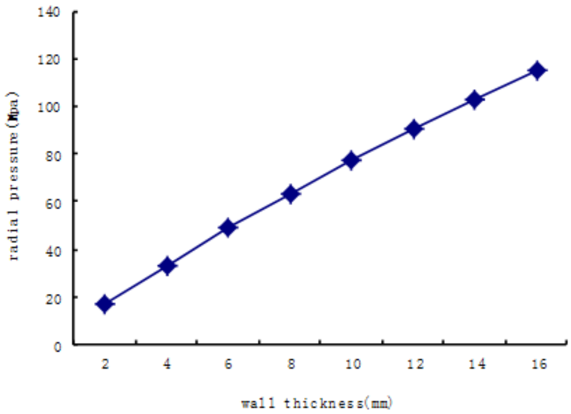

Fig. 3 The relationship between radial pressure and wall thickness

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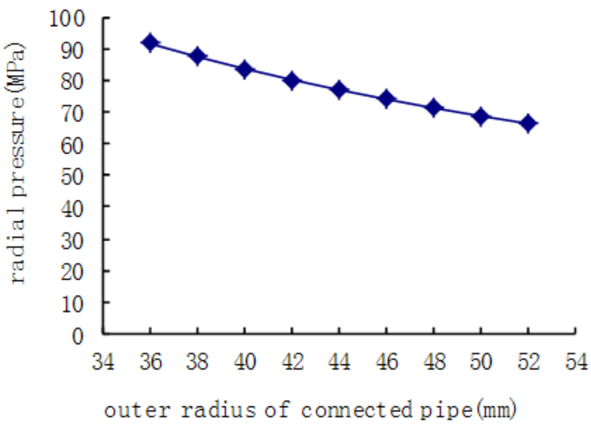

Fig. 4 Relationship between radial pressure and outer radius of SMA pipe

The numerical examples demonstrate that the compressive stress between the connected pipe and SMA joint is influenced by many factors, such as the wall thickness of SMA joint, the temperature and the expanding rate etc. So in order to satisfy the needed compressive stress, we consider comprehensively to select the appropriate SMA pipe wall thickness, hole enlargement ratio and connecting pipe diameter.

Furthermore, in order to verify this simulation results, much more experiments about the SMA pipe couple should be done in the future, which then will be related in another article in detail.

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