Optimization Design of Assembly Performance of NiTiNb Shape Memory Alloy Joint

Xiang Chen\textsuperscript{1,2}, Wei Chen\textsuperscript{3}, Bin Chen\textsuperscript{3}, Hengwei Zheng\textsuperscript{4}, Yang Zhao\textsuperscript{2}\textsuperscript{\textcopyright}

\textsuperscript{1} The State Key Laboratory of Mechanical Transmissions, Chongqing University, Chongqing, China
\textsuperscript{2} Institute of Advanced Manufacturing Engineering, Chongqing University of Posts and Telecommunications, Chongqing, China
\textsuperscript{3}Creec Chongqing survey and Design Institute Co. Ltd., Chongqing, China
\textsuperscript{4}Department of Mechanics, Chongqing University of Science & Technology, Chongqing, China
\textsuperscript{\textcopyright}Corresponding author: E-mails: zhaoyang@cqupt.edu.cn

Abstract. In this study, the whole assembly process from pre-treatment to service of NiTiNb shape memory alloy (SMA) pipe-joint system is numerically simulated by using of the finite element method. With the change of the wall thickness of SMA joints and the pipe outer diameter, the contact pressure and pull-out force under different interferences and pipe diameter ratios are calculated. The results show that the contact pressure between the joint and the pipe increases with the increase of pipe thickness under the same NiTiNb-SMA joint. With the decrease of the joint’s wall thickness, the contact pressure reduces. The pull-out force does not increase with increasing SMA joints’ outer diameter and has a very slightly decrease with the increase of temperature.

1. Introduction
Pipe joints or seal rings are the basic components of the pipe connection project and are widely used for various fluid transports. Pipe joints made of shape memory alloy (SMA) have been widely used in aviation, transportation and petrochemical industries due to their simple structure, easy assembly and high reliability. For instance, SMA-made joints have been used more than 1.4 million in military aircraft oil pipelines and no failure occurred so far, which shows the reliability of its service [1]. Among existing SMA materials, the NiTiNb shape memory alloy has excellent ductility, corrosion resistance, and wide temperature hysteresis characteristics (\~150°C) compared with conventional NiTi binary alloys (temperature lag range \~ 30°C) [2]. The NiTiNb-SMA pipe-joint system overcomes the shortcomings of other SMA joints that must be stored, transported, and assembled at low temperatures, and can be stored and installed at room temperature. Researchers have conducted extensive research on thermo-mechanical of SMA and proposed different constitutive models for SMA application [3-5]. Yan et al. [4] used the finite element method to study the SMA joints. Brinson et al. [6] used finite element analysis to study the effect of plastic strain on two-way shape memory effects. Jiang et al. [7] found that severe plastic deformation based on equal channel angular pressure plays an important role in enhancing the transition delay of Ni\textsubscript{47}Ti\textsubscript{46}Nb\textsubscript{9} (at.\%) shape memory alloys. Uchida et al. [8] found that the recovery stress of NiTiNb alloy increases with the increase of pre-strain. When the pre-strain...
is 9%, the recovery stress reaches the maximum, which is about 450-500 MPa, and then begins to decline. Even there are many studies on the constitutive model of the NiTiNb material [9], however, there are few studies on the overall performance simulation of NiTiNb-SMA joints, mainly on the structural form and loading form [10-12]. A scheme based on the hysteresis effect of Ni$_{47}$Ti$_{44}$Nb$_9$ SMA for the optimal design of assembly performance of pipe-joints is urgently needed.

In present study, the numerical simulation analysis of the contact pressure distribution and pull-out force of the NiTiNb-SMA pipe-joint system based on different internal and external diameter ratios and connection interferences is carried out.

2. Model and parameters

In this section, the material property of steel and NiTiNb-SMA joint is determined. Taking into account the fact that the pipe and joint are all in the form of thin plate structure, a three-dimensional thin-plate structure model, as shown in Fig. 1, is established in the finite element software ABAQUS. Uniaxial tensile tests are performed and compared with experimental results. For both steel and NiTiNb-SMA material, the tensile model in Fig. 1 is adopted.

2.1. Material Parameters of Steel

The steel material parameters in Table 1 are assigned to the tensile model. Considering that the service environment surrounding is nearly room temperature, the uniaxial tensile test of experiment and simulation of steel is carried out at 23°C. The comparative results on the stress-strain curves under experimental and simulated test are shown in Fig. 2. It can be seen that in the stage of elastic deformation, the two curves are completely coincide. In the yield phase, when the stress reaches about 417 MPa, the steel enters yield stage. At this point, the stress-strain curve obtained from the experiment is slightly higher than the stress-strain curve obtained from the simulation. Whereas, during the further tension, the two curves are completely coincides again. The comparative results indicated that the simulation results can be used to describe the actual results. On this basis, to verify the convergence of the model, the effects of mesh counts are performed with the same FE model. The mesh counts change from 1700 to 18600 and the results are shown in Fig. 2(b). It can be found that the curves of different are consistent well with each other. The results indicated that the solution of the FE method is stable and the FE model for the steel pipe is effective.

![Figure 1. Three-dimensional thin plate structure model](image)

| Table 1. Steel Material Parameters |
|------------------------------------|
| **Steel Parameters**               |
| Material  | Elastic modulus | Yield strength | Ultimate strength | Coefficient of thermal expansion | Poisson ratio |
| HR-2 steel | E=205GPa | $\sigma_y=417$MPa | $\sigma_b=720$MPa | $\alpha=1.2\times10^{-5}$ (1/°C) | $\nu=0.28$ |
2.2. Material Parameters of NiTiNb-SMA

As the NiTiNb-SMA joint is usually pre-deformed at Ms+30 °C, and the SMA used in present study has the forward martensitic transformation start temperature Ms=-90.37°C. Therefore, the temperature field of T=-60°C is added during the uniaxial tension simulation. The NiTiNb-SMA constitutive model used in this study is proposed by Chen et al [2], which consider the coupling effect of martensitic transformation and plastic deformation. The relevant parameters necessary in the equation are shown in Table 2.

| NiTiNb Parameters | Transformation temperature(°C) |
|-------------------|--------------------------------|
| Martensite finish | Mf = -130.89°C                 |
| Martensite start  | Ms = -90.37°C                  |
| Austenite start   | As = 68.29°C                   |
| Austenite finish  | Af = -15.75°C                  |

| Material Constants of Joint | E(GPa) | v | B(MPa/°C) | M0(°C) | Ct(MPa) | Cpt(MPa) | ξ | ζ |
|----------------------------|--------|---|-----------|--------|---------|----------|----|---|
|                            | 45000  | 0.3| -60       | 300    | 1000    | 80       | 15 |   |
| Y0(MPa)                    | R0(MPa)| Q0(MPa) | σst(MPa) | σsp(MPa) | Q1(MPa) | εL | θ=1/°C |
|                            | 0      | 550 | 120       | 180    | 220     | 300      | 0.1| 10-5 |

The simulated stress-strain curves are compared with experimental stress-strain curves and the results are shown in Fig. 3(a). It can be seen that in the elastic stage and phase transition stage, the stress-strain curve calculated by FE model is completely coincides with the stress-strain curve obtained from the experimental test. The plastic deformation occurred when the equivalent stress reached 220MPa, during the following yield stage, the calculated result is slightly higher than the experimental curve, and it is closely related to the plastic yield function. When the strain reach 16%, the calculated stress is equal to the experimental result. During unloading process, the calculated result presents elastic unloading, therefore, the residual strain after unloading is larger than experimental test.

On this basis, the mesh counts of the tensile model of the NiTiNb-SMA are verified to exclude the effect of mesh number. The calculated stress-strain curves with 4000 and 8000 mesh counts are shown in Fig. 3(b). It indicated that the FE model for the NiTiNb-SMA joint is effective. Although there are slight differences between the experimental and simulated results, the overall tendency of the stress-strain curve obtained by FE model is consistent well with experimental test.
Figure 3. (a) Comparison of stress-strain relationship curves of NiTiNb-SMA by experimental test and simulation, (b) effects of mesh counts on FE model

3. Assembly process

The assembly process of NiTiNb-SMA pipe-joint system takes the temperature as an independent variable, the self-assembly process is realized through its shape memory effect. The assembly process is divided into 4 stages, as shown in Fig. 4. The first stage: the temperature is dropped to -60 °C, NiTiNb-SMA joint begin to deform at this temperature. The second stage: the pipe is assembled into the SMA joint. In the third stage: the temperature is slowly raised to 100 °C, the NiTiNb-SMA joint tends to recover its initial shape, and as the existence of steel pipe, the SMA joint will hold with the steel pipe. The fourth stage: the temperature is lowered to room temperature (23°C). With the coefficient of friction of 0.2, the self-assembly process of NiTiNb-SMA pipe-joint system is completed.

Figure 4. Self-assembly process diagram

4. Performance Optimization Design

4.1. Pipe-joint size determine

In a given size range, the NiTiNb-SMA pipe-joint system should possess the best overall performance, the strongest anti-jamming capability, and the highest pull-out force. For this purpose, the inner and outer radius dimensions and wall thickness of NiTiNb-SMA joint and pipe are set. The length of NiTiNb-SMA joint is set to 11.00mm, the inner diameter of NiTiNb-SMA joint is set to 1.50mm, and the outer diameter of joint is set to decrease from 2.80mm to 2.20mm.

Two pipes are connected by the SMA joint. The length of each pipe is set to 7.50 mm, the diameter of the pipe is set to 1.00 mm, and the outer diameter of the pipe is set to change from 1.55 mm to 1.61 mm. Each of the given NiTiNb-SMA joint and pipe sizes is arranged and assembled, and nine NiTiNb-SMA steel pipe-joint pairs are obtained, as shown in Table 3.

| Scheme | Joints(mm) | Pipes(mm) |
|--------|------------|-----------|
|        | Inner diameter | External diameter | Wall thickness | Inner diameter | External diameter | Wall thickness |
| 1      | 3.0         | 5.60       | 1.30          | 2.0           | 3.10             | 0.58           |
| 2      | 3.16        | 0.61       |               |               |                  |                |
| 3      | 3.22        | 0.64       |               |               |                  |                |
| 4      | 3.10        | 0.58       |               | 2.0           | 3.16             | 0.61           |
| 5      | 3.0         | 5.00       | 1.00          | 2.0           | 3.16             | 0.61           |
4.2. Contact pressure
Each of the schemes is simulated, and the contact pressure diagrams of different NiTiNb-SMA steel pipe-joint pairs is shown in Fig. 5. It can be seen that when the NiTiNb-SMA joint with R=2.80mm, the contact pressure obviously increases with the increasing of the pipe’s wall thickness (see Fig. 5(a)). In the case of NiTiNb-SMA joint with R=2.50mm, the change of contact pressure is not obviously (see Fig. 5(b)). When the radius of joint is R=2.20mm, the contact pressure decreases with the increasing wall thickness of the pipe (see Fig. 5(c)). From the contact stress cloud distribution, the following conclusions can be drawn: the contact pressure between the joint and the pipe increases with the increase of pipe thickness under the same NiTiNb-SMA joint. With the decrease of the joint’s wall thickness, the contact pressure reduces.

![Figure 5. Contact pressure between the pipe and joint](image)

4.3. Pull-out force
The pull-out force is an important target of the pipe-joint system. It dependents on two factors, which are the contact pressure and the contact area. The contact areas of previous nine pipe-joint pairs are show in Fig. 6(a). It can be seen that the contact area increases slightly with the increase of pipe radius. The change tendency of the contact area is agree with the contact pressure. The pull-out forces of different pipe-joint pairs under room temperature are shown in Fig. 6(b). It can be found that within the specified size range, the pull-out force does not increase with increasing SMA joints’ outer diameter. There is a maximum point, where the SMA joint with R=2.50mm and the pipe with r=1.61mm. For the SMA joint with R=2.80mm and R=2.50mm, the pull-out force increases with the increasing of pipe radius, while for the joint of R=2.20, the pull-out force decreases with the increasing of pipe radius. It can be attributed to the comprehensive effect of martensitic transformation and plastic deformation.

![Figure 6. Curve of contact area and pull-out force change with pipe radius](image)

4.4. Effect of Temperature on pull-out force
The work surrounding temperature may change a small scope around the room temperature. Therefore, the pull-out force values at 3°C and 43°C are calculated to investigate the influence of temperature on
pull-out force. The pull-out force as a function of temperature is shown in Fig. 7. It is not difficult to see that in the range of 3 to 43°C, the pull-out force has a very slightly decrease with the increase of temperature. It means the connection is relatively stable at the work temperature range. In Fig. 7, each colour represents the same size of SMA joint and different marks indicate the same size of pipe. It can be seen that the NO. 6 pipe-joint pair in table 3 has the largest pull-out force and the NO. 1 pipe-joint pair has a minimum.

5. Conclusions
In this study, numerical simulations of the assembly process for SMA-steel pipe-joint system with three different NiTiNb-SMA joint radius and three different pipe radius are performed through finite element method. The following conclusions are drawn out:

(1) Parameters of steel and NiTiNb SMA are determined and applied in the finite element model. The simulated uniaxial tensile behaviors are compared and agree well with experimental tests.

(2) The contact pressure between the joint and the pipe increases with the increase of pipe thickness under the same joint. With the decrease of the joint’s wall thickness, the contact pressure reduces.

(3) The pull-out force does not increase with increasing SMA joints’ outer diameter. There is a maximum for SMA joint radius R=2.50mm and pipe radius r=1.61mm. The pull-out force has a very slightly decrease with the increase of temperature.

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