Advances in Machinery, Materials Science and Engineering Application
M. Chen et al. (Eds.)

doi:10.3233/ATDE220458

Modeling and Simulation of Tubular Form-Fit Joint Forming by Internal Rolling

Xiaoyan DUAN [a], Jingchao YANG [a,b,1], Heng LI [b], Guangjun LI [a], Xiangnan MEN [a] and Zhaohui XI [c]
[a] *Chengdu Aircraft Industry (Group) Corporation Ltd., Chengdu 610092, China*
[b] *State Key Laboratory of Solidification Processing, School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, China*
[c] *AVIC Chengdu CAIC Electronics Corporation Ltd., Chengdu 610092, China*

Abstract. A method of tube joining by plastic deformation has efficient, reliable and environmentally friendly features, so that it is widely applied into the fabrication of aviation pipeline. Internal rolling has potential to join high strength titanium alloy tubes withstanding high pressure medium with better sealing performance. Taking TA18 titanium alloy tubes as the case material, this presentation combines numerical modelling with experiments to describe the deformation behavior of joining by rolling process. The distribution of the residual contact stress and plastic strain was analyzed by partitioning the deformation regions of the tube. Finally, it is concluded that a robust and accurate FE model of Internal rolling can be obtained.

Keywords. Tubular form-fit joint, internal rolling, finite element model, joining by plastic deformation

1. Introduction

Nowadays, the traditional joining methods (e.g. welding and adhesive bonding, etc.) for tubular components may neither meet the performance requirements of tube connectors, nor the demands of ecological civilization. However, a method of joining by plastic deformation presents great potential to improve reliability of the connection components. Up to now, as an important method of manufacturing lightweight and environmentally friendly components, tubes joining techniques by local plastic deformation have wide application in modern industry, such as aerospace industry, power system, petrochemical engineering and transportation [1,2].

Titanium alloy tubes, as a kind of lightweight material with high strength-to-weight ratio, are widely used in the manufacturing of aircraft tubular components. However, they have many disadvantages such as obvious anisotropy, significant deformation resistance, poor plasticity, etc [3,4]. Therefore, titanium alloy tubular form-fit joint forming has been a challenge. Internal rolling process has potential to make high strength titanium alloy tubes deform withstanding high pressure medium with better sealing performance. This process can force the titanium alloy tube material into the grooves of sleeves by the rollers, and thus produces a reliable sealed joining between the tube and

[1] Jingchao Yang, Corresponding author, Chengdu Aircraft Industry (Group) Corporation Ltd., Chengdu 610092, China; E-mail: jingchao-yang@mail.nwpu.edu.cn.

the sleeve. Thus, it is urgent to investigate the deformation behavior for high reliability connecting of high strength titanium alloy tubes in the internal rolling process.

Mori et al. summarized the types and their mechanism of joining by plastic deformation and described form-fit joints that depend on additional geometric elements, plastic deformation and interference pressure of the joined parts [5]. Considering the significance of lighter, cheaper and more environmental demanding, Silva et al. studied an environmentally friendly joining process based on plastic instability for connecting the ends of two tubes [6]. Based on this method, another joining process was proposed by means of tube bulging to make the ends of two tubes lock in a correct position [7]. Additionally, Zhang et al. investigated the method of tube/tube parts joining by rotary swaging [8]. To avoid the problem that is not able to weld in connecting tubes in offshore oil and gas production. It can be concluded that a robust and accurate FE model of internal rolling is significant and would help in improving the efficiency in the exploration of forming parameters of different specifications of tubing.

In this paper, taking TA18 tubes as the case materials, a numerical model will be developed to simulate the tubes joining by internal rolling by means of ABAQUS/Explicit. The accuracy and reliability of the model will be investigated by comparing with experimental results. To validate the quality of tube ends forming, the sealing performance of the joints and the service performance of the joining components to meet the manufacturing requirements of aircraft, a series of performance verification tests were carried out.

2. Experimental Procedure

Figure 1 shows the main forming parts of the experimental set-up and key dimensions of two mechanical parts for joining. As can be seen from it, the joining principle is that the mandrel rotation starts firstly when forming, on one hand, driving the rotation of rollers which interact with the mandrel through the effect of friction; on the other hand, driving the rollers rolling along the inner wall of tube circumferentially through the rotating of cage. Meanwhile, the mandrel moves along the axial direction to make the rollers expand radially. In order to accurately characterize their mechanical properties, uniaxial tension tests were carried out. The titanium alloy tube specification is D8 mm×t0.55 mm. As a consequence, with the aid of digital image correlation technique, the uniaxial tension test was carried out for obtaining the material properties, especially, the normal anisotropic index *r*. By using this parameter, The Hill48 constitutive model was applied to characterize the normal anisotropy of titanium alloy tube. The isotropic hardening model fitted by the Voce function was adopted to present the strain hardening behavior of the titanium alloy tube. The mechanical properties of the stainless steel sleeve were presented by the uniaxial tension test of standardized bar specimen. Also, the Voce function was adopted to fit the true stress-strain curve and describe the isotropic hardening behavior. As a result, table 1 illustrates the mechanical properties of the tube and sleeve.

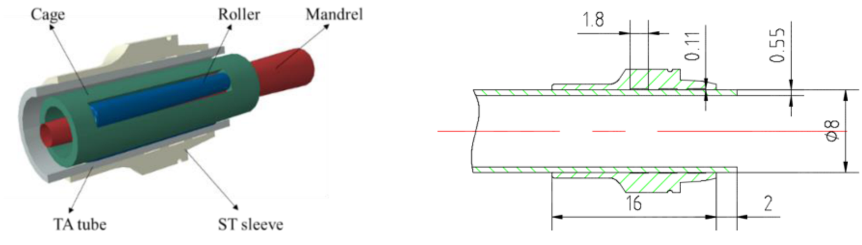


Figure 1. Joining principle: (a) Main forming parts of the experimental set-up; (b) structural sizes of a joining component.

Table 1. Mechanical properties of the joined tube and sleeve.

Material	Elastic modules/MPa	Yield strength/MPa	Ultimate tensile strength/MPa	Elongation/%	*R*
TA18	104870	830	970	15.4	1.4
15-5PH	202000	1350	1430	7.5	—

3. FE Modeling

Because of the complexity of deformation during internal rolling, a whole non-linear 3D-FE model of the tube, sleeve and three rollers was developed. To improve computational efficiency, the cooperative movement of a mandrel and rollers was simplified as the independent movement of rollers. Considering the complicated contact conditions, we employed the ABAQUS/Explicit solver for analysis. The mesh of model is as shown in figure 2. The rollers are driven by the rotation and radial feeding of mandrel in the forming process, as shown in figure 3.

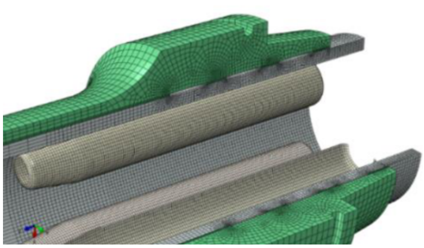


Figure 2. FE model-mesh.

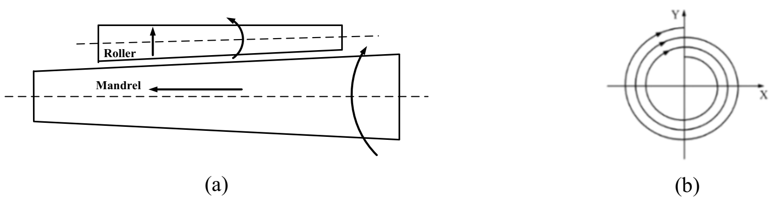


Figure 3. (a) Operation mode of the mandrel and rollers; (b) Revolution path of the rollers.

4. Result and Discussion

4.1. Stress Distribution Characteristics

The stress distribution characteristics of rolling process are shown in figure 4. In the processing, the stress distribution of tube can be roughly divided into seven regions, where are in the front and back of tube, two parts contacting with the groove ridges and three parts sandwiched between the grooves. In the pre-deformation, the tube was not swaged into the groove of tube sleeve. Just at this moment, three-dimensional compressive stress was applied to the entire area 1 and the inner part of area "2, 3, 4, 5, 6 and 7". Meanwhile, the exterior parts of "3, 5 and 7" produced circumferential tension stress, axial and radial compressive stress. Furthermore, the exterior parts of "2, 4 and 6" was subjected to radial compressive stress, circumferential and axial tension stress. So there is a tendency to be elongated circumferentially in these areas and to force the tube material to flow axially.

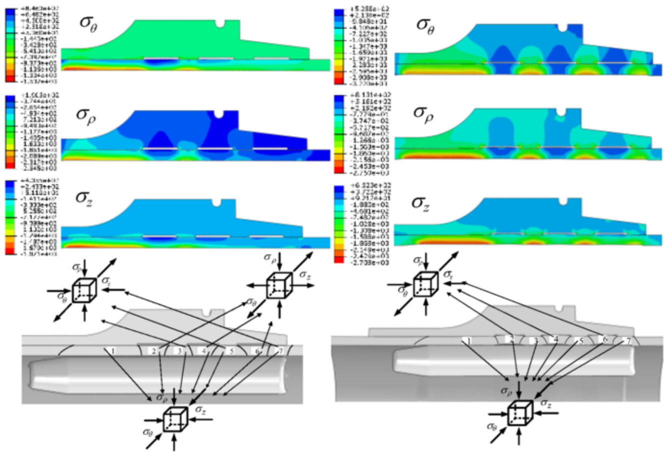


Figure 4. The stress distribution characteristics in the rolling process: a) Early stage; b) Late stage.

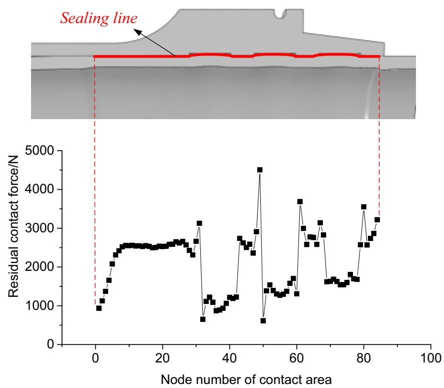


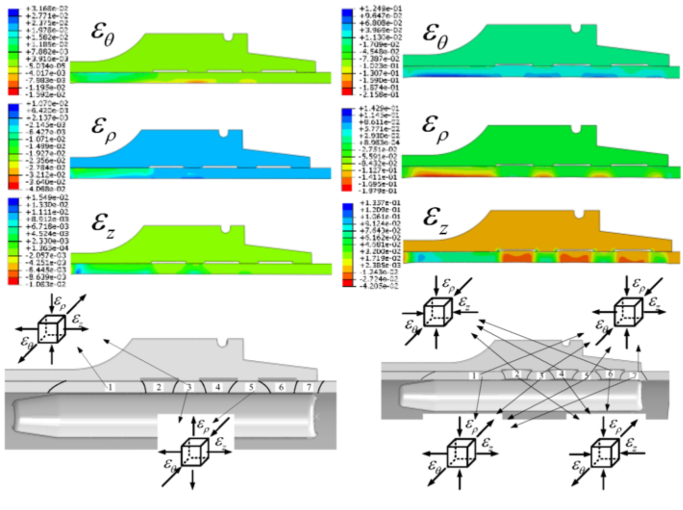
Figure 5. Residual contact force on the sealing line.

In the late deformation, the tube had been locally swaged into the grooves of the sleeve. “1, 3 and 7” areas and the inner parts of “2, 4 and 6” areas of tube were subjected to three-dimensional compression stress; the stress of the exterior parts of “2, 4 and 6” in the axial direction was changed from the tension to compression.

In order to guarantee a good sealing performance, the residual contact force between tube and sleeve can be used to evaluate whether the component is leak or not. Figure 5 shows the residual contact force on the sealing line between the tube and sleeve. As shown in figure 5, the contact force is well above 615 N and maximum up to 4505 N where is in the sharp corner of middle groove. This is in accordance with performance verification tests where the internal pressure levels up to 56 MPa.

4.2. Plastic Strain Distribution Characteristics

The plastic strain distribution characteristics of rolling process are shown in figure 6. Corresponding to the above-mentioned stress distribution, strain distribution of the tube can be also roughly divided into seven regions in the processing. In the pre-deformation, no plastic strain occurred in “2, 4, 6 and 7” areas due to the yield state of the two areas did not reach. The main plastic strain was generated in area 1 where it was subjected to circumferential and axial tension and radial compression, and the exterior part of area 3 was the same with area 1. While the inner parts of area 3 and 5 was subjected to radial and axial tension and circumferential compression.



(a) (b)

Figure 6. The plastic strain distribution characteristics of rolling process: a) Early stage; b) Late stage.

In the late deformation, the plastic strain distribution characteristics of the tube become complicated. The inner and exterior parts of all regions were different. the plastic strain state of the inner parts of “1, 3, 5 and 7” areas had changed from the original state to circumferential and axial tension and radial compression. The inner parts of area 2, 4 and 6 were subjected to circumferential tension and axial and radial compression strain. While the exterior parts of area 1, 3, 5 and 7 were subjected to axial tension and circumferential and radial compression strain, and the exterior parts of area 2, 4 and 6 were subjected to three-dimensional compression strain. This is mainly due to with the rollers continuous pressing, the normal pressure in the inner surface of the tube also increased, so that the friction shear stress between the rollers and tube also increased, causing the circumferential flow in tube processing zone. But in the processing, the circumferential area which did not contact with the rollers did not almost flow, thus producing larger compression deformation around the elements of the area which contacted with the rollers.

5. Conclusion

Using a Hill48 constitutive model, a robust and accurate FE model of TA18 tube joining by internal rolling was developed based on Abaqus/Explicit. With the deformation areas of titanium alloy tube in the internal rolling process subdivided into seven regions, the distribution characteristics of stress and plastic strain were analyzed in detail. It is concluded that the stress and strain state will be changed greatly along with the processing. After unloading, the residual contact force is enough to resist the leaking, which is up to 4505 N.

Acknowledgements

The authors would like to thank the National Natural Science Foundation of China (51775441), the Key Project of the National Natural Science Foundation of China (51835011), Civil Aviation Project (MJ-2016-G-64).

References

[1] Weber F, Gebhard J, Gitschel R., Goyal S., Joining by forming–A selective review. J. Adv. Join. Process. 2021; 3: 100054.
[2] Yang H, Li H, Zhang Z, Zhan M. Advances and trends on tube bending forming technologies. Chinese. J. Aeronaut. 2012; 25(1): 1-12.
[3] Li H, Hu X, Yang H, Li L. Anisotropic and asymmetrical yielding and its distorted evolution: Modeling and applications. Int. J. Plasticity. 2016; 82:127-158.
[4] Yang JC, Li H, Huang D, Li GJ. Deformation-based joining for high-strength Ti-3Al-2.5V tubular fittings based on internal roller swaging. International Journal of Mechanical Sciences. 2020; 171: 105367.
[5] Mori KI, Bay N, Fratini L, Micari F. Tekkaya AE. Joining by plastic deformation. CIRP Ann-manuf. Techn. 2013; 62(2):673-694.
[6] Silva CMA, Nielsen CV, Alves LM. Environmentally friendly joining of tubes by their ends. J. Clean. Prod. 2015; 87(1):777-786.
[7] Gonçalves A, Alves LM, Martins PAF. Tube joining by asymmetric plastic instability. 2014; 214 (1):132-140.
[8] Zhang Q, Jin KQ, Mu D. Tube/tube joining technology by using rotary swaging forming method. J Mater. Process. Tech. 2014; 214(10):2085–2094.