

# Whole process modeling of joining of flareless AA 6061-T4 tube by extrusion-bulging forming using a polyurethane elastomer medium

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**Abstract.** The tube joining by plastic deformation proves to be a more efficient and environmentally friendly way to achieve the tube-tube joining compared with other traditional types, such as metallurgical joining and mechanical joining. In this study, to reveal the effects of the processing parameters on the filling quality and residual contact stress, an axisymmetric finite element (FE) model of the whole joining process, including extrusion-bulging forming and unloading, was established and validated. The aluminum alloy (AA) 6061-T4 tubes, the stainless steel (ST) 15-5PH sleeve and polyurethane (PU) elastomer medium were characterized and modeled. And the implicit algorithm was adopted by comparing the prediction results between explicit and implicit FE models. The characteristics of stress distribution and plastic strain for the tube, PU elastomer and sleeve were discussed.

## 1 Introduction

The tubular components for “bleeding” transforming and loading carrying with enormous quantities and diversities are the aorta of aircraft [1]. The performance of the tube joints is one of the key factors affecting the whole duct systems in aircraft. Compared with other traditional types such as metallurgical joining and mechanical joining, the tube joining by plastic deformation proves to be a more efficient and environmentally friendly way to achieve the tube-tube joining [2]. How to achieve the precision and efficient joining of tubes is a crucial and urgent issue to be solved.

There are two major types of tube joining ends by plastic deformation in aerospace industry, viz., flaring joining consisting of single and double types, and flareless joining including ferrule, taper, extrusion-bulging, roller inner swaging and contraction types [3]. Compared with the flaring joining, the flareless joining presents better performance such as better sealing and vibration resistance, higher pressure resistant, lower cost and higher productivity. Among these flareless joining processes, the flareless tube joining by extrusion-bulging still contributes widely application in the manufacturing of



the aerospace pipeline because of its universality and efficiency [4]. However, the whole process of extrusion-bulging forming and unloading is a strictly multiple-tool constrained process affected by so many coupling parameters such as multiple material properties, extrusion forming pressure, extrusion depth and die clearance. The forming quality is thus difficult to be controlled and the problems of "explosion, seepage, leakage" frequently occur in the tube joints. Compared with the experiments, the finite element (FE) method has become a primary tool to provide the most detailed analysis of forming processes. In this paper, based on ABAQUS platform, a FE model of the whole joining process, including extrusion-bulging forming and unloading, was established; Then, the characteristics of stress distribution and plastic strain for the tube, PU elastomer and sleeve were discussed.

## 2 Experiment

### 2.1. The mechanical properties of AA 6061-T4 tube

The uniaxial tension test of full-size tubular sections was conducted to obtain the mechanical properties as shown in the Table 1. The tube specification is 20mm  $\times$  1mm (the external diameter is 20mm and the wall thickness is 1mm). The quadratic plastic yield criteria Hill48 was applied to describe the normal anisotropic plastic deformation behavior of the material.

**Table 1.** The mechanical properties of AA 6061-T4 tube

Material	$E/GPa$	Poisson's ratio	$\delta\%$	$\sigma_{0.2}/MPa$	$\sigma_b/MPa$	normal anisotropy index $r$
6061-T4	67.531	0.3	16.7	169.4	302.4	0.598

### 2.2. The mechanical properties of PU elastomer

The uniaxial tension and uniaxial compression were carried out and the hyperelastic material model of Ogden was adopted to describe the nonlinear elastic behaviors of the material. The PU tube specification is 17.6mm  $\times$  2.8mm (the external diameter is 17.6mm and the wall thickness is 2.8mm). Table 2 shows the mechanical properties and Table 3 provides the material constants of Ogden model.

**Table 2.** The mechanical properties parameters of PU elastomer

Material	$\delta\%$	Shore Hardness	$\sigma_b/MPa$
PU elastomer	644	95	47.61

**Table 3.** The material constants of Ogden model

Rubber type	Mu-1	Alpha-1	$D_1$	Poisson's ratio
PU elastomer	5.17	2.06	0	0.4999

### 2.3. The mechanical properties of ST 15-5PH

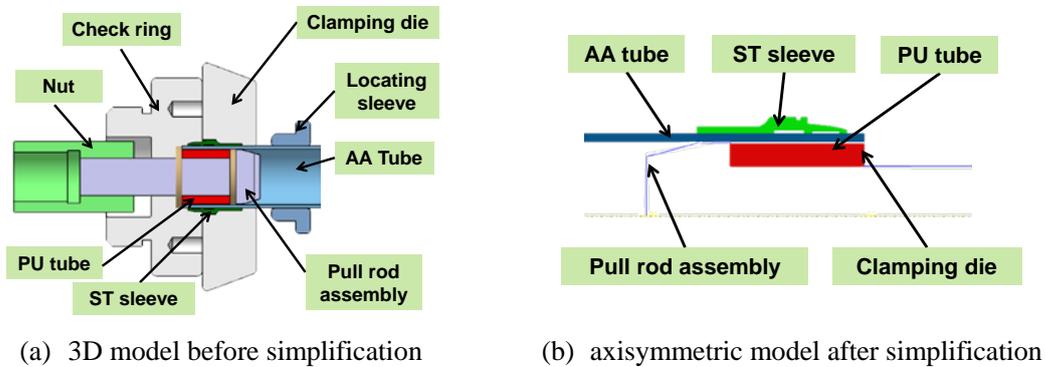
The uniaxial tension test was conducted to obtain the mechanical properties, as shown in Table 4.

**Table 4.** The mechanical properties of ST 15-5PH sleeve

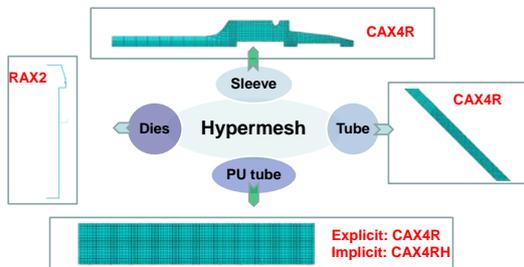
Material	$E/GPa$	Poisson's ratio	$\delta\%$	$\sigma_{0.2}/MPa$	$\sigma_b/MPa$
15-5PH	183	0.26	7.4	1026.07	1042.855

### 3 FE modeling of whole process

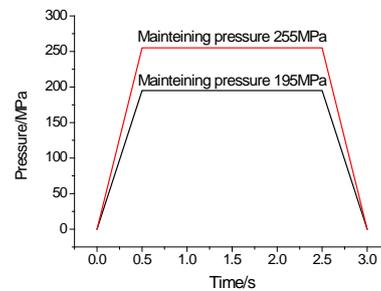
A FE model of the whole process was established to simulate extrusion-bulging forming and unloading. As shown in Figure 1(a), when the pull rod is driven to produce an axial extrusion pressure, the PU elastomer tube is axially compressed to form an internal pressure, then the AA 6061-T4 tube is bulged locally into the two grooves of the ST 15-5PH sleeve; when the pull rod is unloaded, the springback occurs in the PU tube, AA tube and ST sleeve. The key techniques of the FE modeling are summarized: 1) As shown in Figure 1(b), an axisymmetric model could be used to simulate the joining process, and Figure 2 shows the detailed meshing of the five parts; 2) Figure 3 shows the axial load amplitude curve of the pull rod, and the range of maintaining pressure is from 195 MPa to 255 MPa; 3) Instead of the explicit algorithm, the implicit algorithm was adopted to model the whole process including extrusion-bulging forming and unloading.



**Figure 1.** The geometrical model before and after simplification



**Figure 2.** The hypermesh and element type of all the parts

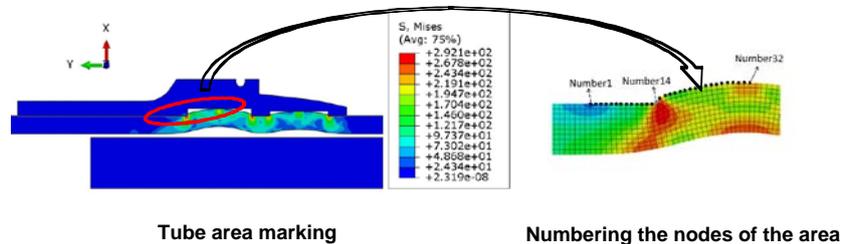


**Figure 3.** The axial load amplitude curve of pull rod

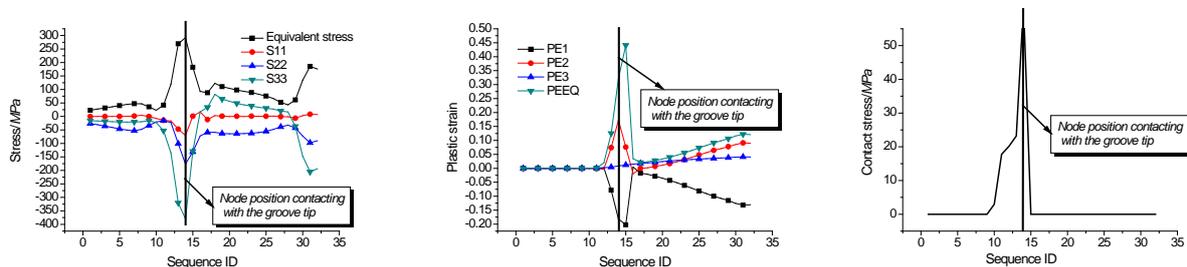
### 4 Results and discussion

The whole process simulation was carried out assigning 255 MPa to maintain the pressure of the pull rod. To obtain the residual stress, the nodes of the tube after springback were numbered and analyzed in the specified area that is shown in Figure 4. Figure 5 shows the distribution characteristics of the residual stress, plastic strain (PE) and equivalent plastic strain (PEEQ). The most reliable position appeared at the sharp corners of the sleeve's grooves where the maximum residual compression stress amounted to 292 MPa, the maximum PEEQ was 0.44 and the residual contact stress was 62 MPa. The contact stress was larger than work pressure 21 MPa. Thus a sealing line could be formed to prevent the possible leakage. The tube joining assembly is more reliable, the sealing performance of that is better, and the service performance can be also improved. The end forming experiments of the joining

assembly were carried out to validate simulation results. The range of oil pressure calculated by the simulation is from 4.57 to 5.98 MPa where the eligible tube joining assembly can be fabricated. It is found that the simulation result was reasonable and coincided with experimental result.



**Figure 4.** Numbering the special codes of the tube after springback



(a) The stress characteristics (b) The PE characteristics (c) The contact stress

**Figure 5.** The distribution characteristics of stress, PE and contact stress in marking area

## 5 Conclusion

The stress and strain distribution characteristics of the AA 6061-T4 tube were obtained and analyzed after springback. At the sharp corners of the sleeve's grooves, the maximum compression stress amounted to 292 MPa, the maximum PEEQ was 0.44, and the maximum residual contact stress was 62 MPa that was larger than work pressure 21MPa. Thus a sealing line can be formed to prevent the leakage. By comparing the experimental result, the simulation result was reasonable and coincided with experimental result.

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