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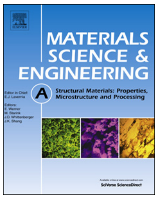

Deformation behavior, microstructure and mechanical properties of pure copper subjected to tube hydroforming

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ABSTRACT

In this study, the deformation behavior, microstructure and the mechanical properties of annealed pure copper through parallel double branched tube hydroforming were investigated. The deformation behavior was studied with hydroforming experiments along with the finite element method. Microstructure and mechanical properties investigations were performed with electron backscatter diffraction, transmission electron microscopy and hardness testing. The results indicated that the stress and strain distribution in the sample were inhomogeneous from region A to region B, during the parallel double branched tube hydroforming. The wall thickness decrease and increase at regions A and B were demonstrated, respectively. The microstructure characterization demonstrated that significant grain refinement could be obtained by the deformation-induced grain refinement mechanism. The grain size decreased and the fraction of low angle grain boundaries increased as the strain increased. The hardness presented a significant increase from the as-annealed sample to the as-deformed sample. Also, the hardness value at region B was almost twice the annealed copper hardness value during the calibration stage. Moreover, the hardness variation agreed with the microstructure changes.

1. Introduction

Tube hydroforming (THF) is a widespread metal forming process, which can produce lightweight tubes or tube components with complex cross sections in many fields of industry manufacture, such as in automotive and aerospace industries [1,2]. THF is conducted to form tube components through simultaneous application of internal high pressure and axial feeding [3]. Compared to the conventional forming processes, the THF has many advantages, such as improved part quality, significant reduction in weight and lower manufacturing costs [4].

Many researchers mainly focused on the deformation behavior and formability study during THF. The effect of loading path on the deformation behavior was discussed [5,6] and various optimization methods, such as the Taguchi method, the simulated annealing method and the response surface method, were presented to obtain the optimum loading path during THF [7–9]. The occurrence of drawbacks, such as wrinkles and fractures, was analyzed under complex stress states [10,11]. The material properties and geometrical factors of tubes and the die effect on the deformation behavior were discussed in other literatures [12,13].

Adversely, only few studies were focused on the relationship among deformation behavior, microstructure evolution and mechanical properties of the tube components during THF in previous investigations [14,15]. Ahmad et al. [14] studied the microstructure evolution of the drawing quality welded steel tube in the THF process. It was discovered that the grain refinement with high percentage of low angle grain boundaries provided an indication of higher plasticity. Liu et al. [15] reported the microstructure evolution of the transformation-induced plasticity steel tube during T-shape hydroforming. The stress-strain state effect on the martensite transformation degree of retained austenite was explored, but the mechanical properties of the tube were not investigated.

It is well known that deformation behavior highly affects the microstructure evolution and the microstructure has significant effect on the mechanical properties of the parts during metal forming [16,17]. In order to obtain improved forming quality of the tube parts, it is necessary to understand the relationship among the deformation behavior, the microstructure and the mechanical properties during different deformation stages. In this present study, the parallel double branched tubes were formed through the THF process. Experiments along with the finite element method (FEM) were employed to research the deformation behavior of the tube parts, such as a variation of the tube shape and the stress-strain state at different forming stages during the THF process. The microstructure and mechanical properties were investigated through electron backscattered diffraction (EBSD), transmission electron microscopy (TEM) and hardness testing.

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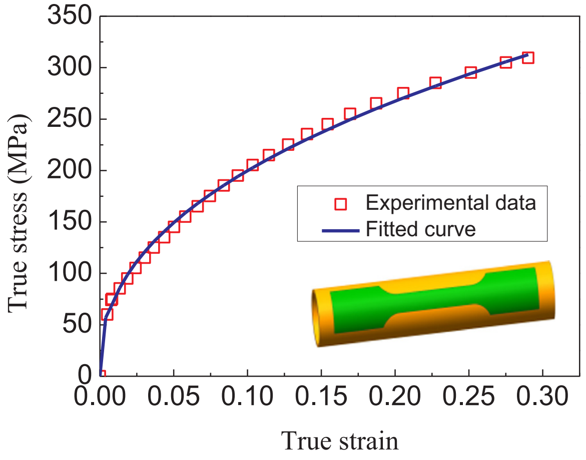


Fig. 1. True stress-strain curve of annealed copper tube along axial direction.

2. Experimental procedure

2.1. Material

A commercial pure copper tube of 99.9% in purity was used for the tube hydroforming. The thickness and diameter of the tube blank were 1.5 mm and 30 mm, respectively. The tube was annealed at 673 K for 60 min, in order to relieve the stress. The mechanical properties of the annealed copper tubes, such as yield strength, ultimate tensile strength, strength coefficient and strain-hardening index, were obtained from uniaxial tensile testing. The true stress-strain curve of an annealed copper tube along the longitudinal direction was experimentally determined, as presented in Fig. 1. Also, the experimental data of the true stress and strain were fitted with the power law, as presented in Eq. (1). The mechanical and physical properties are summarized in Table 1.

$$\sigma = K\varepsilon^{n} \tag{1}$$

where, σ is the true stress, ε is the true strain. K is the strength coefficient and n is the strain-hardening index.

2.2. Tube hydroforming

Fig. 2 presents the schematic diagram of the parallel double branched tube hydroforming. The tube was formed through simultaneous application of internal high pressure and axial feeding. The geometric shape of the parallel double branched tube is presented in Fig. 3. Both diameters of the branch and the main tube were 30 mm. The center distance for the two branches was 70 mm, while the corner radius between the main tube and the branch was 8 mm. The branch height of the tube was 18 mm. The tube hydroforming experiments were carried out with a hydroforming setup, as presented in Fig. 4. The experimental tools consisted of two punches and a die. The tube blank was coated with lubricant and placed in the die. Four bolts were utilized to clamp the upper die with the lower die. The hydraulic pump was utilized to provide the internal pressure with a maximum capacity of 70 MPa. The power source of the axial compressive force was driven by a 5.5 kW servo motor.

Table 1
Material properties of annealed copper.

Density (g/mm^3)	8.9×10^{-9}
Elastic modulus (MPa)	127,000
Poisson's ratio	0.31
Yield strength (MPa)	57
Ultimate tensile strength (MPa)	234
Strength coefficient (MPa)	526
Strain-hardening exponent	0.42

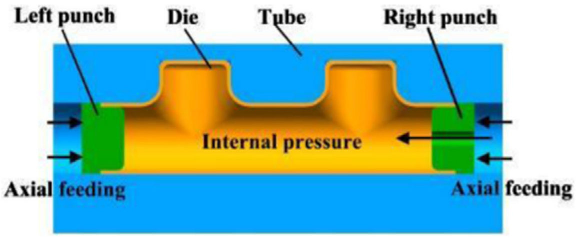


Fig. 2. Schematic diagram of parallel double branched tube hydroforming.

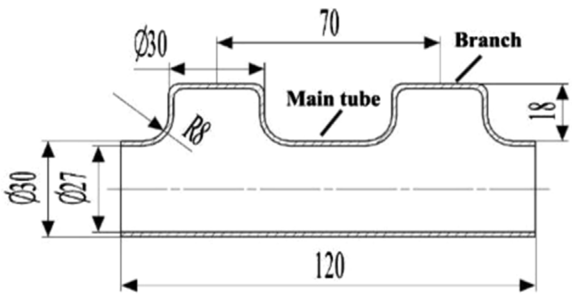
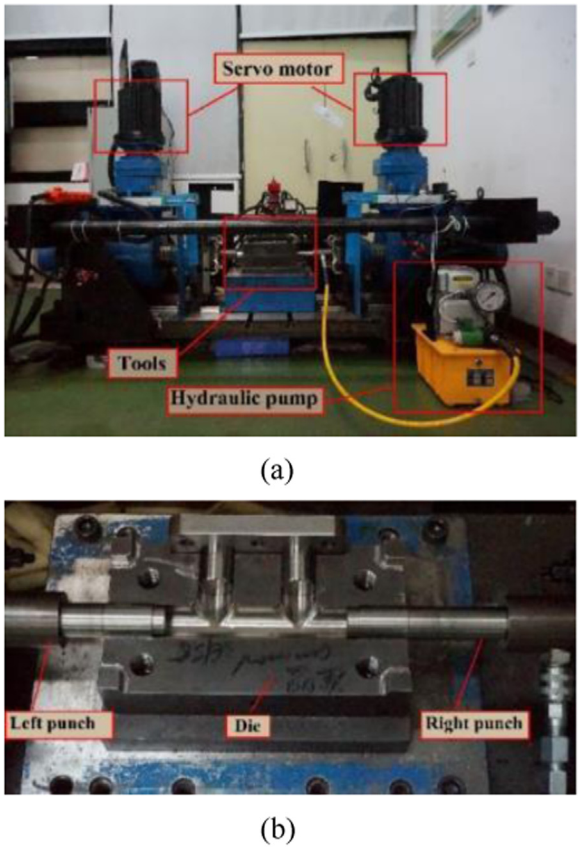


Fig. 3. Geometric shape of parallel double branched tube.



(a)

(b)

Fig. 4. Experimental setup (a) hydroforming machine (b) tools.

The loading path that constituted the relationship between the axial feeding and the internal pressure was utilized to manufacture the parallel double branched tube, as presented in Fig. 5. The axial loading was an external force to compress the tube end, which was generated by two punches. The axial feeding was the feeding distance of the punches. The tube hydroforming was divided into three steps [18]: yielding, expansion and calibration stages. In the yielding stage, the internal pressure was rapidly increased to 20 MPa to initiate the tube deformation and