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Circumferential pure shear test of thin-walled aluminum alloy tubes

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Abstract. In order to obtain the pure shear deformation characteristics along the circumferential direction of tubes, a circumferential shear test for thin-walled tubes is proposed in this paper. The experimental device consists of a tubular sample and two cylindrical mandrels with shear plates. The torque along the circumferential direction was applied to the tubular sample by the two shear plates to make the pre-set shearing zone of the sample under a circumferential pure shear stress state. The two cylindrical mandrels support the inner wall of the tube to avoid buckling so that the pure shear stress state can be maintained during the whole deformation process. A 5052 aluminum alloy tube with an outer diameter of 50 mm and a wall thickness of 1.2 mm was used in the test. It is shown through simulation and experiment that shear deformation is concentrated in the pre-set shearing zone. This test can be used to obtain the circumferential pure shear stress-strain relationship.

Keywords. circumferential pure shear; thin-walled tube; shear stress; aluminum alloy

1. Introduction

The numerical simulation of plastic deformation is of great significance to reduce development cost and shorten development cycle. As there are diversified manufacturing methods for tubes, it is essential to use anisotropic functions to describe the plastic deformation behavior in tube deformation simulation. However, only the characteristics along circumferential and axial direction of tubes have been obtained [1-3].

Meanwhile, popular testing methods, such as uni-axial and bi-axial tension tests, are both based on tensile deformation [4, 5]. For anisotropic material, the shear deformation cannot be precisely simulated by the stress-strain relationship obtained through tension test. If pure shear stress-strain relationship is obtained, the accuracy of deformation simulation for complex parts will be significantly improved. Due to shape limitation, there is little research on shear test methods for thin-walled tubes. The famous Lode test cannot guarantee pure shear state under large deformation and can only be used to testify the initial yielding locus. Wang et al. proposed a new method for pure shear test along axial direction of thin-walled tubes [6]. A pair of semi-circle mandrels are used to exert force along axial direction on the sample, and pure shear loading along the axial direction of the tube is achieved.

A new method for circumferential shear test of thin-walled tubes was proposed in this paper. Pure shear loading along the circumferential direction of the tube was achieved using shear plates and support mandrels.



Nomenclature

M Torque obtained by the torque sensor
 F_1 real-time torsional load force
 τ real-time shear stress
 S real-time section area of shearing zone
 L real-time length of the single shearing zone
 D outer diameter of the tube
 t the thickness of the tube

2. Principle of shear deformation device

The experimental device consists of three parts: tubular sample, shear plates and mandrels, as shown in figure 1. Two pairs of rectangular through-holes are machined on the tube wall. The direction of the hole is perpendicular to the tube axis, while the two through-holes are separated at an angle along the circumferential direction. The upper surface of one through-hole coincides with the lower surface of the other. On the plane of the junction, only two areas are connected along the circumferential direction, which are the pre-set shearing zones.

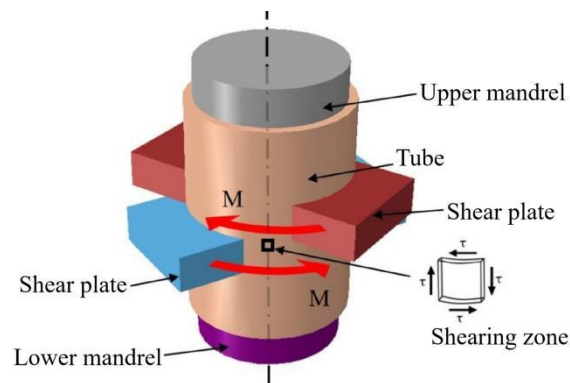


Figure 1. Schematic diagram of tube circumferential shearing device.

Two shear plates are inserted into corresponding through-holes. While one of the shear plates rotate, the pre-set shearing zone is under a shearing state. In order to avoid buckling during shearing, two cylindrical mandrels are placed inside the tube, leaving a small gap between the mandrel and the inner wall of the tube to avoid excessive friction force. The mandrels have the same groove size as the shear plate so that the shear plate can be inserted. If the rectangular shear plates shown in figure 2(a) are used, the force isn't perpendicular to the thickness direction. So, the shearing plates shown in figure 2(b) are used in the test.

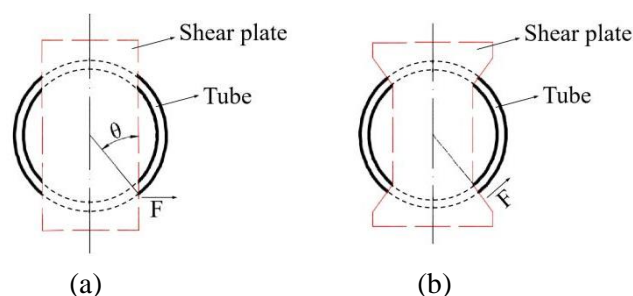


Figure 2. Shape diagram of the shear plate.

One shear plate is fixed during loading and the other one is torqued to rotate. Torque is delivered to the sample through the shear plate, and the material in the deformation zone is under the circumferential shear stress state.

Since the tube is thin-walled, it can be assumed that the shear plate only exerts torsional load on the outer wall of the tube to generate torque and the arm is the radius of the outer wall when calculating the shear stress. Shear stress can be calculated according to equation (1):

$$\tau = \frac{F_1}{S} = \frac{2M}{D} S^{-1} = \frac{M}{DLt} \quad (1)$$

3. Experimental plan

Thin-walled 5052 aluminium alloy tubes were used in the experiment, with an outer diameter of 50 mm and a wall thickness of 1.2 mm. According to the uni-axial tension test result of camber samples along axial direction, the yield strength is $\sigma_s=106$ MPa and the tensile strength is $\sigma_b=250$ MPa. As shown in Figure 3, the height of the two pairs of rectangular through-holes in the sample is 20 mm and the chord width is 33 mm. The arc length in the deformation zone of the sample is 5 mm. As there are compressive forces added by the shearing plate which has negative influence on the pure shearing state in the shearing zone, long grooves with the half-circle notch at the bottom are machined as both ends to eliminate the influence of the compressive force, as shown in figure 3.

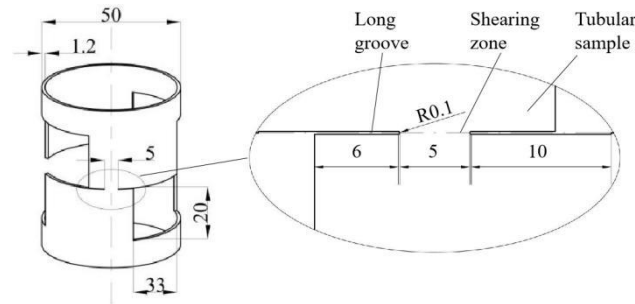
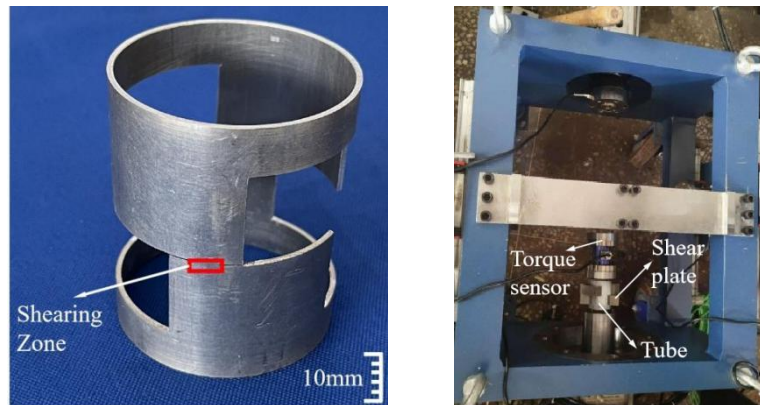


Figure 3. Dimension of the sample.

The outer diameter of the mandrel is $d=47.5$ mm, and the interstices between the mandrel and the tube inner wall is 0.05 mm. The shearing sample and experimental device are shown in figure 4.



(a) Tubular sample

(b) Experimental device

Figure 4. Circumferential pure shear test device.

4. Numerical simulation

The simulation is carried out using implicit solution method of Abaqus software. The element of the tube sample is set as S4R four-point curved reduced integration shell unit with an initial mesh size of 0.1 mm in the shearing zone. The behavior of isotropic elastic-plastic material and the mechanical

property parameters of the tube are set according to the uni-axial tension test. The shear plate is rotated uniformly by 1.5 degrees, and the maximum torque is 53.5 N·m.

The nephograms of shear stress and von Mises stress distribution of the deformation zone are shown in figure 5. It is shown that the deformation of the sample is concentrated at the interface of the through-holes, i.e. the pre-set shearing zones.

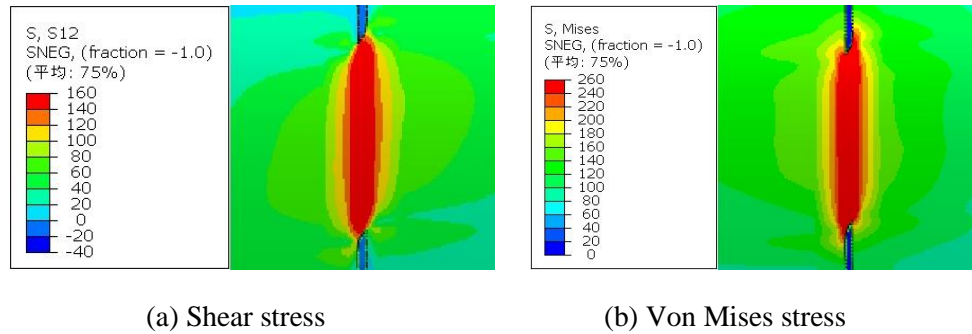


Figure 5. Nephograms of stress distribution of the deformation area.

To investigate the uniformity of strain distribution in the pre-set shearing zone, 5 points are evenly selected along the circumferential direction in the shearing zone, as shown in figure 6, where the Point 3 is the center point of the shearing zone. The distance between Point 1 and Point 5 is 95% of the length of the shearing zone.

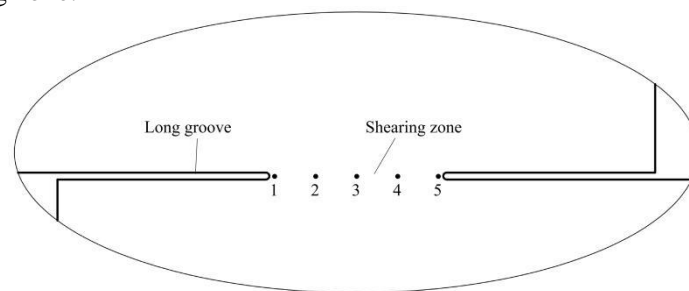


Figure 6. Schematic diagram of location of the selected points in the shearing zone.

As shown in figure 7, the curves of stress triaxiality of points 1-5 are calculated using simulation data, in which the shear strain at the center point of the shearing zone is taken as the horizontal ordinate. For points 1-5, stress triaxiality gradually approach 0 as deformation proceeds. The stress triaxiality is in the $(-0.05, 0)$ interval, so it is indicated that the shearing zone is basically under circumferential pure shear stress state.

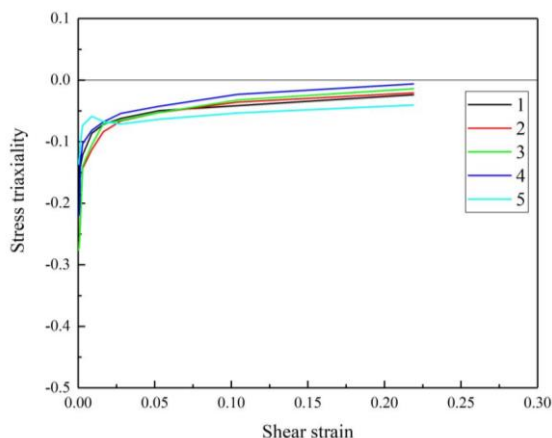


Figure 7. Stress triaxiality changing at different points of the sample.

5. Experimental results

The cracked sample is shown in figure 8. The fracture surface of the sample is flat, i.e. deformation is mainly concentrated on the interface between the two shear plates. It is shown that circumferential shear deformation can be achieved using the experimental device.

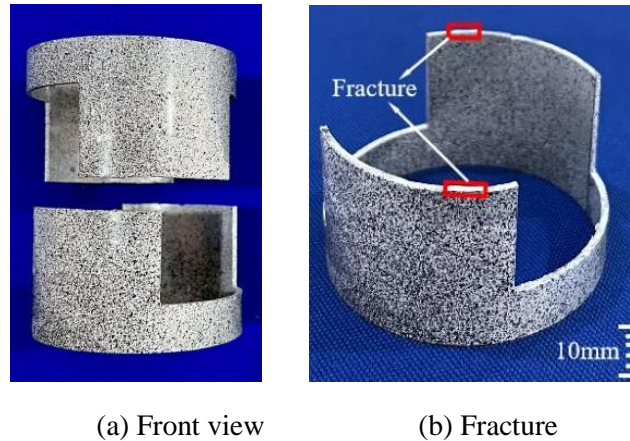


Figure 8. Circumferential shear sample.

A DIC(Digital Image Correlation) device was used to acquire the image of the deformation zone of the sample in the experiment. At the same time, the real-time torque applied to the shear plate was obtained by torque sensor. The shear stress-strain curve at the center point of the deformation zone was obtained, as shown in figure 9. The equivalent stress-strain curves for the circumferential shear test were calculated using Mises criterion and the second order of the plastic work increment and were compared with the stress-strain curve of the uni-axial tension test, as shown in figure 10. There is large difference between the uni-axial tension stress-strain relationship and the equivalent stress-strain relationship of the shearing test.

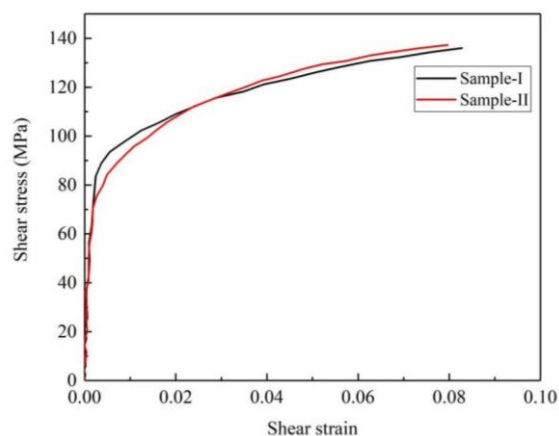


Figure 9. Shear stress-strain curve at the center point of the deformation zone.

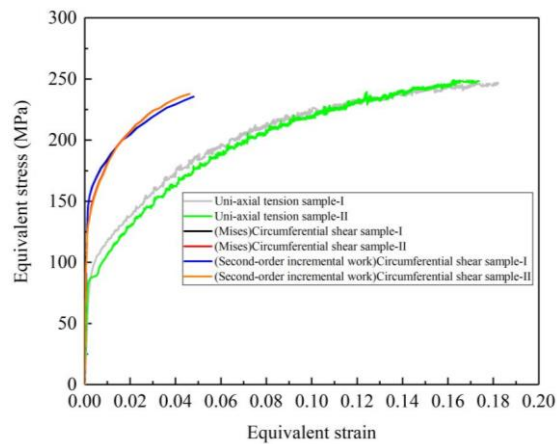


Figure 10. Equivalent stress-strain relationship at the center point of the deformation zone.

6. Conclusion

A novel shear test along the circumferential direction of thin-walled tubes is proposed in this paper. It is indicated by the stress triaxiality result that the stress state in the pre-set deformation zone is close to pure shear. It is shown by the large difference between the uni-axial tension stress-strain relationship and the equivalent stress-strain relationship of the shearing test that it is necessary to bring the shear stress-strain relationship into the anisotropic constitutive model to improve the simulation precision of complex tubular parts.

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