# Cryogenic forming potential of large diameter and thin-walled aluminum alloy tubular materials

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**Abstract.** The large-diameter and thin-walled aluminum alloy tube has superiority in terms of weight reduction and high transmission efficiency which has been widely used in the aerospace field. However, it is a tough issue to deform a desirable bent tube with such extreme specification and small bending radius. In recent years, aluminum alloy materials have been found to show strong enhancement in both strength and ductility when deforms at cryogenic temperature (CT), which provide the cryogenic forming potential for the hard-to-bend aluminum alloy tubes. In this work, tube formability at room temperature (RT) and CT was explored. The anisotropic characterization of the thin-walled tube was realized by combining experiment and viscoplastic self-consistent (VPSC) model. The overall mechanical properties at CT are significantly improved compared to those at RT. Furthermore, a finite element model of cryogenic bending of the thin-walled 6061-O aluminum alloy tube was constructed. The results provide evidence from two aspects of wrinkling and wall thickness reduction that the thin-walled aluminum alloy tube difficult to form at RT can achieve better formability when bent at CT. The average wrinkle height decreases first from 1.182 mm at RT to 0.201 mm at -60 °C with 83.0% reduction, and then increases to 0.425 mm at -180°C. The average thickness reduction rate decreases monotonically with temperature decreasing, and the drop is fastest at -60 °C of 15.4% reduction. Cracks no longer appear in cryogenic bending. In terms of the effect on the two defects of wrinkling and wall thickness reduction, -60 °C is the temperature at which the best forming properties are obtained.

**Keywords:** Cryogenic formability, Aluminum alloy, Anisotropy characterization, Tube bending.

## 1 Introduction

Aluminum alloy tubes have been widely used in aerospace pipeline system and other manufacturing fields due to its advantages of light weight, high formability, as well as good corrosion resistance [1]. Thin-walled, large-diameter, and small-bending radius aluminum alloy bent tubular parts with high transmission efficiency are required in harsh service conditions like aerospace fuel transportation and environmental control systems. However, it is getting harder to forming the bent tubular components when the tube thickness $t$ and bending radius $R_b$ are smaller as well as the tube diameter $D$ is larger [2], which will lead to various forming defects such as wrinkling, cracking and thickness reduction [3]. So, it is a tough issue to obtain a qualified bent tubular part with such extremely specifications.

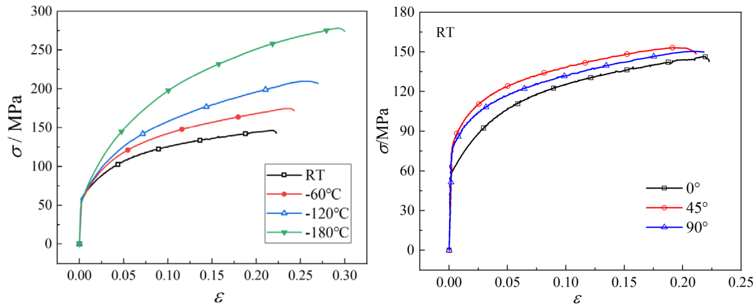
In recent years, aluminum alloy materials have been found to exhibit the characteristic of remarkable enhancement of strength and ductility simultaneously when deformed at CT [4], [5], which makes it possible for the hard-to-bend aluminum alloy tubes. So, scholars have focused their attention on cryogenic forming and found that it can improve the forming performance of aluminum components. Yuan et al. [6] proposed a novel deep drawing process at CT of aluminum alloy sheets and found that the deep drawability was significantly enhanced as the temperature decreased to -160 °C. Schneider et al. [7] carried out a limiting dome height drawing test of EN AW-5182 and EN AW-6016 alloys at low temperatures and explored that the stretch formability of EN AW-5182 alloy can be enhanced obviously at temperatures below 25℃. Liu et al. [8] studied the formability and flow stress of an Al-Cu-Mn alloy sheet under biaxial stress state at various CT and quantified that the formability and deformation uniformity of the sheet at CT were considerably increased. Sotirov et al. [9] found that cryogenic forming of work hardening 5xxx aluminum alloy sheets can offer a higher forming limit for deep drawing. However, the cryogenic forming potential of thin-walled aluminum alloy tube bending still remains unknown.

In this research, taking the 6061-O tube as the research object, cryogenic deformation temperature was set to -60℃, -120℃ and -180℃, respectively. As a comparison, the tube deformation performance under RT, viz 25℃, was also conducted. First, a characterization method combining experiment and VPSC modeling at cryogenic temperature of the tube was investigated to determine the anisotropy of the tube. Then, the simulation method was used to predict the cryogenic formability of the thin-walled aluminum alloy tube. Finally, the formability affected by forming temperature was evaluated from forming defects of wrinkling and thickness reduction.

## 2 Anisotropy characterization at cryogenic temperature

The as-received material is a large-diameter and thin-walled 6061-O aluminum alloy tube with the fully annealed state, which is manufactured by seamless drawing. The tube is with specifications of 63.5 mm in diameter and 0.7 mm in wall thickness. The characterization methods in this research combines the experiment and simulation. For the experimental method, the uniaxial tension test was carried out. For the materials parameters that cannot directly obtained by experiment, a simulation method of viscoplastic self-consistent (VPSC) modeling was employed.

The tests were proposed on an electronic universal testing machine equipped an insulated cabinet with a temperature-controlled system. The temperature control accuracy of the insulation system is 0.1℃. The nominal strain rate was set to 0.001 $s^{-1}$. The specimens and collets of axial tension in $0^o$, $45^o$ and $90^o$ directions were designed to characterize anisotropic index. The true stress-strain curves obtained are shown in Fig. 1 and the material properties are given in Table 1.




(a) (b)

**Fig. 1.** True stress-strain curves obtained by uniaxial tension tests: (a) 0° tension at different temperatures, (b) 0°, 45° and 90° tension at RT.

**Table 1.** Mechanical properties of thin-walled 6061-O aluminum tube in 0º tension.

| Material property | 0º /RT | 45º /RT | 90º /RT | 0º/-60℃ | 0º/-120℃ | 0º/-180℃ |
|---|---|---|---|---|---|---|
| Elastic modulus $E$/GPa | 29.3 | 29.8 | 30.0 | 32.6 | 34.6 | 35.1 |
| Yield strength $\sigma_y$/MPa | 57.2 | 63.1 | 65.3 | 57.5 | 58.8 | 59.1 |
| Elongation $\delta$/% | 22.1 | 20.8 | 21.8 | 24.0 | 26.2 | 29.6 |
| Ultimate strength $\sigma_m$/MPa | 146.2 | 153.2 | 150.4 | 174.6 | 209.6 | 277.2 |
| Anisotropic index $r_0$ | 0.57 | 0.53 | 0.71 | 0.67 | 0.76 | 0.87 |

For the anisotropic parameters that are difficult to determine by experiment methods, namely the properties in 45° and 90° tension at CT and balanced biaxial tension (BBT) at RT and CT, the VPSC simulation method that accounts for full anisotropy in properties and response of the single crystals and the aggregate [10] was adopted.

The deformation mechanism considered in the calculation process is <111>{110} slip system and <111>{112} twinning system for the FCC structure. The key parameters that have to resolve in VPSC model related to the two deformation mechanisms include $\tau_0$, $\tau_1$, $\theta_0$, and $\theta_1$, namely the initial critical resolved shear stress (CRSS), the initial hardening rate, the asymptotic hardening rate and the back-extrapolated CRSS, which determine the CRSS and hardening behavior during deformation. Here self-hardening is used as a reference and the evolution of the threshold stress is based on only the Voce hardening function [11]. The VPSC model of the thin-walled 6061-O aluminum alloy tube was established and validated based on two significant foundations from experiment results. One is the material microstructures obtained by EBSD tests, and the texture of the deformed specimen was used to validate the model. The other one is the stress-strain data obtained in the experiment. 0° tension at RT and CT was used as the input data for parameters solving, and the 45° and 90° tension at RT by experiment was taken to validate the VPSC model. Based on the genetic algorithm in MATLAB, the key parameters related to slip and twinning systems have been solved, as given in Table 2. The material parameters required to further calibrate the constitutive modeling so far have been obtained. As given in Table 3, $\sigma$ refers to the yield strength, and subscript refers to tension direction and BBT state, respectively.

**Table 2.** The solved parameters for VPSC model.

| Temperature | Deformation mechanism | $\tau_0$/MPa | $\tau_1$/MPa | $\theta_0$/MPa | $\theta_1$/MPa |
|---|---|---|---|---|---|
| RT | SLIP <111>{110} | 30 | 29 | 491 | 26 |
| | TWIN <111>{112} | 839 | 42 | 714 | 329 |
| -60℃ | SLIP <111>{110} | 30 | 38 | 510 | 35 |
| | TWIN <111>{112} | 834 | 52 | 716 | 329 |
| -120℃ | SLIP <111>{110} | 31 | 45 | 542 | 47 |
| | TWIN <111>{112} | 834 | 54 | 716 | 329 |
| -180℃ | SLIP <111>{110} | 34 | 64 | 600 | 60 |
| | TWIN <111>{112} | 842 | 52 | 714 | 329 |

**Table 3**. Parameters for thin-walled 6061-O aluminum tube cryogenic modeling.

| Temperature | $\sigma_{y0}$/MPa | $\sigma_{y45}$/MPa | $\sigma_{y90}$/MPa | $\sigma_{yb}$/MPa | $r_0$ | $r_{45}$ | $r_{90}$ | $r_b$ |
|---|---|---|---|---|---|---|---|---|
| RT | 57.2 | 63.1 | 62.2 | 58.8 | 0.57 | 0.53 | 0.71 | 1.46 |
| -60℃ | 57.5 | 64.9 | 62.2 | 58.8 | 0.67 | 0.63 | 0.80 | 1.47 |
| -120℃ | 58.8 | 67.0 | 64.3 | 60.8 | 0.76 | 0.68 | 0.82 | 1.46 |
| -180℃ | 59.1 | 73.5 | 70.5 | 66.6 | 0.87 | 0.71 | 0.83 | 1.45 |

## 3 Modeling of cryogenic bending

YLD2000 yield criterion [12] contains anisotropic parameters related to various deformation conditions which can better describes the anisotropic characteristics of materials. So, it was employed in this research to describe yield behavior of the thin-walled tube. Eight parameters of $\alpha_1$ to $\alpha_8$ related to material anisotropy are to be solved in the function. YLD2000-2D anisotropic yield function reduces to the function proposed by Hershey [13] and Hosford [14]. The function parameters of the two yield criteria for 6061-O aluminum tube at different temperatures have been solved based on the material characterization. The specific solution process is omitted, and the coefficients solved are given in Table 4. Correspondingly, the yield function of the thin-walled 6061-O aluminum tube at different temperatures was established. Deformation yield locus of the tube at different temperatures are proposed, as illustrated in Fig. 2. As the deformation temperature decreases, the yield locus gradually expands outward, and it explains the improvement in yield strength of the 6061-O aluminum alloy tube at CT.

**Table 4.** Yield function parameters of 6061-O tube cryogenic deformation.

| Temperature | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $\alpha_5$ | $\alpha_6$ | $\alpha_7$ | $\alpha_8$ |
|---|---|---|---|---|---|---|---|---|
| RT | 0.967 | 0.887 | 1.179 | 0.989 | 0.991 | 0.839 | 0.876 | 0.859 |
| -60℃ | 0.997 | 0.854 | 1.090 | 0.959 | 0.969 | 0.764 | 0.852 | 0.816 |
| -120℃ | 1.031 | 0.845 | 1.093 | 0.964 | 0.968 | 0.796 | 0.863 | 0.816 |
| -180℃ | 1.142 | 0.660 | 1.002 | 0.891 | 0.922 | 0.638 | 0.787 | 0.735 |

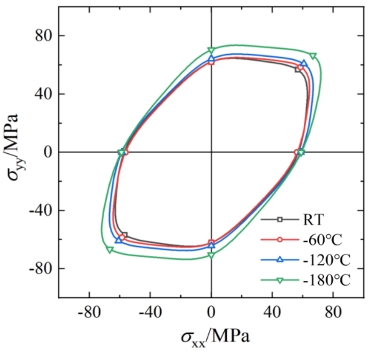
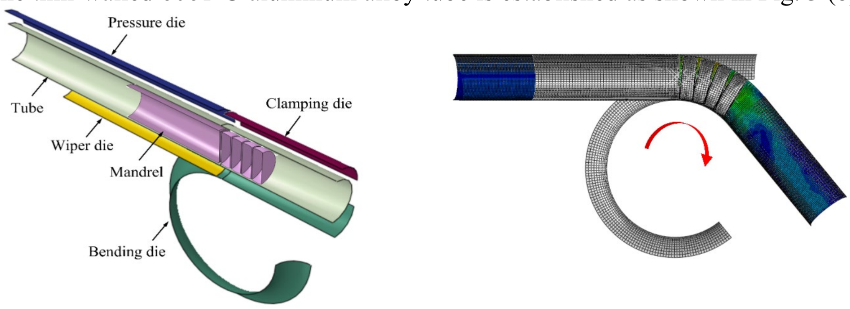



**Fig. 2.** The yield locus of the thin-walled 6061-O aluminum tube at different temperatures.

Further, finite element (FE) model of cryogenic bending of the thin-walled 6061-O aluminum tube was established to study the cryogenic forming potential. The geometric model includes the tube, pressure die, clamping die, wiper die, bending die and mandrel. The tube is set as a deformable body, and all molds are set as rigid bodies. The bending radius is equal to twice the tube diameter, and the bending angle is 90°. For the tube is a large-diameter and thin-walled part, the geometric model is simplified to a shell that ignores the thickness-direction stress. Since the model of the thin-walled tube bending is symmetrical at bending neutral layer, a half-model is adopted to improve the calculation efficiency. The established geometry model is shown in Fig. 3 (a).

During the rotary draw bending process, there are complex contacts between the tube and the molds. The mold with high rigidity is taken as the primary surface, while the tube is set to the secondary surface. The penalty function is used to define the contact constraints and the friction behavior between the contact pairs is described by the Coulomb friction model. The mesh type given to tube is a 4-node linear reduced integral S4R shell element, and the mesh size of the tube is divided into 2×2 mm. Based on the ABAQUS/Explicit platform, the cryogenic rotary draw bending model of the thin-walled 6061-O aluminum alloy tube is established as shown in Fig. 3 (b).




(a) (b)

**Fig. 3.** FE model establishment: (a) geometry model, (b) rotary draw bending FE model.

## 4 Forming potential of the 6061-O aluminum alloy tube by cryogenic bending

The bending process at RT and CT of the thin-walled 6061-O aluminum alloy tube were simulated to explore the cryogenic deformation potential of the tube. The overall view of the tube after bending 90° at different temperatures is shown in Fig. 4.

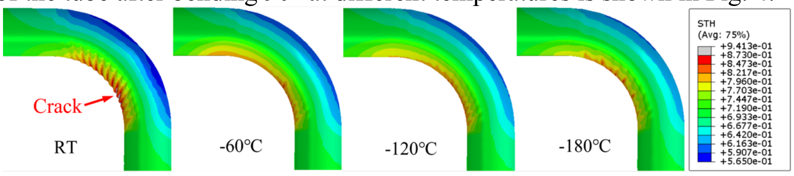



**Fig. 4.** The FE simulation results of the thin-walled 6061-O aluminum alloy tube bending.

In order to quantitatively characterize the wrinkling degree, the bending center is taken as the origin point, the distance from each point along the tube inner side to the origin point is measured and this distance is used as wrinkling height *H* corresponding to bending angle *α*. The wrinkling result is shown in Fig. 5 (a). An obvious trend is that as the temperature decreases, the improvement of wrinkling inhibition is not linear. The average wrinkle height decreases first from 1.182 mm at RT to 0.201 mm at -60 °C with 83.0% reduction, and then increases to 0.425 mm at -180°C.

The wall thickness reduction on the tube outer side is also one of the main defects that restrict the tube forming quality. For tube forming and its later service, thinning of the tube outer side is even more dangerous and worth noting than thickening of the tube inner side. The wall thickness reduction rate is defined as Eq. (1),

$$\Delta t = \frac{|t - t'|}{t} \times 100\% \quad (1)$$

where *t* is the initial wall thickness, and *t*' is the tube wall thickness after bending. The result of $\Delta t$ is given in Fig. 5 (b). The maximum $\Delta t$ at RT is 0.186, and the average is 0.149. While the average $\Delta t$ reduces to 0.126 at -60 °C, 0.119 at -120 °C, and 0.109 at -180 °C, respectively. It is found that the average $\Delta t$ decreases monotonically with temperature decreasing, and the drop is fastest at -60 °C of 15.4% reduction.

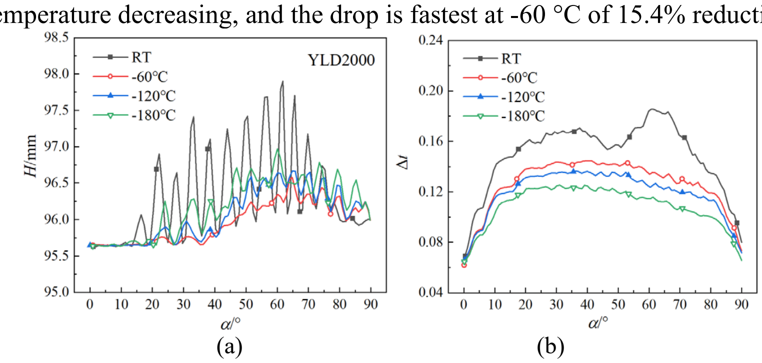



**Fig. 5.** Forming defects of the tube at different temperatures:(a) wrinkling pattern along tube inner ridgeline, (b) wall thickness reduction rate along tube outer ridgeline.

The enhanced material properties at CT are the essential for reduction forming defects of 606-O thin-walled tube. The cryogenic effect of material properties on wall thickness reduction can be explained from two aspects. One is that the strength and hardening of the material are improved at CT, accompanied with a lager elongation, thus the proportion of uniform plastic deformation stage in the entire deformation process will increase accordingly, thereby reducing the wall thickness reduction rate. Another is that the increased anisotropy index $r$ under low temperature also promotes a more uniform deformation. However, the effect of temperature on wrinkling is not monotonous. The reason is that not all enhancements of material properties are beneficial to suppress wrinkling in tube bending and it needs to be analyzed from the influence of different material parameters on wrinkling. Increment in anisotropy index $r$ and material hardening can make deformation more uniform, leading to a reduction of the compressive stress on the tube inner ridge, so that wrinkling is more difficult to occur. While the effects of yield strength and strength factor on wrinkling are on the opposite, which may increase the compressive stress and promote wrinkling accordingly. The final tube bending formability should be the result of the comprehensive superposition of the influence by these material properties, rather than monotonically improving as the temperature getting lower. In terms of the effect on the two main forming defects of wrinkling and wall thickness reduction, -60 °C is the temperature at which the best forming properties are obtained.

## 5 Conclusions

In this study, cryogenic forming potential of thin-walled aluminum alloy tube has been explored to effectively solve the tough issue of precise bending of the hard-to-form tube with extremely specification. Here are the main conclusions.

(1) A characterization method by combining experiment and viscoplastic self-consistent model was investigated to solve the anisotropic parameters at cryogenic temperature. As the temperature decreases, the mechanical properties of 6061-O aluminum tube are improved significantly, indicating the forming potential of 6061-O aluminum tube at CT.

(2) FE model has been established and the simulation results prove that cryogenic forming can effectively improve the forming quality of aluminum alloy tubes. The average wrinkle height decreases first from 1.182 mm at RT to 0.201 mm at -60 °C with 83.0% reduction, and then increases to 0.425 mm at -180°C. For thickness reduction, it can be found that the average $\Delta t$ decreases monotonically with temperature decreasing, and the drop is fastest at -60 °C of 15.4% reduction. Cracks no longer appear in cryogenic bending.

(3) The enhanced material properties at CT are the essential for reduction forming defects of 606-O thin-walled tube. The final tube bending formability should be the result of the comprehensive superposition of the influence by all material properties, rather than monotonically improving as the temperature getting lower. In terms of the effect on the two main forming defects of wrinkling and wall thickness reduction, -60 °C is the temperature at which the best forming properties are obtained.

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