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Trans. Nonferrous Met. Soc. China 22(2012) s357−s363
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Springback law of thin-walled 6061-T4 Al-alloy tube upon bending

LI Heng, SHI Kai-peng, YANG He, TIAN Yu-li

State Key Laboratory of Solidification Processing, School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, China

Received 28 August 2012; accepted 25 October 2012

Abstract: To achieve the precision bending deformation, the springback behaviors under various forming conditions should be clarified preliminarily. Taking the thin-walled 6061-T4 Al-alloy tube of 50.8 mm×0.889 mm (outer diameter×wall thickness) as the objective, the single-factor experimental analysis and the 3D-FE based numerical orthogonal test are conducted to address the effects of forming parameters on the springback behaviors in 6061-T4 Al-alloy tube bending. The results show that: 1) The springback angle increases linearly with increasing of the bending angle. 2) The significant factors from high to low are the clearance between tube and mandrel, the bending radius, the friction between tube and pressure die, the clearance between tube and wiper die, the clearance between tube and pressure die, the coefficient of boost velocity, the friction between tube and mandrel, the number of mandrel balls. 3) The effect rules of significant parameters on springback of 6061-T4 Al-alloy tube are similar to those of stainless steel and Ti-alloy tubes. Springback becomes larger with increasing of the bending velocity, the tube-die clearance, the relative bending radius, the tube-pressure die friction and relative push assistant speed. While the springback decreases with increasing of the mandrel extension length, the number of mandrel balls and tube-mandrel friction.

Key words: springback; Al-alloy tube; tube bending; rotary draw bending; finite element; orthogonal test

1 Introduction

Tube bending is widely used in aerospace, aviation and other high technology industries due to its unique characteristics of manufacturing lightweight and high-strength tubular bent parts [1,2]. Among various bending processes, under multi-tool constraints as shown in Fig.1, rotary draw bending is the most widely used approach to achieve relative high efficiency and precision bending forming. When the tooling is removed, the springback, as the inevitable elastic release phenomenon [3], occurs due to the extrados elongation and intrados compression deformation, which results in the decrease of the bending angle and the increase of bending radius. The springback phenomenon is always one of the key factors restraining the bending quality and increasing the production efficiency [2]. As comprehensive properties, such as relatively high strength, commonly used in the oxygen transportation and environmental control systems in aircraft, the thin-walled 6061-T4 Al-alloy tube can satisfy the current needs of light weight, high strength, high efficiency and low cost in the manufacturing of advanced aircrafts. While, due to high ratio of yield strength and elastic modulus, the significant springback may occur in 6061-T4 thin-walled Al-alloy tube bending. Considering more close tolerance in aerospace, the springback behaviors of 6061-T4 Al-alloy tube upon bending should be clarified.

Many studies have carried out on bending process regarding wrinkling, wall thinning, cross-section flattening [4−6] as well as springback prediction and control. LI et al [7] developed an analytical model for springback control in tube bending. Considering axial force and internal pressure, WANG and AGARWAL [8] derived an analytical springback prediction model in tube bending. ZHANG [9] deduced an approximate calculation formula for springback angle and springback radius based on the analyses of stress and strain distribution in tube bending. An analytical model in which time-dependent springback associated with strain hardening was presented for 321 stainless steel tube by E and LIU [10], and the formulae of time-dependent springback, time-independent springback and total

Foundation item: Project (50905144) supported by the National Natural Science Foundation of China; Program for New Century Excellent Talents in University; Projects (2011JQ6004) supported by Natural Science Basic Research Plan in Shaanxi Province; Project (B08040) supported by Programmer of Introducing Talents of Discipline to Universities ("111" Project)
Corresponding author: YANG He; Tel/Fax: +86-29-88495632; E-mail: yanghe@nwpu.eud.cn; liheng@nwpu.edu.cn
DOI: 10.1016/S1003-6326(12)61731-2

springback were obtained. STRANO [11] proposed a computer-based analytical methodology for process design of rotary draw bending of tubes. GU et al [12] numerically studied the springback of thin-walled tube in rotary draw bending considering the whole process simulation of tube bending, viz., bending, balls retraction and unloading. Considering the strength-differential effect, LIU et al [13] established a finite element (FE) model considering the strength-differential effect for rotary draw bending of thick-walled TA18 tube and improved the precision for predicting the springback angle. Using multivariate and stepwise analysis, JIANG et al [14] studied the coupling effects of material properties and bending angle on the springback angle in TA18 tube bending based on 3D-FE model. WANG et al [15] studied the changing rules of springback of large diameter thin-walled CT20 titanium alloy tube under different bending parameters. Considering both springback angle and radius growth, LI et al [16] clarified the nonlinear springback behaviors of high strength TA18 tube via experiments and 3D-FE as well as analytical analysis. SOZEN et al [17] developed a surrogate model to predict the springback of tube in rotary draw bending via the data obtained from FE analysis. Recently, LI et al [18] addressed the geometry-dependent springback behaviors of thin-walled 6061-T4 Al-alloy tube upon rotary draw bending. The above studies provide beneficial information for springback prediction and control of 6061-T4 tube upon rotary draw bending.

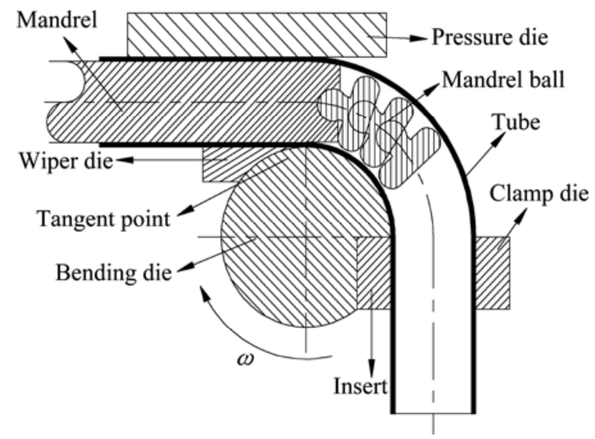

Fig. 1 Schematic of tube rotary draw bending

In this work, taking the 6061-T4 thin-walled Al-alloy tube of 50.8 mm×0.889 mm×101.6 mm (outer diameter (ϕ)×wall thickness (t) ×bending radius (R)) as the objective, using the single-factor experimental analysis and numerical orthogonal method, the effects of bending parameters on the springback were studied. Since the springback radius is so minor, only the springback angle is considered in this work.

2 Experimental

2.1 Mechanical properties of 6061-T4 tube

Uniaxial tensile test was conducted to study the mechanical properties of 6061-T4 Al-alloy tube, and the tensile rate is 12 mm/min. An arc-shaped specimen is directly cut from the tube by Electrical Discharge Machining (EDM) wire cutting. Figure 2 shows the nominal and true stress−strain curves and Table 1 shows the mechanical properties of 6061-T4 Al-alloy tube.

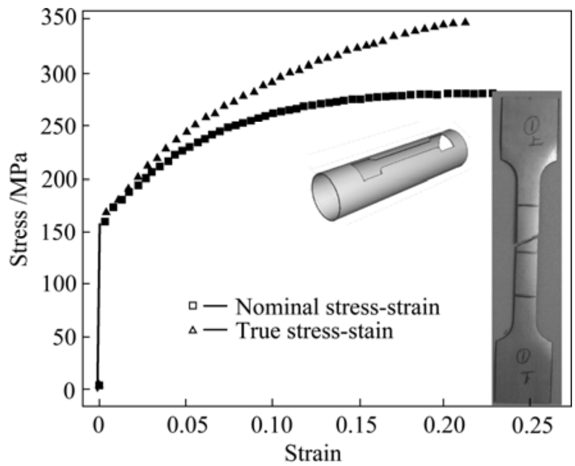

Fig. 2 Nominal and true stress-strain curves for 6061-T4 Al-alloy tube

Table 1 Mechanical properties of 6061-T4 tube

Material properties	Value
Elastic modulus E/GPa	55.4
Elongation δ/%	24.2
Yield strength $\sigma_{0.2}$/MPa	169
Tensile strength σ_b/MPa	283
Strength coefficient k/MPa	542.8
Hardening exponent n	0.28
Normal anisotropy coefficient r	0.660
Ratio of yield stress and elastic modulus	2.794

2.2 3D FE modeling and verification

Based on the nonlinear FE platform ABAQUS, an elastic−plastic 3D-FE model was established to simulate the whole process, viz., tube bending, ball retracting and unloading. A half model of tube bending was developed to reduce the computation cost.

The explicit algorithm was used for simulation of tube bending, while the standard one is employed for calculating the springback. The tube is meshed with four-node doubly curved thin shell S4R. In order to further reduce the computation cost, two different element sizes are applied, viz., 1.5 mm×1.5 mm in the deformation and clamping zones and 3 mm×3 mm in other zones of tube.

Comparison between the results of FE simulation and those of experiments is conducted to validate the reliability and accuracy of the springback prediction model. Figure 3 shows that the maximum difference between the experimental results and the simulation ones is about 12.5%, which indicates that the FE model in reliable.

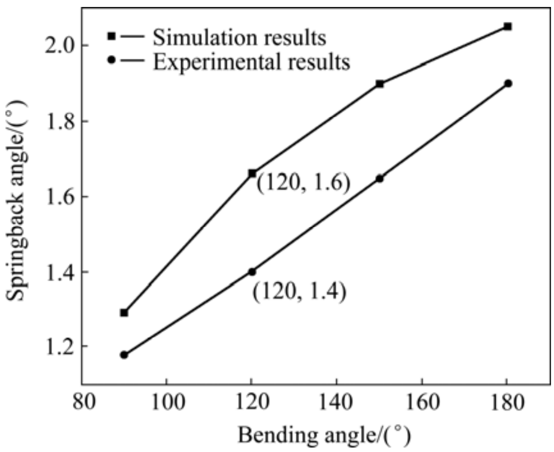

Fig. 3 Comparison between simulation results and experimental ones for springback

2.3 Research procedure

The single-factor analysis of physical experiments and virtual orthogonal test are used to identify the effects and significance of bending parameters on the springback angle of the 6061-T4 Al-alloy tube. The springback angle is represented as:

$$\Delta\theta = \theta - \theta' \tag{1}$$

where $\Delta\theta$ is the springback angle, θ the bending angle before springback, θ' the bending angle after springback.

Firstly, using the physical experiments with the bending conditions listed in Table 2, the effects of bending parameters are studied including the bending angle, the bending velocity, the mandrel extension length and the number of mandrel balls. Table 3 shows the level of bending parameters for the orthogonal test, and Table 4 shows the scheme and results of the orthogonal test.

3 Results and discussion

3.1 Experimental study

Figure 4 shows the effects of bending angle on the springback angle. It is confirmed that the springback angle increases linearly with the increasing of the bending angle [12] and the fitted straight line equation is represented as Eq (2). This is because that, with the larger bending angle, the more elastic deformation store

Table 2 Bending parameters

Condition	Bending angle, α/(°)	Bending velocity, v/((°)·s^{-1})	Mandrel extension length, e_m/mm	Number of mandrel balls, N
1	60 90 120 150 180	2	5	4
2	90	2 4 10	5	4
3	90	2	0 3 5 7	4
4	90	2	5	2 3 4

Table 3 Level of processing parameters

Test	Processing parameters	Level 1	Level 2	Level 3
A	Friction between tube and pressure die, μ_p	0.1	0.2	0.3
B	Friction between e tube and wiper die, μ_w	0.1	0.2	0.3
C	Friction between tube and bend die, μ_b	0.1	0.2	0.3
D	Friction between tube and mandrel, μ_m	0.05	0.1	0.15
E	Clearance between tube and pressure die, c_p/mm	0	0.15	0.3
F	Clearance between tube and mandrel, c_m/mm	0.2	0.4	0.6
G	Clearance between tube and wiper die, c_w/mm	0	0.15	0.3
H	Number of mandrel balls, N	2	3	4
I	Mandrel extension length, e_m/mm	6	8	10
J	The coefficient of boost velocity, (v_p/v)	0.9	1	1.1
K	Bending radius, R	101.6	127	152.4

Table 4 Virtual orthogonal test scheme and results

Test	A μ_p	B μ_w	C μ_b	D μ_m	E c_p	F c_m	G c_w	H N	I e_m	J v_p	K R	L	M	α/(°)
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1.45
2	1	1	1	1	2	2	2	2	2	2	2	2	2	3.85
3	1	1	1	1	3	3	3	3	3	3	3	3	3	3.90
4	1	2	2	2	1	1	1	2	2	2	3	3	3	1.96
5	1	2	2	2	2	2	2	3	3	3	1	1	1	3.26
6	1	2	2	2	3	3	3	1	1	1	2	2	2	3.10
7	1	3	3	3	1	1	1	3	3	3	2	2	2	1.10
8	1	3	3	3	2	2	2	1	1	1	3	3	3	3.48
9	1	3	3	3	3	3	3	2	2	2	1	1	1	2.81
10	2	1	2	3	1	2	3	1	2	3	1	2	3	3.06
11	2	1	2	3	2	3	1	2	3	1	2	3	1	2.82
12	2	1	2	3	3	1	2	3	1	2	3	1	2	3.23
13	2	2	3	1	1	2	3	2	3	1	3	1	2	3.81
14	2	2	3	1	2	3	1	3	1	2	1	2	3	2.99
15	2	2	3	1	3	1	2	1	2	3	2	3	1	3.54
16	2	3	1	2	1	2	3	3	1	2	2	3	1	3.48
17	2	3	1	2	2	3	1	1	2	3	3	1	2	4.00
18	2	3	1	2	3	1	2	2	3	1	1	2	3	2.74
19	3	1	3	2	1	3	2	1	3	2	1	3	2	3.13
20	3	1	3	2	2	1	3	2	1	3	2	1	3	3.67
21	3	1	3	2	3	2	1	3	2	1	3	2	1	3.43
22	3	2	1	3	1	3	2	2	1	3	3	2	1	4.21
23	3	2	1	3	2	1	3	3	2	1	1	3	2	2.15
24	3	2	1	3	3	2	1	1	3	2	2	1	3	3.68
25	3	3	2	1	1	3	2	3	2	1	2	1	3	2.85
26	3	3	2	1	2	1	3	1	3	2	3	2	1	4.12
27	3	3	2	1	3	2	1	2	1	3	1	3	2	3.29

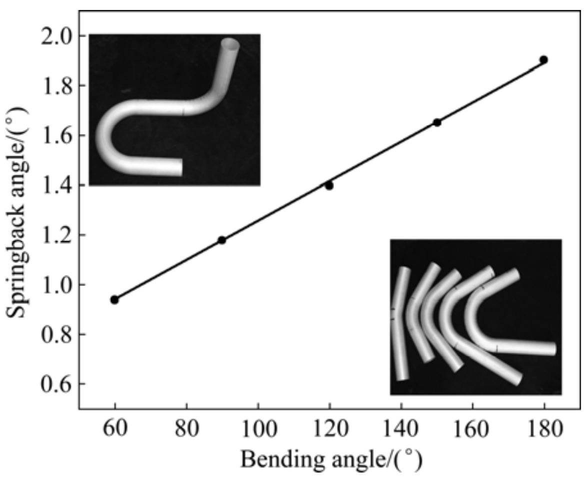

Fig. 4 Effects of bending angle on springback angle

is accumulated, which results in linear springback angle.

$$\Delta\theta = 0.00791\theta + 0.4664 \qquad (2)$$

where $\Delta\theta$ is the springback angle, and θ the bending angle.

Figure 5 shows the effects of bending velocity on the springback angle. It is found that the springback angle keeps constant when the bending velocity is slow, while when the bending velocity is larger than 4 (°)/s, the springback angle increases rapidly. This is because that the yield strength increases with increasing of bending velocity, which induces more elastic deformation and thus larger springback angle.

Figure 6(a) shows the effects of the mandrel extension length on the springback angle. It is found that

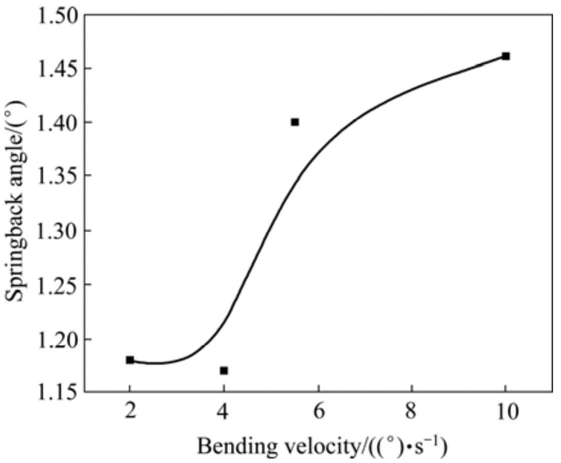

Fig. 5 Effects of bending velocity on springback angle

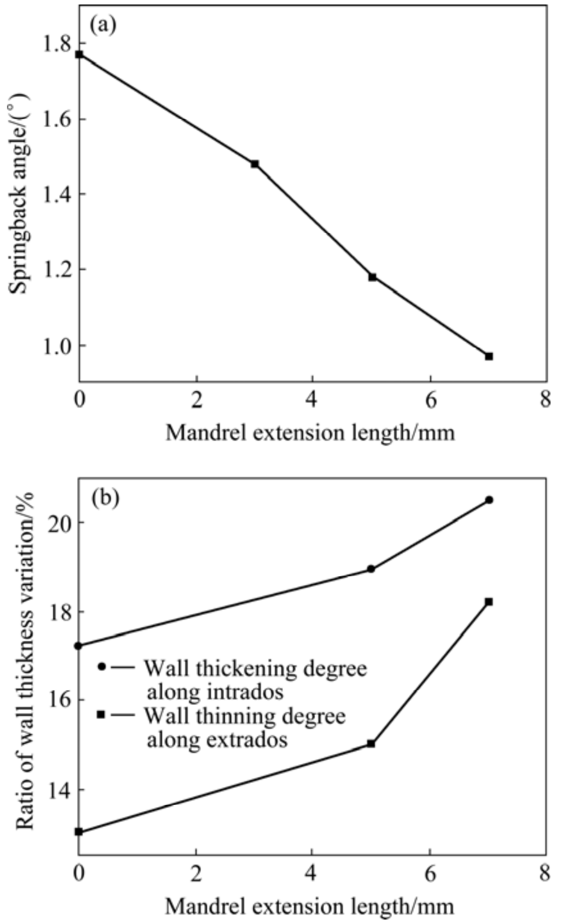

Fig. 6 Effects of mandrel extension length on ratio of wall thickness variation and springback angle: (a) Ratio of wall thickness variation; (b) Springback angle

the total springback angle decreases about 0.8° when the mandrel extension length increases from 0 mm to 7 mm. This is because that both the wall thinning degree along the extrados and the wall thickening degree along the intrados increase with the increasing of the mandrel extension length, as shown in Fig. 6(b), which means more plastic and less elastic deformation occur in tube bending.

Figure 7 shows the effects of the number of mandrel balls on the springback angle. It is found that the springback angle decreases only 0.1° when the number of mandrel balls increases from 2 to 4, which means that the number of mandrel balls has little effect on the springback angle. This is because the number of mandrel balls has little effect on the deformation degree, though it has obvious effect on cross-section deformation of tube.

3.2 Results of orthogonal test

The method of direct analysis and variance analysis is taken to study the significance of the bending parameters on the springback. Table 4 shows the results of the orthogonal test, by which the direct analysis is made, as shown in Table 5 and Fig. 8. Table 5 shows the range value of the springback angle, and it is observed that the significance of bending parameters on the springback angle decreases in the order as c_m, R, μ_p, c_w, c_p, v_p, μ_m, N, μ_b, e_m and μ_w. Figure 8 shows that the effects of bending parameters on the springback angle, and it is found that:

1) R, c_m, μ_p, c_w and c_p are the most significant factors for springback in 6061-T4 thin-walled Al-alloy tube bending. The springback angle increases with the increasing of these bending parameters, which is in line with the analysis results of the 5052O thin-walled Al-alloy and the thick-walled medium strength TA18 tube [12−14]. This is because that the larger R, c_m, μ_p, c_w and c_p facilitate the tube bending deformation, viz. decreasing the plastic deformation and increasing the elastic deformation.

2) μ_m, N and v_p also have effects on the springback angle. The springback angle decreases with increasing of μ_m and N, which is consistent with the results of thick-walled medium strength TA18 tube [14]. This is because that the plastic deformation increases with the increasing of μ_m and N. While, the springback angle increases with increasing of v_p. This is because that the

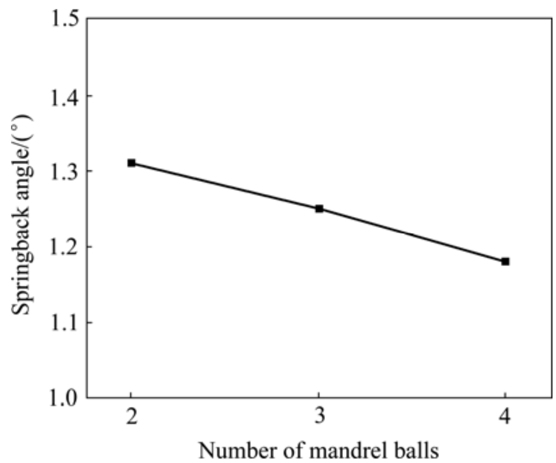

Fig. 7 Effects of number of balls on springback angle

Table 5 Range value of springback angle

Factor	$R_{\Delta\theta}$
μ_p	0.623
μ_w	0.092
μ_b	0.197
μ_m	0.362
c_p	0.59
c_m	0.821
c_w	0.62
N	0.353
e_m	0.14
v_p	0.467
R	0.806

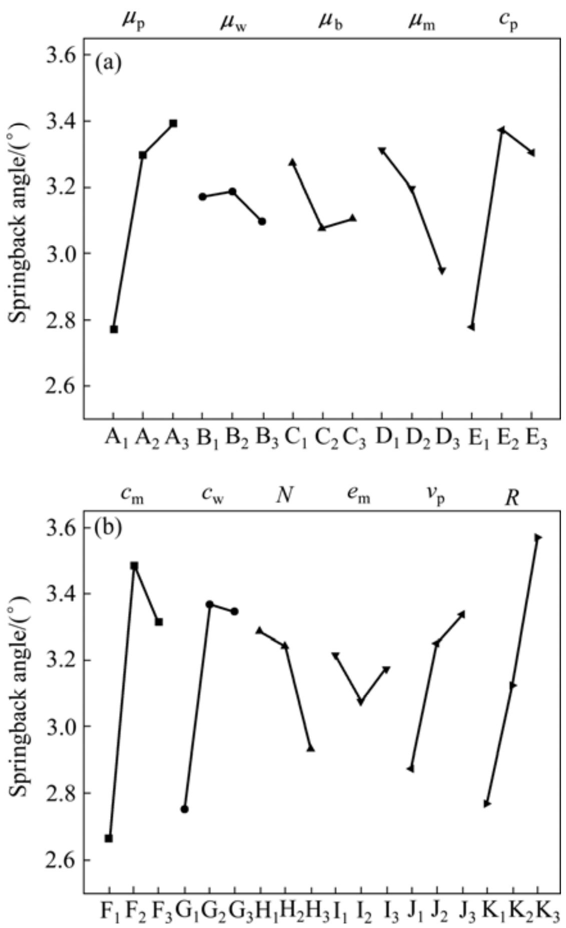

Fig. 8 Effects of bending parameters on springback angle

larger v_p improves the tube bending, which increases the elastic deformation and decreases the plastic deformation.

3) μ_w, μ_b and e_m have little effect on the springback angle.

Table 6 shows the results of the variance analysis, where "*" means $F>F_{0.1}$ (2,4), "**" means $F>F_{0.05}$ (2,4) and "***" means $F>F_{0.01}$ (2,4) [19].

As listed in Table 6, R, c_m, μ_p, c_w and c_p are the most significant factors for the springback angle in tube bending and μ_w, μ_b and e_m have little effect on the springback angle, which is consistent with the results of the above direct analysis.

Table 6 Variance analysis for springback

Bending parameters	Sum of squares	Mean square variance	F-value	Significance
μ_p	2.022	1.011	21.70	***
μ_w	0.043	0.022	0.46	Not significant
μ_b	0.204	0.102	2.19	Not significant
μ_m	0.616	0.308	6.60	*
c_p	1.879	0.939	20.16	***
c_m	3.381	1.690	36.27	***
c_w	2.227	1.113	23.89	***
N	0.666	0.333	7.14	**
e_m	0.094	0.047	1.01	Not significant
v_p	1.111	0.555	11.91	**
R	2.935	1.467	31.49	***
Error	0.816	0.047		
Sum	15.363			
$F_{0.01}(2,4)=18.0$		$F_{0.05}(2,4)=6.94$		$F_{0.1}(2,4)=4.32$

4 Conclusions

1) The springback angle increases linearly with increasing of the bending angle. Thus, the proper compensation angle is needed in tube bending when the bending angle is too large and the compensation angle is estimated as the following equation.

2) The significant factors from high to low are the clearance between tube and mandrel, the bending radius, the friction between tube and pressure die, the clearance between tube and wiper die, the clearance between tube and pressure die, the coefficient of boost velocity, the friction between tube and mandrel, the number of mandrel balls.

3) The effect rules of significant parameters on springback of 6061-T4 Al-alloy tube are similar to those of stainless steel and Ti-alloy tubes. Springback becomes larger with increasing of the bending velocity, the tube-die clearance, the relative bending radius, the tube-pressure die friction and relative push assistant speed. While the springback decreases with increasing of the mandrel extension length, the number of balls and tube-mandrel friction.

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6061-T4 薄壁铝合金管数控弯曲回弹规律

李　恒，师开鹏，杨　合，田玉丽

西北工业大学 材料学院 凝固技术国家重点实验室，西安 710072

摘　要：以规格为 50.8 mm×0.889 mm(管材外径×管材壁厚)的高性能薄壁 6061-T4 铝合金管为对象，采用单因素实验分析和基于全过程三维有限元模拟的正交方法，获得多个弯曲成形参数对 6061-T4 薄壁铝合金管数控弯管回弹的影响。结果表明：1)弯管回弹角随弯曲角度的增大而总体呈线性增大；2)影响弯管回弹的显著性因素从高到低排列为：芯棒−管材间隙，弯曲半径，压模−管材摩擦，防皱块−管材间隙，压模−管材间隙，助推速度，芯模−管材摩擦和芯球个数；3)显著性成形参数对回弹的影响规律与不锈钢和钛合金相似：回弹角随弯曲速度、芯棒−管材间隙、相对弯曲半径、防皱模−管材间隙、压力模摩擦系数、压力模相对助推速度的增大而增大，随芯棒伸出量、芯球个数和芯棒摩擦系数的增大而减小。

关键词：回弹；铝合金管；弯管；绕弯；有限元；正交分析

(Edited by DENG Lü-xiang)