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Analysis of Factors Affecting Springback Angle in Bending of ASTM A-210 Gr. A1 Seamless Carbon Steel Tube

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Abstract

Rotary Draw Bending (RDB) is a common process in the tube bending industry but the problem of springback often occurs. When the clamp die part is released after the bending process, the bent tube will spring back as a result of the material deforming. Several studies have attempted to determine the factors of springback but there is no convincing empirical evidence to establish a relationship between the input and output factors of the tube bending process variables in springback problem. In this research, the factors affecting the springback angle by the Taguchi method in bending seamless tubes ASTM A-210 Gr. A1, outside diameter 44.45 mm, were established. The Taguchi method is used for medium carbon seamless tubes for steam boilers. The four factors that were considered included wall thickness, bending radius, dwell time and bending angle. The results showed that all factors have a significant influence on the springback angle in the tube bending process, and each factor affects the springback angle differently. The factors that affect the springback angle the most are Bending Radius with an impact of 43.01%, Bending Angle 25.16%, Wall Thickness 16.05%, and Dwell Time 15.78%. As well, the time-dependent springback principle has a significant effect on the springback response in tube bending.

Keywords: Springback Optimization, CNC Tube Bending, Taguchi Method, ASTM A-210 Gr. A1, Seamless Steel Tube

1. INTRODUCTION

NC Mandrel-Less Rotary Draw Bending (RDB) is the most commonly used metal tube bending machine today. When the clamping parts in the RDB are removed, the shape of the tube will be restored and springback inevitably occurs. The actual geometry of the tube bending will deviate from the design requirements. This directly affects the forming accuracy and the quality of the metal tube. Therefore, accurate springback prediction is the key to springback compensation and control. Springback factor analysis, mechanism and law of springback and predicting springback have been extensively researched (Zhou et al., 2021). The process involves factor inputs and the responses between these inputs are complex. However, there has been no convincing empirical proof for establishing the relationship between the input and output factor variables in the tube bending process relevant to springback (Podder et al., 2020).

Several studies have investigated springback from bending tubes. Mentella et al. (2008) developed a new method for a feasibility study and the determination of the loading curves in the RDB process by controlling some of the main tooling parts, namely boosters and pressure dies. The main factors that were considered were thickness, outer diameter, bending radius and bending angle. Jiang et al. (2010) studied the coupling effects on the springback angle of the material properties and the bending angle during numerically controlled bending of a titanium alloy tube TA18. Yang et al. (2010) studied the role of friction in the bending behaviors of thin-walled tube in RDB with a small bending radius. Ho-Seung Jeong et al. (2012) conducted a predictive study of the springback angle during the bending process of Inconel 625. By applying Elastic Theory to predict the bending moment and springback of the tube, Mei Zhan et al. (2016) created an analytical model for tube bending springback that considered different parameter variations of titanium alloy tubes. Borchmann et al. (2020) studied the influence of the stiffness of the machine axes on the formation of wrinkles during RDB by finite element method (FEM) simulations that considered the stiffness of each machine axis. Huifang Zhou et al. (2021) studied springback angle prediction of circular metal tube considering the interference of cross-sectional distortion in mandrel-less rotary draw bending by distinguishing the variables affecting springback.

2. PROBLEM DESCRIPTION

Several studies have attempted to study the factors that influence the occurrence of springback and the input variables influencing springback are still important for future research. One factor related to springback is the time dependence which has been the subject of various studies. Daxin and Liu (2010) studied springback and time-dependent springback of 1Cr18Ni9Ti stainless steel tubes under bending. Jun Ma et al. (2020) studied the influence of natural deterioration Pre/Post-Aging of springback in bending Al-Mg-Si alloy tubes using the time-dependent principle to study the springback angle. However, these studies relied on the time condition before and after forming only but did not consider the time factor during the manufacturing process as shown in Figure 1. This alloy can improve its mechanical properties when it is heat treated and in the aging process.

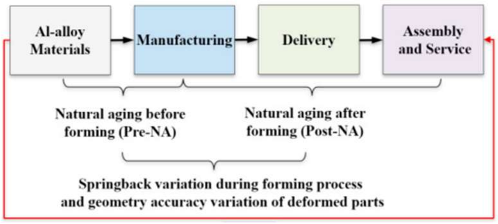


Figure 1 The influence of natural deterioration Pre/Post-Aging of springback. (Ma et al., 2020)

The time-dependent springback phenomenon has been experimentally observed in aluminium (Wang et al., 2004), stainless steel tubing (Daxin and Yafei Liu., 2010), high-strength steel (Lim et al., 2012), pure titanium sheets (Hama. et al., 2017), and Al-alloy (Ma et al., 2020). The mechanisms underlying the time-dependent springback are stress relaxation and creep behavior driven by the residual stress in the deformed materials (Ma et al., 2020).

The objective of the current study was therefore to fill the research gaps remaining from previous tube bending springback studies by studying other important factors, including the time-dependent factor, in the manufacturing process and the use carbon steel material. The predictions relevant to seamless steel tube bending for steam boiler applications are included in this comprehensive study.

3. EXPERIMENTAL DESIGN

In this study, metal tube bending experiments were conducted with the design of the experiments following the Taguchi method. The various factors affecting the springback angle were identified.

Table 1 Chemical composition and mechanical properties of ASTM A-210 Gr. A1

Chemical Composition					
C	Mn	P	S	Si	
0.27%	0.93%	0.035%	0.035%	0.10%	
Mechanical Properties					
Tensile Strength		Yield Strength		Hardness	
415 MPa		255 MPa		79 HRB	

3.1 Overview of the experimental method

The experimental equipment and tools included the Herber 76 CNC TB Bending Machine without the use of a mandrel is illustrated in Figure 2. This was necessary given the outer diameter-to-thickness ratio in the range of 7-10 mm (OD/t≤20) (Ma et al., 2020). The material used was medium carbon seamless steel tube ASTM A-210 Gr. A1. OD = 44.45 mm medium carbon steel tube. The chemical composition and mechanical properties of these materials are shown in Table 1.

3.2 Design of experiment

Experimental design and analysis by the popular Taguchi Method. The method that was adopted in the current research followed an orthogonal array type L27 (3^4), 27 bending operations were included in the process. The input factors were wall thickness, bending radial, dwell time and bending angle. The response factor was the springback angle. The level of these factors uses 3 level in the tube bending process is illustrated in Table 2.

Table 2 Description of the influence factors.

Input Factors	Level		
	Low	Medium	High
[A] Wall thickness (mm)	4.57	5.59	6.10
[B] Bending radius (mm)	76.2	114.3	152.4
[C] Dwell time (s)	0	3	6
[D] Bending angle	60°	90°	120°

In the calculation of the signal-to-noise ratio for the springback angle, where the springback angle is small, the impact of the input factors is small. Therefore, in this case, smaller is better, and the calculation is as follows:

$$S/N_s = -10\log\left\{\frac{\sum y_i^2}{n}\right\} \qquad (1)$$

where S/N_s is the signal-to-noise ratio characteristic value where smaller is better, y_i is the sum of observations at level i, and n is the number of observations.

Figure 2 Herber 76 CNC TB Bending Machine.

3.3 Measurements Method

The springback angle of metal tube workpieces were checked with a Mitutoyo CMM model Beyond Apex 707. The angle Δθ is calculated as follows (Ma et al., 2020).

$$\Delta\theta = \theta_b - \theta_a \tag{2}$$

where $\Delta\theta$ is the springback angle, θ_b is the targeted bending angle and θ_a is the actual angle.

4. RESULTS AND DISCUSSION

The Taguchi method was followed in the design of these experiments.

4.1 Results of the Taguchi experiment L27 (3^4)

The results of the experiments on the orthogonal array L27 (3^4), performed according to the experimental plan, are shown in Tables 3 and 4. The springback angle Δθ was calculated using Equation (2) and the Signal-to-Noise Ratios in the case of Small-the-Better is shown in Table 3 and the average S/N Ratio of the level of the various factors affecting the springback angle are shown in Table 4.

Table 3 The average S/N Ratio of springback angle factor

Level	Input Factors			
	A	B	C	D
1	-18.01	-18.46	-17.28	-17.09
2	-17.39	-17.54	-17.63	-18.06
3	-17.40	-16.80	-17.89	-17.66
Delta	0.62	1.66	0.61	0.97
Percent	16.05	43.01	15.78	25.16
Rank	3	1	4	2

Table 4 The L27 test matrix and measured springback angles

Bending	Input Factors				Responds factor	
	A	B	C	D	$\Delta\theta$ (degree)	$\Delta\theta$ (Signal-to-Noise Ratios)
1	4.57	76.2	0	60	7.93	-17.99
2	4.57	76.2	0	60	8.02	-18.08
3	4.57	76.2	0	60	7.97	-18.03
4	4.57	114.3	3	90	8.27	-18.35
5	4.57	114.3	3	90	8.39	-18.48
6	4.57	114.3	3	90	8.41	-18.50
7	4.57	152.4	6	120	7.58	-17.59
8	4.57	152.4	6	120	7.45	-17.44
9	4.57	152.4	6	120	7.61	-17.63
10	5.59	76.2	3	120	8.19	-18.27
11	5.59	76.2	3	120	8.33	-18.41
12	5.59	76.2	3	120	8.26	-18.34
13	5.59	114.3	6	60	7.15	-17.09
14	5.59	114.3	6	60	7.19	-17.13
15	5.59	114.3	6	60	7.16	-17.10
16	5.59	152.4	0	90	6.85	-16.71
17	5.59	152.4	0	90	6.91	-16.79
18	5.59	152.4	0	90	6.82	-16.68
19	6.10	76.2	6	90	8.92	-19.01
20	6.10	76.2	6	90	8.87	-18.96
21	6.10	76.2	6	90	8.95	-19.04
22	6.10	114.3	0	120	7.14	-17.07
23	6.10	114.3	0	120	7.08	-17.00
24	6.10	114.3	0	120	7.21	-17.16
25	6.10	152.4	3	60	6.49	-16.24
26	6.10	152.4	3	60	6.39	-16.11
27	6.10	152.4	3	60	6.31	-16.00

Considering the average S/N Ratio of the level and various factors affecting the springback angle, as shown in Table 3, it can be concluded that the bending radial factor (B) affects the springback angle the most. This factor had an impact as high as 43.01%. The bending angle (D) contributed 25.16% to the springback angle, the tube wall thickness (A) 16.05% and the least impact factor was dwell time (C) at 15.78%. Also, it was noticed that the tube wall thickness factor and the stopping time factor were similar percentages with only a 0.27% difference.

Figure 3 shows the residual plots for the springback angle that were examined and were found to be normally distributed with a linear distribution plot and a normal histogram. It can also be concluded that the fitted values are normally distributed. When verifying the independence of the data it was found that the distribution of fitted values has an independent distribution pattern. The pattern cannot be predicted with certainty which shows that the error values are independent of each other.

The mean value of the main effects plot for S/N ratios shown in Figure 4, showed that the lowest tube wall thickness factor was 4.57 mm., the mean of S/N ratios was -18.01, but when the tube wall thickness was increased to 5.59 mm, the mean of S/N ratios was -

17.39, where the original value was +0.62, and the springback angle increased. The minimum bending radius factor was 76.2 mm, and the mean of S/N ratios was -18.46. When the bending radius was increased to 114.3 mm, the mean of S/N ratios was -17.54, an increase of +0.92, and when the bending radius was increased to 152.4 mm, the mean of S/N ratios was -16.80, a further increase from the lowest factor of +1.66. Also, when the lowest Dwell time factor was 0 seconds, the mean of S/N ratios was -17.28 and when the dwell time was increased to 3 seconds, the mean of S/N ratios was -17.63, a decrease of -0.35. Increasing the dwell time to 6 sec, the mean of S/N ratios was -17.89, down from the lowest factor of -0.61.

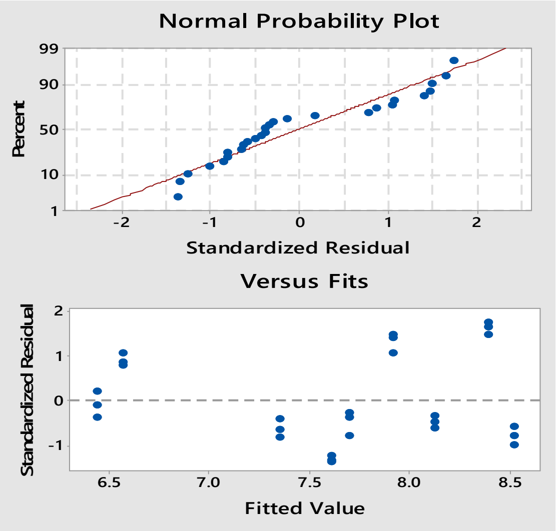
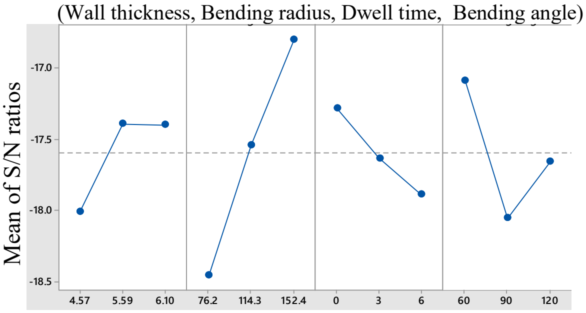


Figure 3 Residual plots for the springback angle.



Signal-to-noise: Smaller is better

Figure 4 Mean of main effects plot for S/N ratios

Considering the fourth factor, the minimum bending angle factor of 60 degrees had a mean of the S/N ratios of -17.09. When the bending angle was increased to 90 degrees, the mean of the S/N ratios was -18.06, a decrease of -0.97. Then, when the bending angle was increased to 120 degrees, the mean of S/N ratios was -17.66, down from the minimum factor of -0.57.

The results of the analysis of each factor affecting the springback angle to the lowest value at $A_1B_1C_3D_2$ are tube wall thickness factor at 4.57 mm, bending radius factor at 76.2 mm, stopping time factor at 6 sec and bending angle factor degree at 90 degrees.

Table 5 ANOVA of the springback angle

Source	df	SSA	MSA	F-Value	P-Value
A	1	1.2630	1.2630	9.91	0.005
B	1	9.4323	9.4323	74.02	0.000
C	1	1.3613	1.3613	10.68	0.004
D	1	0.9988	0.9988	7.84	0.010
Error	22	2.8034	0.1274		
Total	26	15.8587			

S = 0.356966, R-sq. = 82.32%, R-sq. (adj) = 79.11%

The analysis of variance (ANOVA) in Table 5, at the significance level of 0.05, showed that the main factors were tube wall thickness, bending radius, dwell time and bending angle, at $p < 0.05$. It was shown that these four main factors significantly influenced the springback angle in the tube bending process. In addition, the reliability of the data is $R^2 = 82.32\%$, R^2 (adj) = 79.11%, so $R^2 > 80\%$. Therefore, the values obtained are reliable. for use in further research. The regression equation can be created as follows:

$$y_{\Delta\theta} = 10.657 - 0.34x_1 - 0.019x_2 + 0.0917x_3 + 0.00785x_4 \tag{3}$$

where yΔθ is the response of the springback angle, x_1 is the tube wall thickness, x_2 is the bending radius, x_3 is the dwell time, x_4 is the bending angle.

4.2 Discussion

1. Experimental design and analysis by Taguchi Method is a popular method, and can determine the relationship of variables influencing the springback angle of ASTM A-210 Seamless Cold Drawn Medium-Carbon Steel Tubes Grade ASTM A-210. Gr. A1. If used in mass production, factory plant, production engineering or other engineering processes, the Taguchi Method will increase the efficiency of the work.
2. The main effect of all 4 factors, namely Wall Thickness, Bending Radius, Dwell Time, and Bending Angle, influence the value of the springback angle in significant tube bending process at 0.05. These findings will be useful in future research of factors such as the stress on the material, tube diameter, material type, and bending speed.
3. The factors that affect the springback angle the most are Bending Radius with an impact of 43.01%, Bending Angle impact 25.16%, Wall Thickness 16.05%, and Dwell Time 15.78%. It was also observed that the tube Wall Thickness factor and the Dwell Time factor were similar percentages, with only a 0.27% difference. If other factors are studied, as discussed in Item 1, the relationship between each factor may have different significance.
4. For the influence of the low effect of springback factor level when considering all 4 main factors, it can

be concluded that the wall thickness of the tube must be low. The bending radius must be low. Dwell time takes a lot of time. and the bending angle must be high.

5. Time-dependent in addition to considering before and after the manufacturing process, when considering in the manufacturing process, especially the forming process, for example, controlling the time during the material forming process can also help with the springback angle. In the future, if the time-dependent factors are further studied, all three processes of pre-forming, forming and post-forming should be included in the study. The details of the behavior of the material can then be more validly obtained.

5. CONCLUSION

In this research, the factors affecting the springback angle by the Taguchi method in bending seamless tubes ASTM A-210 Gr. A1, outside diameter 44.45 mm, were established. The experimental equipment and tools included the Herber 76 CNC TB Bending Machine without the use of a mandrel. This was necessary given the outer diameter-to-thickness ratio in the range of 7-10 mm (OD/t≤20). The Taguchi method is used for medium carbon seamless tubes for steam boilers. The four factors that were considered included wall thickness, bending radius, dwell time, and bending angle. The results showed that all factors have a significant influence on the springback angle in the tube bending process, and each factor affects the springback angle differently. The factors that affect the springback angle the most are Bending Radius with an impact of 43.01%, Bending Angle impact of 25.16%, Wall Thickness 16.05%, and Dwell Time 15.78% percent. As well, the time-dependent springback principle proved to exert a significant effect on the springback response in tube bending.

The results of this research can be used for further, such as springback angle prediction from regression equations to compare with other methods such as machine learning, another input factor affecting the springback angle value, another response factor related to tube bending such as ovality, has deserve further study.

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