OPTIMIZING THE TECHNOLOGICAL PARAMETERS FOR SHEAR SPINNING OF A CONICAL COMPONENT ON A CNC LATHE

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ABSTRACT

An experiment involving the shear spinning process of a conical component fabricated from copper sheet C1100 on a CNC lathe has been investigated. Employing the Box-Behnken response surface planning method, the extent of wall thickness deviation and the mechanical characteristics of the resulting product have been systematically assessed. Specific technological parameters including mandrel revolution (rev/min), roller feed (mm/rev), and roller nose radius (mm) have been involved in this assessment. The obtained results revealed the influence of these technological parameters on both the degree of wall thickness deviation and the mechanical properties of the product. Consequently, this analysis facilitates the identification of an optimal operational mode aimed at minimizing wall thickness deviation and maximizing the mechanical properties of the produced component.

Keywords: *Shear spinning; response surface planning; optimizing; conical component; mechanical characteristics.*

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1. INTRODUCTION

In various industrial sectors, the utilization of axisymmetric components, crafted through the spinning technique employing sheet blanks composed of the C1100 alloy, is prevalent. This method is characterized by the localized plastic deformation within the metal during the manufacturing process [1, 2]. By orchestrating the rotational movement of the workpiece and guiding the rollers along meticulously predefined trajectories, the desired product takes shape [1, 3-5]. Notably, the shear spinning process necessitates only a modest application of force to the roller for the successful deformation of the workpiece. In the context of fabricating small-dimensioned conical components, as exemplified in Fig. 1, the employment of a CNC lathe is recommended [6, 7]. It is within this framework that the distinction between conventional spinning and shear spinning processes becomes discernible: conventional metal spinning primarily increases the depth of the workpiece while maintaining its material thickness at a constant level. Conversely, in shear spinning, the material thickness of the workpiece steadily decreases while the diameter flange remains uniform. Additionally, this process leads to a concurrent increase in the depth of the workpiece. The component depicted in Fig. 1 has a conical wall thickness that is less than the flange thickness, and it can be formed using the shear spinning method.

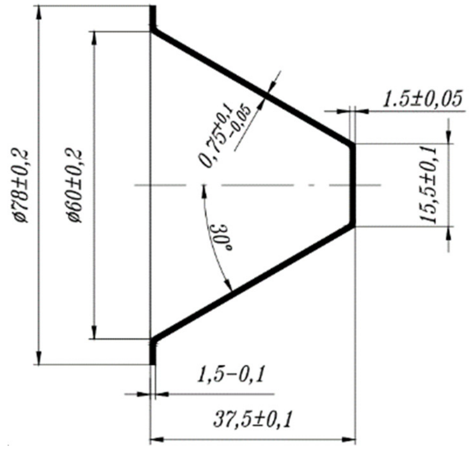


Fig. 1. Model of a conical component

To produce such a component, the traditional stamping method with multiple operations (including cutting a circle, drawing 1, drawing 2, and so on, followed by punching a flange) can be employed. However, a single shear spinning operation on a CNC lathe is sufficient to form this component. When utilizing shear spinning for the fabrication of a conical component, the wall thickness follows the sine law [1]:

$$S_1 = S_0 \sin\alpha \tag{1}$$

where, S_0 and S_1 - respectively, the thickness of the workpiece and the conical wall thickness of the semi-finished product; α - the angle of inclination of the generatrix of the cone of the semi-finished product (Fig. 2).

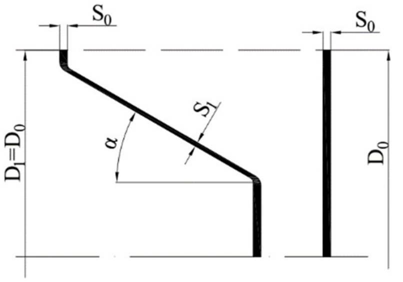


Fig. 2. Blank and semi-finished product of the spinning process

Due to the thinning of the semi-finished product's wall during shear spinning, both the mechanical properties and the deviation in wall thickness undergo alterations. Theoretical investigations do not provide the means to predict and optimize the formation of the mechanical properties of the resulting component, contingent upon the technological parameters of the process in question. In shear spinning the gap between the roller and the mandrel along the entire stroke of the driving tool is determined by the expression $Z = S_1 = S_0\sin\alpha$. In situation $Z < S_0\sin\alpha$ the walls of the semi-finished product will experience excessive thinning, leading to the occurrence of compressive stresses in the flange. These stresses can result in the bending of the flange. On the contrary, in the case of $Z > S_0\sin\alpha$ the wall of the semi-finished product exhibits insufficient thinning [1, 3]. In this case, wrinkles can form on the flange, causing it to bend. However, if a tool gap of $Z = (1.3 \div 1.5).\ S_0\sin\alpha$ is chosen for the first shear spinning process, high-quality components can be obtained [3].

Matthias Kleiner et al. [8] employed a mixed-level design of experiments, which included three factors with two levels (roller nose radius, roller feed, mandrel revolution) and two factors with three levels (distance of gap, inclination of tool path) to evaluate the quality of the inner and outer surfaces, as well as the amplitude of wrinkling in the conical component obtained after the shear spinning process using sheet aluminum AA-1050A.

Kim Jae Hun et al. [9] developed a mathematical model to compute the tangential force, feeding force, and normal force, considering parameters such as roller feed, cone angle of the mandrel, material thickness, roller diameter, and roller nose radius. This model is based on the assumption of a uniform distribution of roller pressure on the contact surface. A comparison between the calculated forces and the experimental results revealed that the proposed model reasonably agrees with the experimental findings.

Chen et al. [10, 11] conducted research using an experimental design to create second-order regression models for the tangential force, feeding force, normal force, and roughness of the inner and outer surfaces. These models were established, considering four input parameters, including blank thickness, roller nose radius, mandrel revolution, and roller feed. The regression models were developed to assess the impact of these input parameters on the shear spinning process of the hexagonal aluminum 1100-O sheet, specifically on processing forces and the quality of the inner and outer surfaces of the conical component.

Certainly, in the design of the shear spinning process, the selection of technological parameters, including Mandrel revolution, roller feed, roller nose radius, tool clearance, and others, significantly influences product quality aspects such as the relative deviation of wall thickness, mechanical properties, and the quality of the inner and outer surfaces. This presents the challenge of optimizing the input factors to achieve the highest possible product quality. As a result, an optimization study was conducted for the shear spinning process of a conical component on a CNC lathe with the objective of minimizing the relative deviation of wall thickness while maximizing tensile strength and relative elongation.

2. EXPERIMENTAL DETAILS

2.1. Material and Methodology

The investigation utilized a copper alloy of grade C1100, adhering to the specifications outlined in JIS H 3100-2006, with an initial thickness of 1.5mm [12]. Tensile test specimens were prepared in accordance with the guidelines outlined in standard TCVN-197-1:2014 [13]. Subsequently, a tensile test was conducted utilizing the MTS Landmark 810 machine. The outcomes related to the mechanical properties, as well as the engineering stress-strain curve, have been represented in Fig. 3.

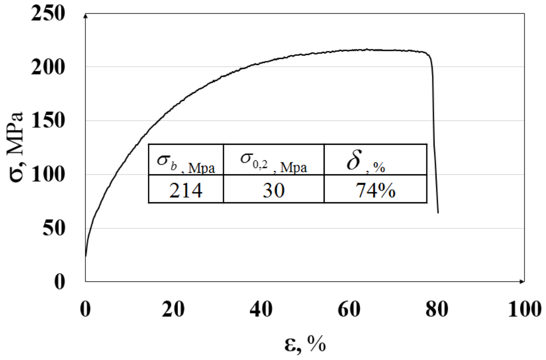


Fig. 3. Tensile test chart and mechanical properties of the copper sample C1100

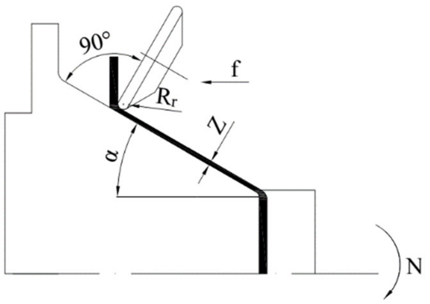


Fig. 4. Scheme of the process of spinning of a conical component

Fig. 4 shows a scheme of the shear spinning process of a conical component on a CNC lathe. The main technological parameters include the mandrel revolution (N, rpm), the roller feed (f, mm/rev), the roller nose radius (R, mm), the selected gap between the roller and the mandrel $Z = 1.4S_0\sin\alpha = 1.1$mm.

To receive the best product within the allowable limits of the input parameters, the response surface methodology (RSM) can be used for research. RSM, also known as Box-Wilson methodology is an optimization method applying statistical techniques based upon the factorial designs of central composite design (CCD) and Box-Behnken Design (BBD). To fit a second-order regression model (quadratic model), the BBD only needs three levels for each factor, rather than five levels in CCD. The BBD set a mid-level between the original low- and high-level of the factors, avoiding the extreme axial (star) points as in the CCD. Moreover, the BBD uses face points, often more practical, rather than the corner points in CCD. The addition of the mid-level point allows the efficient estimation of the coefficients of a second-order model [6, 7]. The BBD is almost as rotatable as the CCD. Moreover, often, the BBD requires a smaller number of experimental runs. Therefore, in this study, the Box-Behnken experimental design is used with three levels of variation of the factors. The interval of variation and the level of factors are shown in Table 1.

Table 1. Factors and the interval of their variation

Factors	Coded variations	Level		
		Lower	Basis	Upper
		-1	0	+1
N, rpm	x_1	800	1000	1200
f, mm/rev	x_2	0,0125	0,0250	0,0375
R, мм	x_3	2	4	6

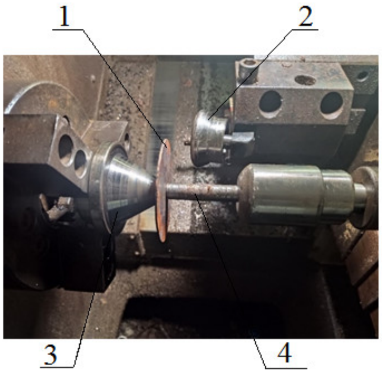
The planning matrix of the Box-Behnken design with 3-level for three factors includes 17 experiments shown in Table 2.

Table 2. The planning matrix of the Box-Behnken

Experience No.	x_1	x_2	x_3	N, rpm	f, mm/rev	R, mm
1	-	-	0	800	0.0125	4
2	+	-	0	1200	0.0125	4
3	-	+	0	800	0.0375	4
4	+	+	0	1200	0.0375	4
5	-	0	-	800	0.0250	2
6	+	0	-	1200	0.0250	2
7	-	0	+	800	0.0250	6
8	+	0	+	1200	0.0250	6
9	0	-	-	1000	0.0125	2
10	0	+	-	1000	0.0375	2
11	0	-	+	1000	0.0125	6
12	0	+	+	1000	0.0375	6
13	0	0	0	1000	0.0250	4
14	0	0	0	1000	0.0250	4
15	0	0	0	1000	0.0250	4
16	0	0	0	1000	0.0250	4
17	0	0	0	1000	0.0250	4

2.2. Experiment

The experiment was carried out on a CNC lathe of the AKEBONO brand from copper blank C1100, diameter 80mm, thickness 1.5mm in the annealed state. The scheme of the experiment of shear spinning experiments on a CNC lathe AKEBONO is shown in Fig. 5.



1 - Blank; 2 - Roller; 3 - Mandrel; 4 - Tailstock

Fig. 5. Scheme of the experiment of spinning on a CNC lathe AKEBONO

The quality of this component is evaluated by the relative deviation of the wall thickness (ΔS, %) and the mechanical properties of the component wall (tensile strength σ_{ult} and relative elongation δ):

$$\Delta S = 100\cdot(S_{max} - S_{min})/S_{max} \qquad (2)$$

Where S_{max} and S_{min} - maximum and minimum wall thickness of the component.

Tensile test specimens are cut along the generatrix of the components. The tensile test is carried out on the MTS Landmark 810 machine shown in Fig. 6.

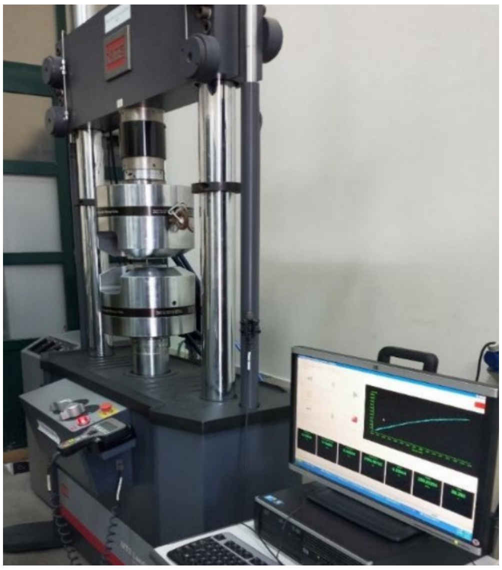


Fig. 6. MTS Landmark 810 Tensile Testing Machine

The data obtained from Formula (2) and the tensile tests were processed and analyzed using Minitab software.

3. RESULTS AND DISCUSSION

The obtained results *for* shear spinning experiments and tensile test are shown in Table 3.

Table 3. Results by Experiment Design Matrix

Experience No.	x_1	x_2	x_3	ΔS, %	σ_{ult}, MPa	δ, %
1	-	-	0	12.08	340.8	7.3
2	+	-	0	4.34	338.9	7.7
3	-	+	0	10.75	379.6	8.2
4	+	+	0	9.48	375.8	9.1
5	-	0	-	2.54	361.9	6.4
6	+	0	-	3.55	380.1	7.0
7	-	0	+	18.78	370.8	8.5
8	+	0	+	8.85	344.7	9.3
9	0	-	-	3.74	353.8	6.7
10	0	+	-	7.23	426.4	6.4
11	0	-	+	15.84	375.1	8.1
12	0	+	+	16.45	379.1	9.6
13	0	0	0	8.30	378.3	8.1
14	0	0	0	6.81	379.6	7.6
15	0	0	0	7.56	376.8	8.3
16	0	0	0	8.30	377.2	8.4
17	0	0	0	6.52	380.6	8.7

After assessing the adequacy of the model and eliminating non-significant coefficients, the regression equations are derived:

$$\begin{aligned}\Delta S &= 7.346 - 2.241x_1 + 0.989x_2 + 5.357x_3 + 2.006x_2^2 \\ &\quad + 1.273x_3^2 + 1.618x_1x_2 - 2.735x_1x_3\end{aligned} \tag{3}$$

$$\begin{aligned}\sigma_{ult} &= 378.395 - 1.7x_1 + 19.038x_2 - 6.562x_3 \\ &\quad - 19.488x_1^2 + 5.337x_3^2 - 11.075x_1x_3 - 17.15x_2x_3\end{aligned} \tag{4}$$

$$\begin{aligned}\delta &= 8.1556 + 0.338x_1 + 0.437x_2 \\ &\quad + 1.125x_3 - 0.406x_3^2 + 0.450x_2x_3\end{aligned} \tag{5}$$

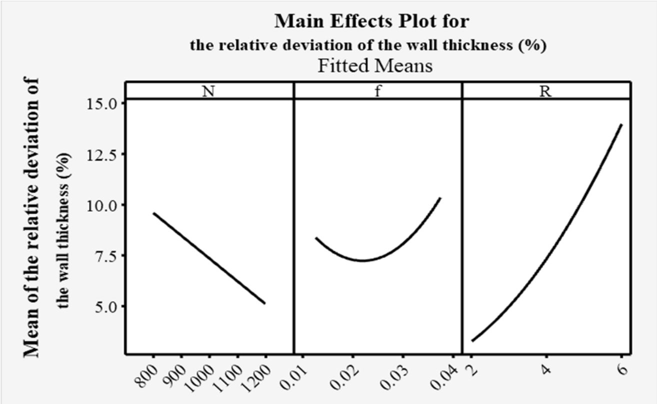


Fig. 7. Main Effects Plot for the relative deviation of the wall thickness (%)

In Fig. 7, an analysis of the N, f, R factors influencing the relative deviation of wall thickness is presented. It is evident from the illustration that the roller radius, coded by x_3, exerts the most substantial influence on the relative deviation of wall thickness. As the roller radius increases, there is a corresponding increase in the relative deviation of wall thickness.

Simultaneously, the influence of the rotating speed of the machine spindle on the relative deviation of wall thickness is comparatively modest, exhibiting an opposite effect when contrasted with the roller radius. Notably, the roller feed exerts the least influence on the relative deviation of wall thickness.

Similarly, as illustrated in Fig. 8, an analysis is presented to elucidate the factors that impact tensile strength. Notably, roller feed emerges as the most influential factor, exhibiting a direct relationship where an increase in the roller feed corresponds to an increase in tensile strength. The two remaining factors have a relatively smaller impact on tensile strength. Specifically, an increase in roller radius is associated with a decrease in tensile strength. Concurrently, within the range of [800, 1000] rev/min, an elevation in the rotating speed of the machine spindle results in increased tensile strength, while within the range of [1000, 1200], the tensile strength undergoes a change in the opposite direction.

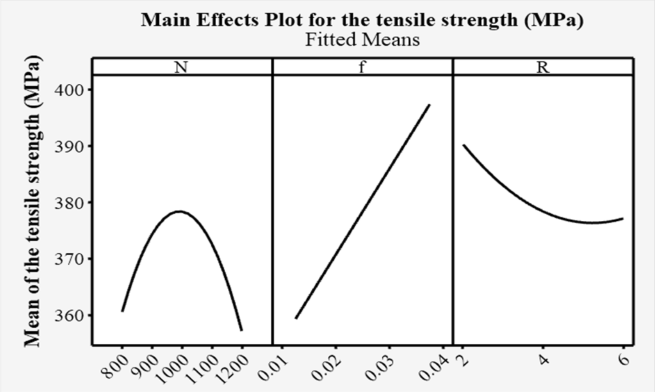


Fig. 8. Main Effects Plot for the tensile strength (MPa)

Fig. 9 illustrates the influence of factors on relative elongation, with the roller radius emerging as the most influential factor. All three factors exhibit an increasing influence on relative elongation.

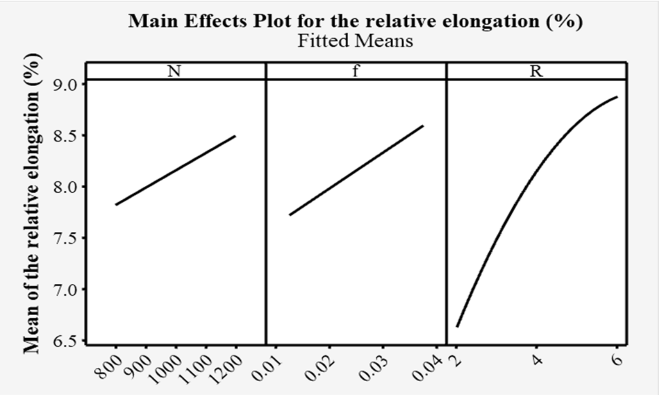


Fig. 9. Main Effects Plot for the relative elongation (%)

In the range of input factors, the optimization problem involves determining values to achieve the required output factors. Specifically, the optimization problem aims to minimize the relative deviation of the wall thickness while maximizing both tensile strength and relative elongation. The results of the optimization problem are presented in Table 4, indicating that the optimal mode for the shear spinning process on a CNC lathe is at N = 1063rev/min, f = 0.037mm/rev, and R = 3.6mm, resulting in the output factors of ΔS = 9.1%, and σ_{ult} = 399.9MPa, δ = 8.35%.

Table 4. Multiple Response Prediction

Variable	Setting
N	1062.63
f	0.0369949
R	3.59143

Response	Fit	SE Fit	95% CI	95% PI
The relative deviation of the wall thickness, %	8.35	0.146	(8.02, 8.67)	(7.62, 9.07)
The tensile strength, MPa	399.9	0.608	(398.5, 401.2)	(396.9, 402.8)
The relative elongation, %	9.06	0.431	(8.09, 10.03)	(7.06, 11.06)

4. CONCLUSION

In sum, the equations of regression of the objective functions depending on the technological parameters during the process of shear spinning of a conical component with a flange on the CNC lathe were defined using the Box-Behnken planning method. The obtained results demonstrated the possibility of determining the influence of technological parameters on the value of objective functions and predicting the technological regime of multi-objective optimizations. The roller nose radius exhibits the most significant impacton the difference in wall thickness, while the roller feed has the greatest influence on both the strength and elongation. The optimal technological mode for the smallest thickness difference, maximum strength and relative elongation was determined: N = 1063rev/min, f = 0.037mm/rev, and R = 3.6mm.

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