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Statistical Analysis and Optimization of Variables Affecting the End Diameter of AISI 304 Steel Tube Produced by Flaring Process

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ABSTRACT: The flaring of the ends of thin-walled tubes is a subset of single-point incremental forming. In this research, the experimental study and statistical analysis of the variables affecting the end diameter of formed tubes were considered. In the present paper, the design of the experiment was done based on the response surface methodology. In order to form the end of the AISI 304 steel tube and perform the statistical analysis, process input variables including tool diameter, tool angular step, tool vertical step, and type of lubricant were selected. Then the effect of input variables on the tube end diameter was analyzed. Also, the tube end diameter function was extracted from the input variables in terms of linear, interactive, and quadratic expressions, and its competency and adequacy were confirmed. The analysis of variance results showed that the expressions of the tool vertical step, tool diameter, and the interactive effect of the product of tool diameter and tool angular step are the most effective expressions on the tube end diameter. Finally, the optimal combination of process input variables to achieve the maximum tube end diameter was determined using the desirability method, and by running the verification test, the correctness of the regression equation to predict the tube end diameter was confirmed.

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1- Introduction

Incremental Sheet Forming (ISF) is recognized as one of the leading methods in the field of rapid prototyping [1]. Single Point Incremental Forming (SPIF) is one of the subsets of the ISF process in which sheet deformation is performed without the need for a die [2]. In this regard, the expansion of the ends of thin-walled tubes using the SPIF process has been a concern for researchers [3]. Cristino et al [4] numerically and experimentally studied the forming limit of the end of an aluminum tube with two methods: pressing and SPIF. They found that the forming limit in the SPIF process is higher than in the pressing process. Also, the results showed that a greater thinning occurs in the tube wall in the SPIF process. Considering the capability of the SPIF process and its advantages compared to traditional forming processes, in this research, the variables affecting the flaring of the ends of AISI 304 steel tubes are studied.

2- Methodology

In this research, incremental forming of the end of the steel tube with an outer diameter of 38 mm (*d*) with a half angle of 20 degrees (*α*) and a forming length of 20 mm (*L*) will be done (Fig. 1). Hence, the Tube End Diameter (TED), denoted by the symbol *D* in Fig. 1, was chosen as the response parameter. The tube thickness is 0.5 mm.

In this research, the input variables of the process along with their change levels were selected according to Table 1.

The experimental tests were designed based on the Response Surface Methodology (RSM) and using the Box-Behnken Design (BBD). In this method, the effect of each of the input variables on the response parameter (y) is expressed as Eq. (1):

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i}\sum_{j} \beta_{ij} x_i x_j + \varepsilon \qquad (1)$$

In the above function, β_0 is a constant value, β_i is a linear coefficient, β_{ii} is a quadratic coefficient, β_{ij} is an interactive coefficient, x is the independent variable, k is the number of independent variables and ε is the observed error in the response. The design of the experiment was done using Minitab software with 27 runs [5]. The forming of the end of the tube was done with spherical-head tools with diameters of 8, 10, and 12 mm. This process was done with a feed rate of 800 mm/min, without spindle rotation, and in a spiral path. Fig. 2 shows some of the formed samples. The Tube End Diameter (TED) was measured using a profile projector.

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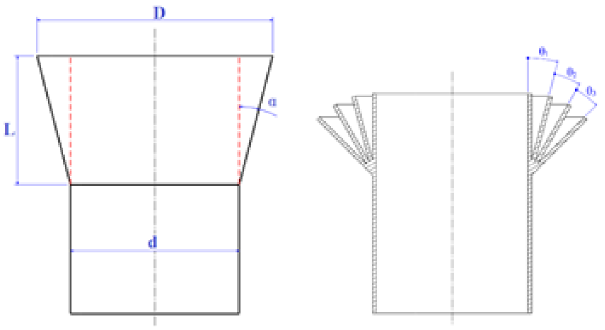

Fig. 1. Schematic of tube end flaring

Fig. 2. Some of the formed samples

3- Results and Discussion

3- 1- Statistical analysis

Analysis of the results is done using Analysis Of Variance (ANOVA). The confidence level was considered equal to 0.05. According to the ANOVA results, it can be seen that the variables of tool diameter (*D*), tool vertical step (*V*), and the interactive effect of the product of tool diameter and tool angular step (*DA*) are effective terms on the response parameter (TED). The regression model of the TED was extracted as coded form according to Eq. (2):

$$TED = 48.16 + 0.544D - 0.131A - 0.576V + 0.016L - 0.552D^2 + 0.5A^2 - 0.386V^2 + 0.701L^2 - 0.568DA + 0.066DV - 0.046DL - 0.221AV + 0.268AL - 0.184VL \quad (2)$$

Also, with a tool diameter of 12 mm and a vertical step of 0.2 mm, the maximum TED can be achieved (Fig. 3). As can be seen, in small vertical steps due to the continuous movement of materials, a larger diameter is obtained in the expanded section of the tube. Also, increasing the tool diameter and reducing the tool's vertical step will lead to a decrease in the spring-back of the tube edges and an increase in the TED.

Table 1. Experiment factors and their change levels

Variable	Symbol	Unit	-1	0	+1
Tool diameter	*D*	mm	8	10	12
Tool angular step	*A*	Degree	4	7	10
Tool vertical step	*V*	mm	0.2	0.5	0.8
Lubricant type	*L*	-	Oil	Grease	Graphite

3- 2- Optimization

In this research, the desirability method was used to optimize the input variables [6]. The objective of the desirability function is to maximize the response parameter (TED). The desirability value obtained from the optimization process was 0.602. The optimal values of the input variables were obtained as follows: tool diameter is equal to 12 mm, angular step is equal to 4 degrees, vertical step is equal to 0.46 mm and oil was chosen as the optimal lubricant.

3- 3- Studying the thickness change in the expanded section of the tube

In order to investigate the thickness change in the expanded section of the tube, three samples were selected. The nominal size of the TED is equal to 52.559 mm. The samples were cut longitudinally using a wire- Electrical Discharge Machine (EDM). The thickness of the tubes in the expanded section was measured using a Kroeplin gauge. It was observed that by increasing the forming angle and applying the maximum tensile force, thinning occurs at the end of the expanded section of the tubes.

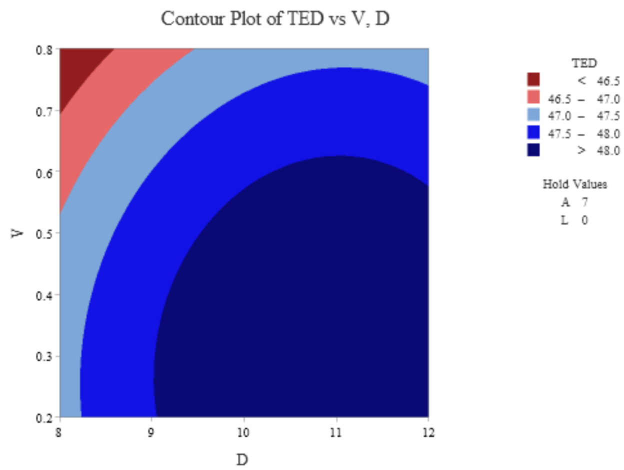

Fig. 3. Effect of tool diameter and tool vertical step

4- Conclusion

The important results of this research are summarized as follows:

- The regression model for predicting the tube end diameter (TED) was extracted.
- According to the ANOVA results, the terms affecting the TED are tool diameter, tool vertical step, and the interactive effect of the product of tool diameter and tool angular step.
- The optimal values of the input variables to achieve the maximum TED were extracted.
- By increasing the tool diameter and decreasing the tool's vertical step, a larger diameter is obtained at the end of the tube. Hence, in addition to reducing the spring-back, will cause more thinning in the thickness of the end of the expanded section.

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