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Numerical and Experimental Analysis of Bow Defect in Flexible Roll Forming of Double Layered Copper-Aluminum Sheets

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Abstract
In this article, the experimental investigation and numerical simulation of the flexible roll forming of double-layer sheets are discussed. For this purpose, a single-station flexible roll forming machine is used. The effects of several parameters affecting the bow defect in the flexible roll forming process including forming angle, sheet thickness, wing length, and the arrangement of the sheet layers have been studied using the finite element simulations. The numerical model is validated by means of experimental tests. The results show that with the increase of the forming angle and the wing length, the amount of bow defect increases, while it decreases with the increase of the sheet thickness. Also, the placement of the sheets is effective in the rate of occurrence of the bow defect.

Keywords: Numerical simulation, flexible roll forming, bow defect, double layer sheet

1. Introduction

In order to study and investigate the flexible roll forming process, it is necessary to know about the cold roll forming process. The cold roll forming machine consists of several stations, each including several rollers. Rollers are usually upper or lower types, although side rollers are also used if required. In the cold roll forming process, by applying a low amount of forming by a series of rollers in each station, continuous and consecutive bends are created in a metal sheet, and the desired cross-section is formed [1]. In this method, the thickness and cross-section of the sheet are fixed. In recent years, the use of sheets with composite and multilayer structures has been developed. Double-layered metal sheets are considered a suitable solution for the production of multi-purpose products having features such as improving formability, increasing resistance to corrosion and wear, creating electrical or magnetic properties, reducing weight, and reducing costs.

Today, with the advancement of technology, many parts which are used in the automotive and aerospace industries are profiles with variable cross-sections. To produce this type of part, the flexible roll forming method can also be used [2]. In this process, in addition to the rotational movement around their axis, the rollers have also linear and angular movements, which are controlled by the computer numerical control system (CNC). By changing the control program of the device, the position of the rollers can be changed and a new product can be produced with the least possible cost and time. Certain defects in the products produced this way are observed due to the presence of two tensile and compressive zones in the transition zone (the zone where the width of the profile changes). After forming into a certain size, the size of the sheet edge decreases in the compressive area and increases in the tensile area [3]. The important defects of the product in this process include web warping, edge distortion, spring-back, and bow defect. The forming process of metal sheets can be analyzed using methods such as the finite element method, so that it is possible to predict the effective parameters of the process and tool design. Kim [4] modeled the cold roll forming process using the 3D finite element program called "Shape-RF" and investigated the effective parameters. He proposed different basic sheet shapes for different thickness-to-diameter ratios. Groche et al. [5] introduced the flexible roll forming process as a suitable method for producing parts made of high-strength steel used in the car body. They also discussed the economic comparison of this method and the usual methods. Jiao et al. [6] studied the web warping phenomenon. A major problem in flexible roll forming is the deformation of the bottom of the sheet, which is the height difference caused by the deviation of the bottom of the sheet compared to its length. They presented an analytical model for the prediction of warping defect in the flexible roll forming process of a part with variable width [6]. Dadgar Asl et al. [7] studied the rupture in the transition zone of the bend edges, where the thickness of the sheet is large compared to the radius of the bend. They investigated the phenomenon of rupture in the flexible roll process with a channel-shaped cross-section using six soft failure criteria. By comparing the results obtained from the soft failure criteria and the experimental results, it was observed that the Argon failure criterion is the most suitable criterion for investigating the rupture. Woo et al. [8] concluded that the web warping defect strongly depends on the longitudinal strain formed in the flange (edge) of the part. Their research was carried out during the flexible roll forming process of two-layered steel/aluminum sheets in three stations. They investigated defects such as floor warping, wrinkling, and sheet delamination using experimental tests and numerical simulations. The results showed that the longitudinal strains caused by this process significantly affect the occurrence of forming defects. In addition, the longitudinal strains strongly depend on the mechanical properties of the constituent layers.

Defects created in the flexible roll forming process reduce the geometric accuracy of the profile and can cause the profile to become defective. Therefore, designing a product that has minimal defects is considered one of the priorities of the flexible roll forming process. This requires knowing the effect of product geometrical parameters on the defects. Until now, some defects have not been considered in the literature including the bow defect of double-layer sheets. In this article, after experimental validation of the numerical model, the effects of the forming angle, sheet thickness, wing length, and the placement of layers on the bow defect in the flexible roll forming of double-layer sheets have been investigated.

2. Methodology

The sheets used in this research are made of copper and aluminum. The mechanical properties of Cu and Al6061-T6 were applied to each layer separately. The density and Poisson's ratio for Al6061-T6 are respectively 2700 kg/m^3, 0.33, and for Cu 8930 kg/m^3, 0.35. To simulate the flexible roll forming process, the general static solver of Abaqus software version 2021 has been used. The sheet is defined as a deformable shell. The S4R element was selected for meshing. As can be seen in Figure 1, the sheet is placed in such a way that its beginning is placed between the rollers of the first station. The upper roller of the first station is tangent to the upper surface of the sheet, but the lower roller is placed at an angle so that its highest edge is at least as far as the thickness of the sheet from the upper roller. Unwanted changes start significantly from the beginning of the transfer zone and end at the end of the transfer zone, which is the basic requirement of the desired cross-section of the product from the same zone.

In order to be able to use the engineering stress-strain diagram in the Abaqus software to introduce material properties, the true stress-strain values must be entered into the software in the form of numerical data. Based on this, the number of points from the plastic part of the true stress-strain diagram of Figure 2 is entered in the plastic properties of the material in the software.

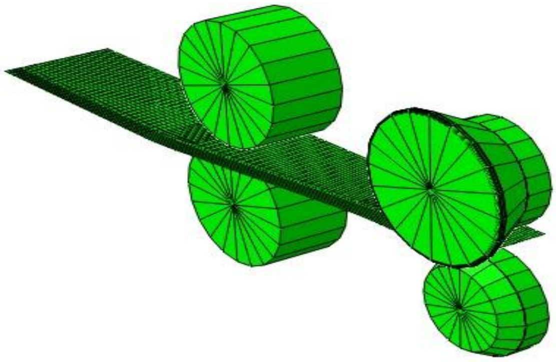

Figure 1. Designed model of sheet and rollers

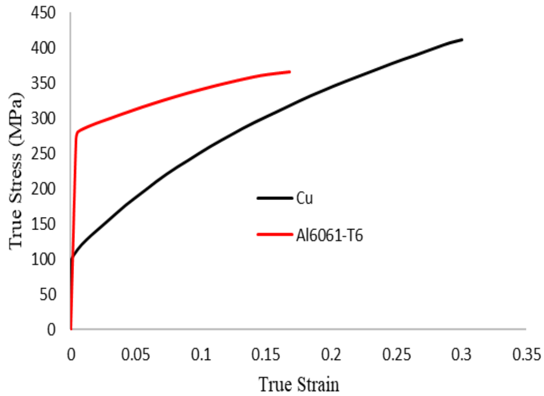

Figure 2. True strain-stress curve of Al 6061-T6 and Cu

The double-layer sheets are made of copper (pure commercial copper of Bahonar Kerman Copper Company), Cu and Al6061-T6 aluminum, and the mechanical properties extracted from the tensile test of the standard sample are shown in Table 1. Each of the sheets with a thickness of 1 mm are glued together with white MS Polyband commercial glue. The sample with the upper layer of aluminum and the lower layer of copper is defined as a type A sample while with the replacement of the sheet as type B sample.

Table 1. Mechanical properties of materials

Layer material	Cu	Al 6061-T6
Fracture strength (MPa)	165	207
Ultimate tensile strength (MPa)	225	310
Yield strength (MPa)	190	276
Young's modulus (GPa)	124	68

The amount of rotation of the rollers is such that the length of the sheet that is between the zero station and the first station (L) passes between them. Therefore, the amount of rotation can be calculated from the following equation:

$$\theta = \frac{L}{R} \tag{1}$$

where, R is the radius of the rollers. The time of this stage is determined based on the speed considered for the line. The linear speed should be enough to provide the condition of a quasi-static process. If v is the linear speed, the rotational speed of the rollers ω can be calculated from the following equation:

$$\omega = \frac{v}{R} \quad (2)$$

The time of this step is calculated from the following equation:

$$t = \frac{\theta}{\omega} \quad (3)$$

The condition of the continuity of the wing slope at the beginning of the deformation region is obtained from the following equation for the deformation length:

$$L = a\sqrt{[\frac{8}{3}(\frac{a}{t})\theta p]} \quad (4)$$

where θp is the increase in the bend angle between two consecutive stations, in radians. Eq. (4) suggests that the deformation length L is independent of the material properties. The reason for this issue is the assumption of rigid-completely plastic material behavior.

3. Results and Discussion

Statistical analyzes were performed using the ANOVA method in Minitab software. The determined parameters and levels are given in Table 2 to measure the bow defect. With this method, all the main and interaction effects of the parameters are considered together.

Table 2. The parameters and levels determined for the design of the experiment

Parameter	Level 1	Level 2	Level 3
Forming angle	30º	40º	50º
Thickness	0.5 mm	0.75 mm	1 mm
Wing length	18 mm	25 mm	
Layer order	Al-Cu	Cu-Al	

To verify the validity of the simulations, experiments were carried out on pre-cut sheets exactly according to the dimensions and material specified in the simulations. Then, the effect of the forming angle, sheet thickness, sheet wing length, and layer order were checked and compared for the bow defect as well as the percentage of the defect.

Design of Experiments (DOE) is a method of investigating the effects of multiple parameters on a variable (response). In other words, DOE includes a series of experiments that deliberately changes the input variables of the process to observe and identify the amount of changes in the output response of the process.

The most important indicator in the results is the P-Value: The value of 95% is considered for the confidence level (α=0.05). If the P-value is less than 0.05, it is concluded that the effect of the acquired factor is significant. Table 3 shows the ANOVA table for the effect of the parameters on the bow defect along with their contribution percentages.

Table 3. Analysis of variance table

Source	Contribution (%)	P-Value
Model	98.86%	0.000
Linear	97.44%	0.000
Angle	52.86%	0.000
Thickness	34.06%	0.000
Layer	1.70%	0.000
Wing length	8.82%	0.000
2-Way Interactions	1.42%	0.000
Angle×Thickness	1.42%	0.000
Error	1.14%	
Total	100.00%	

Figure 3 shows the diagram of the main effects influencing the bow defect in the simulation results using Minitab software analysis. As it is clear in the figure, the forming angle is the most effective parameter. With the increase of the forming (roller) angle, the amount of bow defect increases. As the thickness of the sheet increases, the bow defect decreases. In constant thickness and forming angle, with the increase in the length of the sheet wing, more surface of the sheet is in contact with the rollers and the deformation length also increases. As the length of the deformation increases, the longitudinal strains of the edge also increase, and then the bow of the output product also increases. The arrangement of the material of the sheet layer is another influential parameter. When Cu is used as the upper layer, a smaller bow defect occurs. The contribution percentage of each parameter is 52.86% for forming angle, 34.06% for thickness, 8.82% for wing length, and 1.70% for layer placement.

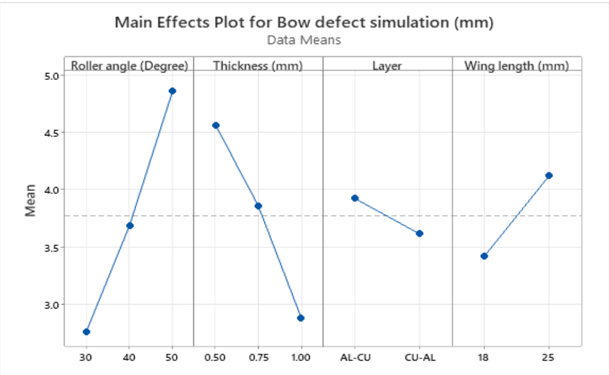

Figure 3. The main effects of the parameters affecting the bow defect in the simulation results

Figure 4 shows the effective parameters of forming angle, sheet thickness, wing length, and sheet layer on the bow defect of double-layered sheets. The interaction effect diagram shows that, as it was shown in Table 3, the parameters do not have a significant interaction effect except for the interaction of the roller angle and thickness.

Figure 4. Interaction effects plot of the effective parameters on the bow defect.

4. Conclusions

- The bow defect is smaller in the lower forming angles.
- Larger forming angle distorts the edge of the sheet and aggravates the bow defect.
- With the increase in the length of the sheet, the longitudinal strains of the edge also increase; As a result, the bow defect also increases.
- The size of the bow defect is also dependent on the differences in the mechanical properties of the upper and lower layers.
- The bow defect decreases with the increase in the sheet thickness.

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