Influence of Spiral Tool Path Strategy Towards Incremental Backward Hole-flanging process using Curved Shoulder Forming Tool on Copper Sheet

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Abstract. Many studies have been done as hole flanges have important functional elements in many lightweight construction parts such as to provide sufficient fastening area, stiffness, bearing support, and allow for positioning, etc. Advancement of CAD/CAM software integrated to CNC machines technology has opened a new technology to enable pre-cut hole on sheet metal formed incrementally into required flange profile and height on its periphery known as incremental hole-flanging (IHF). Unlike conventional hole-flanging, the forming of the flange in the IHF process was using a simple tool pressed incrementally into a pre-cut hole with motion path performed by the NC programs on CNC machine. Hence, low volume production and rapid prototyping to reduce initial cost can be achieved to meet today’s production flexibility. There have not been many types of research to study the forming of flanges in incremental backward hole-flanging (IBHF) of closed or semi-closed profiles. By employing full factorial experimental design, this research focused on whether curved shoulder flange forming tool, process variables, and tool geometry of IBHF on copper plate through a spiral tool path strategy affect the produced flange height. The research yielded the results that the curved shoulder flange forming tool was successfully produced flange height through the spiral path strategy. From the data processing, it is shown that the variable of horizontally forming step, the forming rate, the forming tool rotation, and the tool shoulder radius significantly affects the flange height resulted from the IBHF process.

Keywords: Incremental Hole-Flanging, Incremental Backward Hole-Flanging, Tool Path Strategy

1. Introduction

The need for cost reduction and increased efficiency in making construction for movable or stationary products encourage increased application of light construction which generally utilizes thin plates or thin profiles. The main advantage of utilizing thin or thin profile plates is the reduced weight of the material so that it can reduce costs including material costs, transportation costs, the process of making and assembling a construction to become easier and faster. For moving constructions, the use of lightweight construction provides the main advantage that the product will have better maneuverability, or the product will have better transport capability. The light construction assembly process in many cases is faced with the problem of proper and economical bonding methods because conventional bonding methods become less suitable and expensive [1].

Light construction formed from a thin profile series will be faced with the selection of the right binding method. The process of binding thin section construction parts with other parts achieved
through the drilling process and the process of brushing or brazing process will not be enough to provide binding strength because there is not enough flange area around the hole. The forming of flanges for an open profile can be achieved easily through conventional hole-flanging by placing the initial perforated plate on the die, then pressing it by punching the cylindrical shape in one direction forward [5][6].

The application of conventional hole-flanging is only suitable for mass production with a simple hole shape. This process is difficult to meet the needs of small quantities of products with complex hole shapes in a fast time. Complex hole profiles will require a complex punch and die, expensive punch and die forming costs with long manufacturing times. In the 2000s, a new technology approach developed the plate forming process known as incremental sheet forming (ISF). Unlike the conventional sheet metal forming process that requires a punch and dies specifically dedicated to obtaining a certain shape, the ISF allows the forming of flanges with a simple forming device that does not depend on the complexity of the shape of the hole in the forward or backward movement. The basic concept of the ISF method plate forming process using a tool with a spherical shape is mounted on a CNC machine and then moved to press the plate programmatically through a certain path designed with CAD/CAM. The forming tool presses incrementally on the plate until the final shape of the product is reached [2].

The ISF process has many advantages including the ability to produce fast and cheap to produce prototypes and components with low volume because it eliminates the process of making and construction of die shapes. The ability to form geometries is more complex than can be made using conventional hole-flanging technology. Forms and dimensions can be controlled by changing parameters such as the steps of the tool movement path, tool diameter, and speed of forming. Higher forming limits can be achieved than conventional hole-flanging processes. The ISF method requires only one clamping device and one forming device, compared to the need for various die and punch for different forming stages in conventional metal forming processes [3].

For some cases, ISF technology which tends to make the process of going forward (based on CNC machines that are in the direction of Z-) has not been able to do the forming process where the resulting geometry requires backward direction. The inability to produce outward flanges on closed profiles is also a weakness of the ISF process. Therefore, the incremental backward hole-flanging (IBHF) process is carried out to overcome the problem. The working principle is the same as the ISF process, but the resulting geometry is backward (based on CNC machines, namely the Z+ direction).

2. Literature Review

The strategy of the trajectory of the forming tool to produce the flange height in the Incremental Forward Hole Flanging (IFHF) has been a concern by several researchers. Three strategies have been developed to optimize the IFHF process as proposed, as shown as figure 1. Strategy (a), in horizontally one step diameter larger than the initial diameter, the forming tool begins to press the plate, do, moving incrementally on the helical path forward with the programmed spindle rotation and forming rate. The forming tool is then pulled back vertically above the plate surface and then shifted to the next diameter. The process is repeated until the final diameter is reached, dp Strategy (b), the forming tool starts to press on the final diameter, dp, with an incremental angle of forming equal to θi. The tool is moved through a spiral-helical path towards the end of the path at the initial forming angle of θi with the programmed spindle rotation, the forming, and the spiral step. With the angle of θi the process is repeated until the angle 90o is reached with the final diameter dp. Strategy (c), is a combination of strategy (a) and strategy (b)[2].

Other researchers conducted Incremental Backward Hole Flanging research. IBHF, using a ball-tipped tool with a tool body diameter smaller than the diameter of the ball. The tool is moved vertically under the plate and then moved one step horizontally larger than the initial diameter of the plate. Through the helical path, the forming tool is driven vertically to bend the plate in programmed spindle rotation, horizontal step, and forming rate as shown in figure 2. This movement is repeated until the final diameter is reached. DC 05 steel material and CNC FAMUP machine based on 3 axes
are used in the forming process. The results of the research show that the parameters that have the most significant effect on the height and thickness of the flange are tool diameter, the size of the radial forming step, and the size of the axial direction forming step. Due to the gradual forming and proper process parameter selection, the Limit Forming Ratio (LFR), where LFR is D1 / D0, and the height of the flange can be achieved greater than conventional hole flanging [4].

![Fig 1. Example of IFHF Toolpath Trajectory proposed by Cui, Z., et. al[2]](image1)

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![Fig 2. Example of IBHF Toolpath Trajectory Proposed by Petek, A., et. al.[4]](image2)

Fig 2. Example of IBHF Toolpath Trajectory Proposed by Petek, A., et. al.[4]

3. Methods

The forming strategy through a pure helical trajectory or an incremental helical-spiral combination will take a long time to reach the final diameter size, dp, because it requires repetitive horizontal and vertical movements. The forming strategy carried out in this study uses a forming tool with curved shoulders with a certain radius that moves through a spiral path to incrementally push the plate horizontally which will bend the plate backward due to the curve with a spiral path until it is reached dp, as shown in Figure 3.

![Working Table of the Machine](image3)

Table 1. Variable and Levels

| No | Variables                          | -   | +   |
|----|------------------------------------|-----|-----|
| 1  | rd= Forming tool radius, mm       | 2.5 | 3.5 |
| 2  | ah=Horizontal step size, mm       | 0.5 | 1.0 |
| 3  | vf = Forming speed, mm/minute     | 100 | 200 |
| 4  | n = spindle speed, rpm            | 100 | 300 |
Because the height of the flanges is generated on a horizontal trajectory, this strategy will allow accelerating the flanges formation. The study focused on how the process variables and the basic geometry of the forming tool on the IBHF copper plate influence the flange height. The selection of copper material is intended to immediately be able to provide research results that can be directly applied in the field of heating and cooling equipment which generally use copper pipes to distribute the heating fluid or cooling.

Fig 3. IBHF with Spiral Toolpath Trajectory

The factorial design with two replication was used to determine the effect of the curved shoulder forming tool radius (rd, mm), the horizontal step forming direction (ah, mm), the forming rate (vf, mm / minute), spindle speed (n, rpm), and the dominant variable interaction on the height of flanges (y) from the results of the IBHF process, Table 1. MINITAB statistical package program, version 14 is used to process observed data.

Fig 4. Forming Tool Geometry

Fig 5. Clamping and Perforating Process.

Fig 6. Spiral IBHF Forming Process and Final Product
The specimen is made of the copper plate with dimensions of 1 mm thick with a length and width of 53 mm each. The forming tool is made of carbon steel with dimensions: shoulder diameter of 22 mm, the diameter of the forming body of 16 mm and with a shoulder radius of forming tool of 2.5 mm and 3.5 mm, as shown in Figure 4. Shoulder forming tool profile is machined using CNC lathe, while the forming process using the IBHF spiral method to produce flange height is carried out by a CNC milling machine. Test specimens are mounted on a clamping device that has been designed to perfectly clamp the test specimen, as shown in Figure 5. After the test specimen has been perfectly clamped, the initial hole of 22 mm is then machined using an end mill cutter. Then, the test specimen is formed by IBHF to produce the flange height with a final diameter of 33 mm, as shown in Figure 6.

4. Results and Discussion

From the forming process on the test specimen to produce the height of the flange carried out in accordance with the experimental design, proceed with the measurement process to obtain the results of flange height. Digital Vernier caliper with 0.01 precision was used to observe flange height in each level and variable combination. From the observational data, the main results are obtained that the design of the forming tool with curved shoulder with a certain radius driven through pure spiral trajectories, as shown in figure 3, can produce flange height, Figure 7, with variations in flange height according to process variables and tool geometry determined. This discovery is important because the forming process through a purely spiral trajectory strategy will open the opportunity to accelerate the process of forming flange height. The software performs reading of text files from the results of measurements carried out using the network analyzer, mathematical processing to determine the minimum, average and maximum values of these data, achieving charts and their evolution in time, as well as generating spreadsheet files containing the processed data.

Table 2. General fit ANOVA.

| Source      | DF | Seq SS   | Contribution | Adj SS   | Adj MS | F-Value | P-Value |
|-------------|----|----------|--------------|----------|--------|---------|---------|
| rd          | 1  | 0.08405  | 6.74%        | 0.084050 | 0.084050| 4.49    | 0.046   |
| ah          | 1  | 0.00125  | 0.10%        | 0.001250 | 0.001250| 0.07    | 0.799   |
| vf          | 1  | 0.12005  | 9.63%        | 0.120050 | 0.120050| 6.41    | 0.019   |
| n           | 1  | 0.11045  | 8.86%        | 0.110450 | 0.110450| 5.89    | 0.024   |
| rd*ah       | 1  | 0.11761  | 9.43%        | 0.117613 | 0.117613| 6.28    | 0.021   |
| rd*vf       | 1  | 0.05951  | 4.77%        | 0.059512 | 0.059512| 3.18    | 0.089   |
| rd*n        | 1  | 0.17111  | 13.72%       | 0.171113 | 0.171113| 9.13    | 0.006   |
| ah*vf       | 1  | 0.04061  | 3.26%        | 0.040612 | 0.040612| 2.17    | 0.156   |
| ah*n        | 1  | 0.10811  | 8.67%        | 0.108113 | 0.108113| 5.77    | 0.026   |
| vf*n        | 1  | 0.04061  | 3.26%        | 0.040612 | 0.040612| 2.17    | 0.156   |
| Error       | 21 | 0.39351  | 31.56%       | 0.393512 | 0.018739|         |         |
| Lack-of-Fit | 5  | 0.17541  | 14.07%       | 0.175412 | 0.035082| 2.57    | 0.068   |
| Pure Error  | 16 | 0.21810  | 17.49%       | 0.218100 | 0.013631|         |         |
| Total       | 31 | 1.24689  | 100.00%      | 0.913734 | 0.2672  |         |         |
| S           |    | 0.136899 | 68.44%       | 0.136899 | 0.136899|         |         |

Model Summary

| R-sq | R-sq(adj) | PRESS | R-sq(pred) |
|------|----------|-------|------------|
| 53.41% | 68.44%  | 0.913734 | 26.72% |
Furthermore, to determine how significant the influence of these variables on the flange height is used the MINITAB statistical program. The results of this study from processing observational data through statistical review of factorial analysis involving all the main factors and second order interactions obtained a significant picture of all the main variables and their interactions with flange height, can be shown in table 2.

In table 2, it can be observed that an empirical model to explain the relationship of each major factor and its interaction can be done with a percentage of confidence of 68.44% (R-sq). In this mathematical model, it can be shown that almost all the main factors have a significant influence on the height of the flange of the spiral IBHF process results. This can be indicated by the p-value <0.05.

A mathematical model with a confidence of 68.44% can be improved by eliminating data that has a discrepancy. In this case the data with high residual values. This is justified in statistical methods with experimental designs that have replication. From some of the eliminated data, 27 experimental data were collected which represented a mathematical model that had a high percentage of confidence, which was 94.13%. This gives a statement that the experiments carried out can be explained mathematically with a percentage level of confidence of 94.13% with a mathematical model as shown in table 3.

Table 3. ANOVA after Eliminating Unusual Observation.

| Source | DF  | Seq SS  | Contribution | Adj SS  | Adj MS  | F-Value | P-Value |
|--------|-----|---------|--------------|---------|---------|---------|---------|
| rd     | 1   | 0.33750 | 53.91%       | 0.25591 | 0.25591 | 111.37  | 0.000   |
| ah     | 1   | 0.03835 | 6.13%        | 0.01035 | 0.01035 | 4.51    | 0.050   |
| vf     | 1   | 0.06006 | 9.60%        | 0.11400 | 0.11400 | 49.61   | 0.000   |
| n      | 1   | 0.00179 | 0.29%        | 0.02111 | 0.02111 | 9.19    | 0.008   |
| rd*ah  | 1   | 0.00552 | 0.88%        | 0.01158 | 0.01158 | 5.04    | 0.039   |
| rd*vf  | 1   | 0.00317 | 0.51%        | 0.01727 | 0.01727 | 7.52    | 0.014   |
| rd*n   | 1   | 0.08250 | 13.18%       | 0.10933 | 0.10933 | 47.58   | 0.000   |
| ah*vf  | 1   | 0.01584 | 2.53%        | 0.02194 | 0.02194 | 9.55    | 0.007   |
| ah*n   | 1   | 0.04433 | 7.08%        | 0.04105 | 0.04105 | 17.87   | 0.001   |
| vf*n   | 1   | 0.00138 | 0.02%        | 0.00013 | 0.00013 | 0.06    | 0.810   |
| Error  | 16  | 0.03676 | 5.87%        | 0.03676 | 0.00229 |         |         |
| Lack-of-Fit | 4  | 0.00891 | 1.42%        | 0.00891 | 0.00229 | 0.96    | 0.464   |
| Pure Error | 12 | 0.02785 | 4.45%        | 0.02785 | 0.00232 |         |         |
| Total  | 26  | 0.62600 | 100.00%      |         |         |         |         |

Model Summary

| S     | R-sq | R-sq(adj) | PRESS | R-sq(pred) |
|-------|------|-----------|-------|------------|
| 0.0479360 | 94.13% | 90.46% | 0.103759 | 83.43% |

Regression Equation

\[
Y = 9.33096 - 0.10275 \cdot \text{rd}_{2.5} + 0.10275 \cdot \text{rd}_{3.5} + 0.02067 \cdot \text{ah}_{0.5} - 0.02067 \cdot \text{ah}_{1.0} - 0.06948 \cdot \text{vf}_{100} + 0.06948 \cdot \text{vf}_{200} + 0.02990 \cdot \text{n}_{100} - 0.02990 \cdot \text{n}_{300} + 0.0225 \cdot \text{rd*ah}_{2.5} + 0.0225 \cdot \text{rd*ah}_{2.5} + 0.10 \cdot 0.0225 \cdot \text{rd*ah}_{3.5} + 0.5 \cdot 0.0225 \cdot \text{rd*ah}_{3.5} + 1.0 \cdot 0.0225 \cdot \text{rd*ah}_{3.5} + 0.5 \cdot 0.0225 \cdot \text{rd*ah}_{3.5} + 1.0 \cdot 0.0277 \cdot \text{rd*vf}_{2.5, 100} - 0.0277 \cdot \text{rd*vf}_{2.5, 200} - 0.0277 \cdot \text{rd*vf}_{3.5, 100} + 0.0277 \cdot \text{rd*vf}_{3.5, 200} - 0.06794 \cdot \text{rd*n}_{2.5, 100} + 0.06794 \cdot \text{rd*n}_{2.5, 300} + 0.06794 \cdot \text{rd*n}_{3.5, 100} - 0.06794 \cdot \text{rd*n}_{3.5, 300} - 0.03044 \cdot \text{ah*vf}_{0.5, 100} - 0.03044 \cdot \text{ah*vf}_{0.5, 200} - 0.03044 \cdot \text{ah*vf}_{1.0, 100} - 0.03044 \cdot \text{ah*vf}_{1.0, 200} + 0.0427 \cdot \text{ah*n}_{0.5, 100} - 0.0427 \cdot \text{ah*n}_{0.5, 300} - 0.0427 \cdot \text{ah*n}_{1.0, 100} + 0.0427 \cdot \text{ah*n}_{1.0, 300} - 0.0025 \cdot \text{vf*n}_{100} + 0.0025 \cdot \text{vf*n}_{100} + 0.0025 \cdot \text{vf*n}_{200} - 0.0025 \cdot \text{vf*n}_{200} + 0.0025 \cdot \text{vf*n}_{200} + 0.0025 \cdot \text{vf*n}_{200} |
\]
The mathematical model represented by the regression formula in table 3 can be simplified to show the location of the p-value or the location of the factors that have a dominant influence on the flange height. The consequence of simplifying this mathematical model is that the error value on lack-of-fit will increase according to the percentage of simplification of the mathematical model. This step to simplify the mathematical model is done by eliminating the mathematical model that has the least influence, which can be indicated by the p-value > 0.05. So that the analysis of variance, the percentage of the mathematical model, and the regression formula can be seen in table 4. After going through the simplification process of the regression formula, the confidence percentage value for the mathematical model becomes 91.95% or it can be said that 8.05% of the mathematical model is incorrect. The percentage of the uncertainty of 8.05% is the breakdown of lack-of-fit and pure error. Where the value of each error configuration is below 15% or <15%, this indicates that a simplified mathematical model is categorized as a valid mathematical model.

Table 4. General Fit ANOVA after simplifying the regression formula.

| Source    | DF | Seq SS  | Contribution | Adj SS  | Adj MS  | F-Value | P-Value |
|-----------|----|---------|--------------|---------|---------|---------|---------|
| rd        | 1  | 0.34372 | 55.05%       | 0.34210 | 0.342099| 129.26  | 0.000   |
| ah        | 1  | 0.04978 | 7.97%        | 0.03355 | 0.033555| 12.68   | 0.002   |
| vf        | 1  | 0.04770 | 7.64%        | 0.06633 | 0.066327| 25.06   | 0.000   |
| n         | 1  | 0.00337 | 0.54%        | 0.01842 | 0.018418| 6.96    | 0.016   |
| rd*n      | 1  | 0.09162 | 14.68%       | 0.10325 | 0.103246| 39.01   | 0.000   |
| ah*n      | 1  | 0.03784 | 6.06%        | 0.03784 | 0.037841| 14.30   | 0.001   |
| Error     | 19 | 0.05028 | 8.05%        | 0.05028 | 0.002647|         |         |
| Lack-of-Fit| 8 | 0.02963 | 4.75%        | 0.02963 | 0.003704| 1.97    | 0.147   |
| Pure Error| 11 | 0.02065 | 3.31%        | 0.02065 | 0.001877|         |         |
| Total     | 25 | 0.62433 | 100.00%      |         |         |         |         |

Model Summary

| S          | R-sq | R-sq(adj) | PRESS | R-sq(pred) |
|------------|------|----------|-------|------------|
| 0.0514442  | 91.95% | 89.40% | 0.0951296 | 84.76% |

Regression Equation

\[
\begin{align*}
  y &= 9.3463 \cdot 0.1171 \cdot rd_{2.5} + 0.1171 \cdot rd_{3.5} + 0.0372 ah_{0.5} + 0.0372 ah_{1.0} - 0.0518 vf_{100} + 0.0518 vf_{200} + 0.0275 n_{100} \\
  &\quad - 0.0275 n_{300} - 0.0646 rd*n_{2.5} + 0.0646 rd*n_{3.5} + 300 + 0.0646 rd*n_{3.5} + 100 - 0.0646 rd*n_{3.5} + 300 \\
  &\quad + 0.0390 ah*n_{0.5} + 100 - 0.0390 ah*n_{0.5} + 300 - 0.0390 ah*n_{1.0} + 100 + 0.0390 ah*n_{1.0} + 300
\end{align*}
\]

In table 4, in terms of the p-value, all the main factors and interactions are dominant, namely the interaction between the tool radius with the spindle speed (rd * n) and the interaction between the steps of forming horizontally with the spindle speed (ah * n) having an effect against the height of the flange (y) resulting from the IBHF spiral process. The influence of each of the main factors and dominant interactions has their respective level of significance to the height of the flange. This level of significance can be seen from the percent contribution of each variable or interaction. Statistically, the radius of the forming tool has the greatest influence on the height of the tool with the percentage contribution of 55.05%, followed by the interaction between rd * n of 14.68%, the step of forming horizontally at 7.97%, the speed of forming of 7.64%, ah * n of 6.06 %, lack-of-fit of 4.75%, pure error of 3.31%, and spindle speed of 0.54%.

The values of each level in the main factors (rd, ah, vf, and n) that are statistically observed can be explained individually in relation to the height response of the flange (y) as a result of the incremental backward hole-flanging with spiral trajectory. The relationship of each of the main factors to the response can be seen in Figure 7.
In the tool forming radius factor $(rd)$, it can be explained that the greater the radius value of the forming tool, the higher the resulting collar. This is comparable to the strain hardening rule, where a larger radius is more capable of accommodating greater areas of forming force so that the strain hardening that occurs can be minimized. On the large factor of forming in the horizontal direction $(ah)$ it can be explained that the greater the value of the forming in the horizontal direction, the smaller the height value of the collar produced. This is because the friction time of each segment is getting shorter due to the fewer number of steps in the forming. So that the deforming time is getting shorter and the hardening strain is getting bigger. In another factor, namely the forming speed $(vf)$, the greater the forming speed that occurs during the IBHF spiral process, the greater the height of the collar produced. In the last observation factor, the greater the spindle speed value $(n)$, the smaller the height value of the collar produced.

Fig 7. Main Effects Plot toward Flange Height $(y)$.

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