Hole-flanging of 2205 Dual-Phase Steel using Incremental Forming Process

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Abstract: In this study, hole-flanging of a dual-phase steel sheet is conducted using incremental forming approach. In this process, a hole with a certain diameter is pre-cut on a sheet. Then, this hole is transformed into a cylindrical flange shapes, by contacting the forming tool with the hole edges. During the process, the tool is moved in spiral paths. The parameters affecting the height and thickness distribution of the formed flange include axial step, radial step, and rotational speed of the tool. Results show that the axial step has the most significant effect on the process, among other parameters; when the axial step is tripled, the flange thickness increases by 19%. On the other hand, a decrease in the radial step decreases the flange edge thickness. When the radial step is tripled, the flange thickness increases by 8%, while the flange height decreases about 3%.

Keywords: Dual-Phase Steel, Hole Flanging, Incremental Forming, Process Parameters

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Research paper

1 INTRODUCTION

Incremental forming process is a sheet metal forming technique, in which a small local area of the sheet is formed at any instant. The idea of incremental forming was first put forward by Edward [1] on the lathe machine. Incremental forming is a flexible sheet forming process that does not require any special punch or die setup; where the movement of the initial sheet is restricted by a simple jig, and the final desired shape is obtained by the relative displacement of a CNC-driven forming tool. Thus, die and equipment cost is greatly reduced in this process, and could therefore be used in batch production and rapid prototyping applications [2]. Also, hole-flanging using incremental forming is a process in which an initial sheet metal with symmetrical or concentric pre-cut holes is clamped on a simple jig, then a cylindrical or conical flange is produced as a result of an incremental displacement of the forming tool; this tool with specified process parameters is in continuous local contact with the hole edge. However, some studies have recently been conducted in order to produce non-circular flanges (e.g., square hole-flanging) using incremental forming approach [3].

So far, extensive research has been carried out on the hole-flanging incremental forming process: Cui et al. [4] investigated the forming force and thickness distribution through this process. They have claimed that the tool with higher diameter and more axial step should be utilized to achieve more flange heights. In another study, Cui and Gao [5] used a multi-stage incremental forming process to produce circular flange shapes. They showed that a more uniform thickness distribution could be obtained by choosing the optimum flange height in each forming stage. Centeno et al. [6] carried out the forming stages at specific angles to construct a vertical flange on the sheet. They also investigated the effect of the initial hole diameter on the sheet formability and flange failure. There are also some studies comparing the flange forming limit in the incremental forming process and conventional forming processes; indicating that the process formability window is placed higher in the incremental process than the conventional press-working [7-8]. Borrego et al. [9] used a cylindrical helical path for the forming tool in single-stage incremental forming process, and showed that tearing could be possibly observed in the flange walls as a result of a biaxial tension mode. Yang et al. [10] used the dieless incremental hole-flanging process to produce branched tubing. Force values and deformation behaviour of the products were evaluated in this study. The results show that an investigation of the pre-cut hole size is a necessary parameter to produce specific branched products. Cristino et al. [11] studied two hole-flanging of two different material categories (i.e. metals and polymers) using single point incremental forming process. They investigated the plastic flow of the materials and the failure mode on the resulted products, especially, when compared with the conventional pressworking. Bambach et al. [12] developed a new method to enhance the formability condition in hole-flanging of sheet metals. This development includes designing blank holder as well as die setup in order to control the sheet deformation and increase the process speed. Cao et al. [13] used a new featured tool for hole-flanging, and a cross section with hyperbolic curvature was considered during the process. Results showed that this new tool is capable to generate greater meridional bending, and hence a more uniform thickness distribution was achieved. Dewang et al. [14] studied the different methods to conduct the hole-flanging of the sheets. Results show that incremental forming process with different strategies would be less complicated and more accurate in hole-flanging, compared to other conventional forming approaches. Hussain et al. [15] investigated the hole-flanging of aluminum sheets in the single point incremental forming process. Results show that the initial hole diameter is significantly effective on the stress/strain distribution on the flange wall. As well, an increase in the hole size leads to an increase in the flange thickness. Martínez-Donaire et al. [16] analyzed the effects of stress triaxiality on the formability of the sheet during single-stage incremental forming. The results then were compared with conventional Nakajima tests. On the other hand, the use of dual-phase steel alloys in various industries (especially in the automotive industry) has been considered due to its high strength to weight ratio [17]. These alloys have a very hard martensitic phase that is dispersed in a ferrite matrix as martensite islands. The percentage of martensite phase affects the strength of dual-phase steel and varies from 5% to 20% [18]. Wen et al. [19] performed a dieless incremental flanging process using a special shaped tool. Their results show that implementing a forward/backward flanging could compensate the conventional dies. Despite extensive research about the forming of dual-phase steel sheets by various forming techniques, there are limited investigations on the forming of these alloy sheets by the incremental forming process; In fact, the high strength of dual-phase sheets would increase the forming force and requires high rigidity levels of the forming tool. In this regard, Bastos et al. [20] investigated the amount of applied force to the forming tool and the surface roughness of the dual-phase steel products formed during the process. As well, the effects of wide ranges of tool velocities (i.e. 1500 to 12000 mm/min) were evaluated on the products.

As is stated in the literature review, there are very limited studies on the forming of dual-phase sheets. In this manuscript, a spiral path is used to perform the hole-flanging of 2205 dual-phase steel sheets in the incremental forming process. The scope of this study is to determine the influences of all effective forming parameters, including axial step, radial step and rotational speed of tool on the height and thickness distribution of the formed flange, which is not presented in this process and material. In this regard, finite element simulations have been performed, and the numerical results are compared with the experimental results; which shows a very good accordance of the extended numerical model. It is shown that axial step is more effective on the flange height and thickness distribution, compared to other parameters. Also, tool rotational speed has the least effect on the height of the flange.

2 EXPERIMENTAL PROCEDURE

The initial thickness of the 2205 dual-phase steel sheet is 2 mm, which was cut in 100 × 100 [mm] to be used in the incremental forming process. The column drill BT-BD 401 was used to make the pre-cut hole in the centre of the sheet, with a diameter of 30 mm. However, in order to improve the drilling performance and reach the final hole diameter, 5, 10, 20, 30 mm drills with a drilling speed of 300 rpm were used, respectively. The forming tool is 20 mm in diameter and 100 mm is its height ("Fig. 1"); a cylindrical DF2 tool steel punch with hemispherical head.

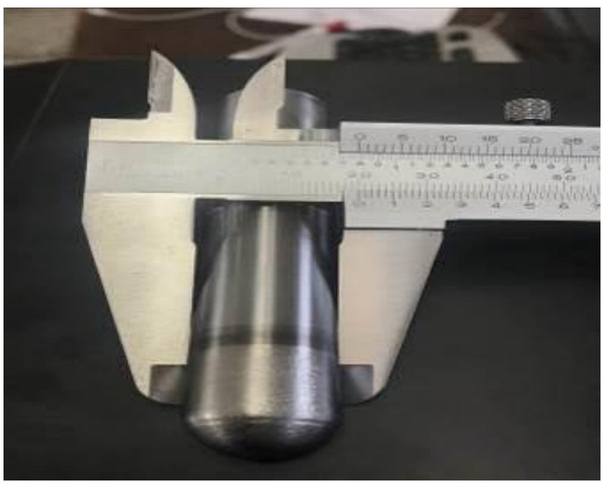

Fig. 1 Hemispherical head tool with the diameter of 20 mm.

The initial hardness number of tool steel was about 15 HRC, which after plating operation was augmented to 52 HRC. CNC milling machine, model FP4ME, was used to implement the specified programmed parameters and tool movement in the defined path. The geometry of the desired path is circular, named radial step (i.e. corresponding to the x-y sheet plane). The tool also has an incremental step along the z axis (i.e. parallel to the direction of hole axis), named axial step ("Fig. 2").

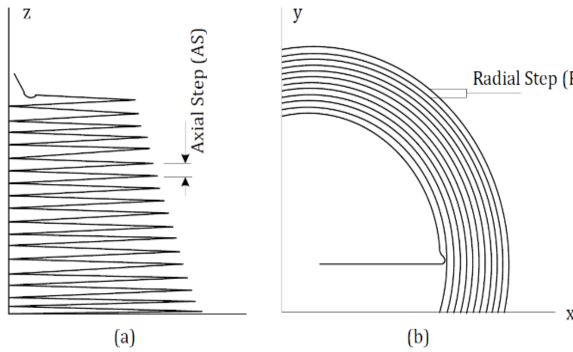

Fig. 2 Geometry of tool path: (a): axial step, and (b): radial step.

The tool path was specified by Mastercam software (CAD/CAM software applications) and the required G-codes were extracted there, then imported to CIMCO software. Finally, a needle type micrometer with the accuracy of 0.001 mm was used to measure the thickness of the product.
Whereas an augmented thermal stress and frictional force is created between contact faces of the workpiece and forming tool, the machine-tool lubrication oil is utilized to improve the friction condition and control the process temperature. Also, a jig is designed to clamp the sheet during the process, as shown in "Fig. 3(a)". A blank holder is mounted on the top layer of the sheet and clamps it by using four screws. Since the final diameter of the flange is 50 mm, the inner jig hole diameter of 60 mm is intended to avoid the flange walls being in contact with it. An image of a product with a formed circular flange is illustrated in "Fig. 3(b)". As well, a dial gauge indicator with an accuracy of 0.01 mm is used to measure the flange wall thickness distribution.

(a) (b)

Fig. 3 (a): Sheet clamped in the jig, and (b): Final hole-flanging product.

3 NUMERICAL APPROACH

Equations are centred and numbered consecutively, with equation numbers in parentheses flush right. Numerical simulation of the incremental forming process was carried out in the finite element Abaqus package. The sheet is modelled as a shell and the tool as a rigid part, the tool path is defined as a cylindrical helical path, shown in the previous section. Coefficient of friction between the tool face and the sheet is also assumed to be 0.1. The sheet is fully clamped and has no degree of freedom (i.e. the outer edges of the sheet is assumed to be cantilevered). The steel material properties are defined as listed in "Table 1". Stress-strain curve of the material was obtained according to ASTM E8 tension test under uniaxial tensile stresses at a strain rate of 0.01 S-1 at 30°C ("Fig. 4").

Table 1 Mechanical and geometrical properties of the modelled sheet [21]

Parameter	Magnitude
Density	7800 kg/m3
Elastic modulus	200 GPa
Poisson's ratio	0.3
Yield stress	218 MPa
Ultimate tensile stress	521 MPa
Length	100 mm
Width	100 mm
Thickness	2 mm

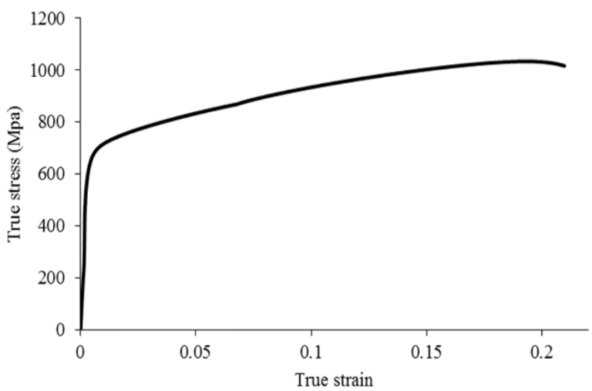

Fig. 4 True stress-strain of the sheet material.

Dynamic Explicit method was used to solve the dynamic problem of the process. The whole time process is equal to 1297 sec. The interaction between the faces was defined as mechanical tangential behaviour by consideration of Coulomb's law of friction. A partition face was considered on the sheet in order to achieve a uniform and symmetrical mesh layout. The global size of 2 mm and 4-node general-purpose shell S4RT element type were utilized for meshing the sheet metal. Furthermore, the rigid element type of R3D3 with a global size of 1 mm in radial direction and 3 mm in axial direction was assigned to the rigid tool model. The finite element model of the process is shown in "Fig. 5". The final shape of the hole-flanging product is also shown in "Fig. 6".

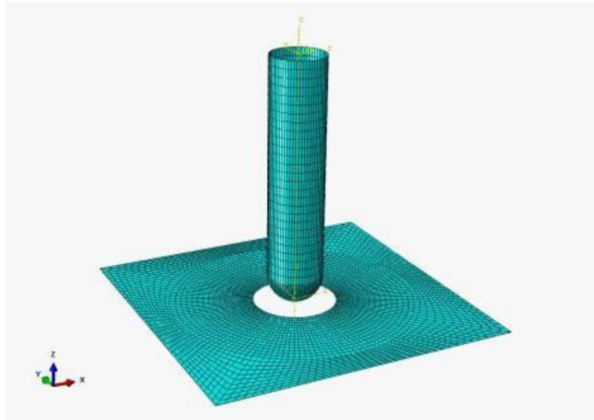

Fig. 5 Final element model of the process.

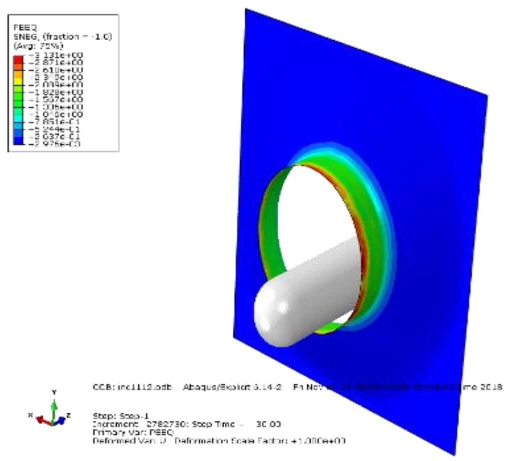

Fig. 6 Hole-flanging of the sheet.

4 RESULTS AND DISCUSSION

In order to determine the effect of the process parameters on the sheet deformation, various simulations were performed with different input parameters, which are listed in "Table 2". It is worth mentioning that the responses here are flange height and thickness of the flange wall.

Table 2 The range of input parameters

Parameter	Radial step [mm]	Axial step [mm]	Rotational speed [rpm]
Values	0.15	0.5	50
	0.3	1	75
	0.45	1.5	100

4.1. Effects of Radial Step on the Product

To investigate the effect of radial step on the thickness and height of the flange, all input parameters are assumed to be constant in their center point and the radial step varies from 0.15 to 0.45 mm. In this regard, "Table 3" lists the effect of radial step on thickness and height of the flange.

Table 3 Flange height and thickness with respect to different radial step

Radial step [mm]	Flange height [mm]	Flange edge thickness [mm]
0.15	14.39	1.25
0.3	14.1	1.33
0.45	13.98	1.36

According to the results, the flange height decreased with increasing radial step, however the edge thickness increased. In fact, given the constant volume of the material in the process, it could be expected that an increase in flange height is associated with thinning of the walls. On the other hand, with increasing the radial step, the total forming time decreases. The higher the radial step, the less time required for the tool to reach the edge of the flange, which reduces the contact length between tool and sheet, and hence the less plastic strain on the sheet is observed. The higher radial step also creates a larger elastic strain on the flange walls and increases the springback magnitude. The equivalent plastic strain distribution on the flange wall for three different radial steps is shown in "Fig. 7". As is obvious, increasing the radial step reduces the total plastic strain on the flange wall, particularly at the flange edges. Thus, reducing the radial step from 0.45 to 0.15 mm increases the flange height by the factor of 3%.

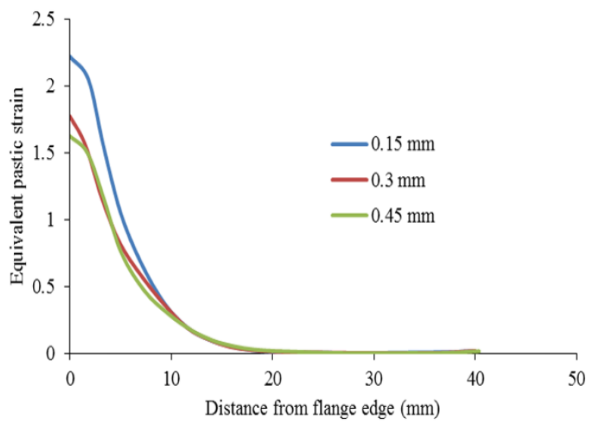

Fig. 7 Equivalent plastic strain as a function of radial step.

4.2. Effects of Axial Step on the Product

Here, all input parameters are set constant in their center point and the axial step varies from 0.5 to 1.5 mm. The effect of different axial steps on the process responses is presented in the "Table 4". In fact, the flange height is decreased with increasing axial step. Hence, the thickness of the flange edge is expected to increase. By changing the axial step from 0.5 to 1.5 mm, the final flange height decreased by about 7%. Increasing the axial step reduces the number of circular path required for the tool to reach the flange edge. That is, the axial distance between the tool path on the flange wall increases, and the total contact face area between the tool and flange wall decreases. Therefore, that region of the wall that has no direct contact with the tool experiences a less plastic deformation. As a result, with the larger axial step, the plastic strain distribution decreases and, the flange height decreases.

Table 4 Flange height and thickness with respect to different axial step

Axial step [mm]	Flange height [mm]	Flange edge thickness [mm]
0.5	14.1	1.33
1	13.48	1.48
1.5	13.11	1.58

4.3. Effects of Tool Rotational Speed on the Product

To investigate the effect of rotational speed of the tool, radial step and axial step are set equal to 0.3 mm and 1 mm, respectively. The effect of three different rotational speeds of 50, 75 and 100 rpm was studied on the product geometry. Figure 8 shows that how the changes of rotational speed affect the thickness of the flange edge. With increasing the tool rotational speed, thinning at the flange edge has increased. As the process goes on, the differences in edge thickness between different velocities are also increased. The effect of tool rotational speed on flange height is shown in the "Table 5", which shows a positive correlation.

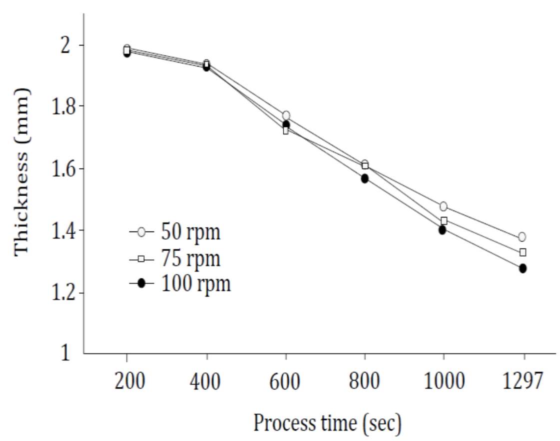

Fig. 8 Flange thickness as a function of tool rotational speed.

Table 5 Flange height with respect to different speeds

Rotational speed [rpm]	Flange height [mm]
50	13.28
75	13.48
100	13.66

4.4. Numerical Results Validation

In order to check the accuracy of finite element simulation results, series of experiment with the same process parameters was conducted. In fact, parameters were radial step of 0.3 mm, axial step of 0.5 mm and rotational speed of 75 rpm, both for numerical and experimental run. Figure 9 indicates specimens produced in experiments and process simulation. According to the results, the flange height of 14.1 mm is measured in the simulation, which is 13.75 mm in the experiment. Also, the thickness distribution of the product is compared in "Fig. 10". The difference between the numerical and experimental curves is due to the different frictional conditions in practice, and assumed homogeneous property of the material in the simulation.

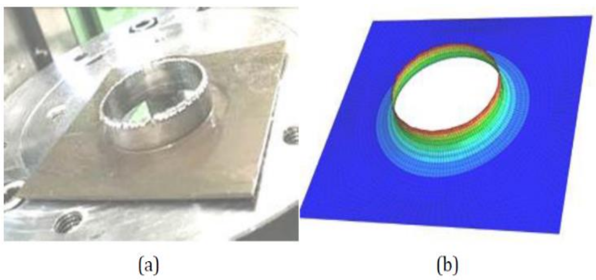

Fig. 9 (a): Hole-flanging product in practice, and (b): the numerical result.

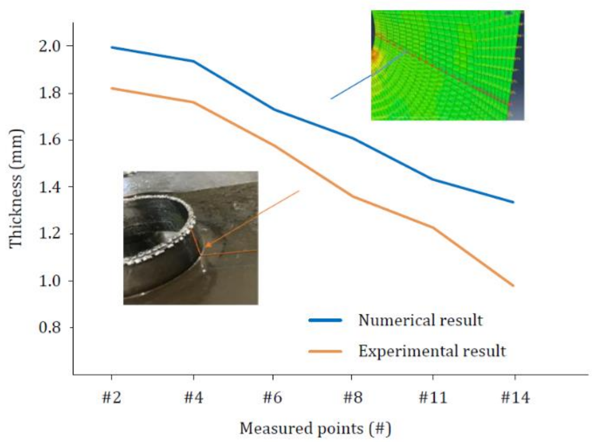

Fig. 10 Flange wall thickness distribution in numerical and experimental results.

5 CONCLUSION

The scope of this study was to determine the influences of all effective forming parameters on the height and thickness distribution of the formed flange, which is not presented in this process and material. Numerical and experimental investigation of hole-flanging of a sheet metal was performed by incremental forming process. In this study, a cylindrical flange was formed in a high strength dual-phase steel sheet as the initial blank; without any mechanical die and on a CNC milling machine. Numerical and experimental results showed good agreement, as well. The effect of three process parameters, including radial step, axial step and tool rotational speed on the edge thickness and flange height was studied. The results show that:

1. Axial step and rotational speed have the highest and least effect on the height of the flange, respectively.

2. A decrease in the radial step decreases the flange edge thickness. When the radial step is tripled, the flange thickness increases by 8%, while the flange height decreases about 3%.

3. Increasing the axial step results in a higher magnitude of springback and decreases the flange height. When the axial step is tripled, the flange thickness increases by 19% and the flange height decreases about 7%.

4. As the tool rotational speed increases, the thickness decreases and the flange edge experiences higher degrees of thinning. However, the flange height increases.

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