Insights on Force Trends and Geometrical Discrepancies in Single Point Incremental Bending Process

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Abstract

Sheet metal or monolithic thin structure components with complex geometries are used in wide range of applications in aerospace, marine and automobile sectors. Fabrication of such sheet metals with complicated geometries and profiles generally requires complex manufacturing setup (dies, jigs and punches) resulting in process inflexibility, in addition to large tooling, equipment costs. In the present work, a novel process 'single point incremental bending (SPIB)' is proposed, employing the tooling and equipment already in practice. SPIB is a die less forming process where a solid hemispherical shaped single point tool is used to deform the thin structure to a desired shape incrementally using a computer numeric controlled setup. In this process the thin structure or sheet metal is deformed locally into plastic stage, enabling creation of complex shapes according to the generated tool path. An experimental and numerical (finite element) study on the bending force trends in single point incremental sheet metal bending has been presented. In addition, different types of geometrical discrepancies associated with the process have also been discussed. In the present work, sheet metals with variety of complicated geometries which have been fabricated are also presented.

Keywords: Manufacturing, sheet metal, bending, flexibility, rapid prototyping, computer numeric control (CNC).

1. INTRODUCTION

Fabrication of thin components complicated geometries and profiles at reasonable manufacturing cost without compromising with the quality is a huge challenge for the researchers and engineers. Generalized and conventional approach for the fabrication of such components include (i) designing freeform components; (ii) fabrication of component specific individual die and punch set; (iii) fabrication of individual components. Moreover, employing conventional manufacturing techniques and approaches for such applications result in process inflexibility, in addition to large tooling, equipment costs.

Sheet metal bending process and its various aspects using conventional press brakes and dies has been well established by Gupta *et al*. [1] and Duhovnik *et al*. [2] in the past. Use of computer aided techniques such as in-process measuring methods by Finckenstein *et al*. [3], adaptive techniques by Serruys [4], sequencing of the operation by Duflou *et al*. [5], modeling and part classification in the process by Greiger and Greska [6] and introduction to robot assisted press brake bending by Stamp and Earl [7] have greatly enhanced the flexibility, quality and productivity of the conventional sheet metal bending process. Incremental bending, introduced by Jin *et al*. [8] and Kuboki *et al*. [9], is a recent addition to the sheet metal processing, further enhancing the process accuracy through spring back control and significantly improving process bendability. But, these improvements are only limited to the inflexible, part oriented conventional sheet metal bending process using dedicated impression dies and presses.

Introduction of computer aided and control manufacturing has been instrumental in development of incremental forming process, where the sheet metal geometry is formed incrementally with localized deformation in accordance with the tool path movement as introduced by Matsubara [10] and described by Hagen and Jeswiet [11] and Jeswiet *et al*. [12] in the literature. Therefore, this provides an opportunity to explore the same in conventional sheet metal bending, making it more flexible through a tool path controlled incremental bending employing simpler tooling on widely used and accepted machining centers or certain robotic platforms.

Single point incremental bending process (SPIB) is introduced as a novel, flexible and cost effective solution for generation of complex shapes and profiles of desired shapes, sizes and orientations on the sheet metal components. Single point incremental bending is a die-less forming processes where a solid hemispherical shaped single point tool is used to bend a thin structure or sheet metal to a desired shape incrementally according to a given tool path on a commonly employed 3 axis computer numeric controlled (CNC) machine or a robotic setup. Figure 1 shows the schematic of single point incremental bending depicting its dimensional attributes and major process parameters viz. a) sheet thickness (t); b) exposed sheet area to be bent ($h \times l$); c) maximum bent angle (α); d) incremental bent angle in each pass ($\Delta\alpha$) resulting from tool movement in Δx and Δz Cartesian directions; e) bending feed rates (f_b) in Y Cartesian direction; and f) tool diameter (d).

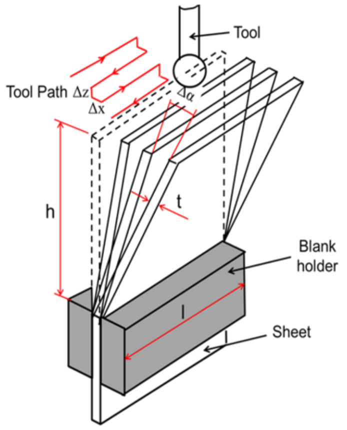

Fig. 1. Schematic of single point incremental bending

Flexible tool path controlled incremental bending process was introduced by Smith et al. [13] in the process called "Deformation Machining" in conjunction with thin structure machining. The work presented was primarily "in line" bending i.e. parallel bending with equal amount of increments in each pass. Later on, Agrawal et al. [14] compared the dimensional repeatability and fatigue life of incrementally bent in line sheet metal components with conventionally bent sheet metal components. Singh and Agrawal [15] compared the magnitude of bending forces, induced residual stresses and spring back of incrementally bent in line components with conventionally bent corresponding sheet metal components.

In the present work, an experimental and numerical (finite element) study on the bending force trends in single point in line incremental sheet metal bending have been presented and discussed. In addition, different types of geometrical discrepancies associated with the process have also been discussed schematically. Finally, sheet metals with variety of complicated (not in line) geometries which have been fabricated using the process are also presented.

2. METHODOLOGY

2.1. Experimental Methodology

Experiments pertaining to force trends in incremental in line bending have been carried out on a 3 axis CNC vertical milling machine (Make: BFW, Model: VF 30 CNC VS). The sheet metal components were clamped on Kistler 9257B six-component force dynamometer, a table type force sensor, which was mounted on the machine table (fig.2). Sheet metal components with variety of complicated (not in line) geometries have been fabricated employing a specially designed and fabricated fixture capable of holding sheet metal of varied dimensions and at varied orientations (fig. 3).

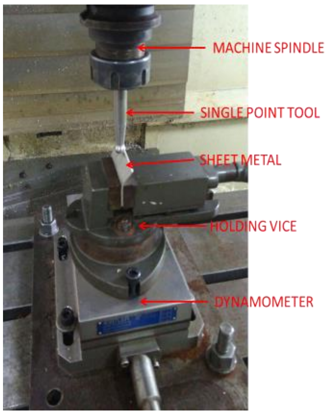

Fig. 2. Experimental setup for the force measurement

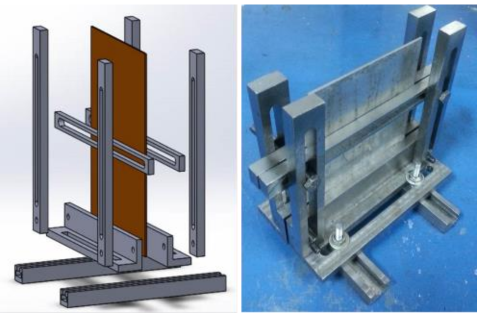

Fig. 3. Sheet metal holding fixture

2.2. Numerical simulations

Incremental bending process has been simulated for bending forces induced using Abaqus 6.14, a commercial finite element based software.

Part and material model: The material considered for the sheet metal to be bent was AA 6063 T6 and the material model used in FE simulations was Johnson–Cook elasto-plastic model. The dimensions of sheet metal and process parameters considered in the experiments and corresponding simulations have been given in table 1.

Table 1. Process parameters and dimensional attributes employed

Process Parameters	Value
Spindle RPM	50
Feed Rate (m/min)	0.1
Tool Diameter 'd' (mm)	10
Incremental Bending angle '$\Delta\alpha$' (°)	5
Maximum Bent angle 'α' (°)	75
Bent Wall Thickness 't' (mm)	1
Bent Wall Height to length ratio 'h/l'	0.4

Interactions and contact properties: Interaction between single point tool and sheet metal was considered to be tangential. The frictional formulation is in the form of a penalty with sliding frictional coefficient between tool-workpiece taken 0.3.

Mesh control: Solid hexahedral elements with global size of 0.5 mm were used for the workpiece in the process simulations.

Boundary conditions and degrees of freedom: Sheet metal end at the bottom was fixed in all three directions (encastred) in incremental bending. Rotational and translational degree of freedom was provided to the tool for corresponding tool path generated determining the extent of bending (fig.4a). Incremental bending simulation and tool retraction step was done in dynamic explicit module.

Output fields: The force evaluations were done by obtaining the reaction forces at a preset reference node on the tool (fig. 4b).

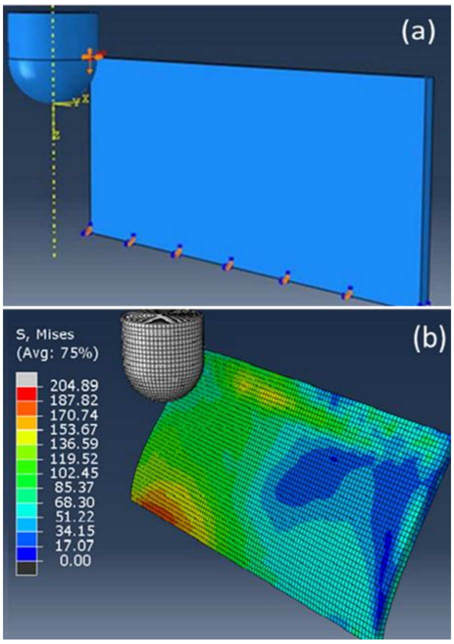

Fig. 4(a) Boundary conditions in incremental bending; 4(b) Output field in the process simulations

3. RESULTS

3.1. Bending force trends

Figure 5 depicts three force components in Cartesian system during incremental bending of the sheet metal bent up to angle of 75°. A crest and trough is noticed with each increment for all three force components, depending upon stiffness of the thin structure relative to the single point tool movement along the length (*l*).The trends from the figure show that the maximum deforming force acts in X-direction (perpendicular to the axis of tool). Forces in Z-direction also increase with the increment but the magnitude is less in comparison to F_X. At bending angle 45° the magnitude of F_X and F_Z is almost the same. Bending beyond 45°, F_Z is the major contributor in the bending forces (along the axis of tool), as F_X starts decreasing. The magnitude of F_Y is negligible in comparison to F_X and F_Z components and increases with each incremental angle depending upon the friction between the rotating tool and the wall surface. The force trends and magnitude obtained from numerical modelling using the finite element approach have been quite similar to the experimental one, simulating the same process parameters (Fig. 6).

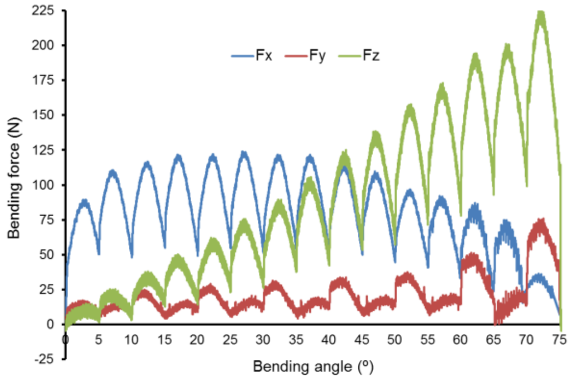

Fig. 5 Experimental trends of three force components in incremental bending (F_X, F_Y and F_Z)

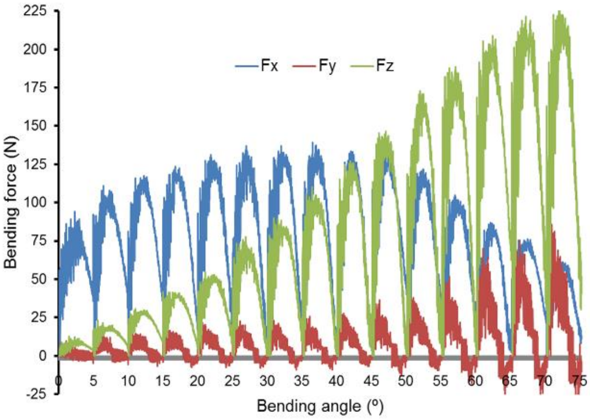

Fig. 6 Numerical simulation trends of three force components in incremental bending (F_X, F_Y and F_Z)

3.2. Geometrical discrepancies in incremental bending

Elastic springback

The schematic shows the effect of elastic springback in incremental bending (Fig. 7). The absolute average springback is calculated by measuring the angle of inclination of the actual bent structure (α) in comparison with the target (ideal) inclination angle (α^*).

Elastic springback (°) = α^*- α

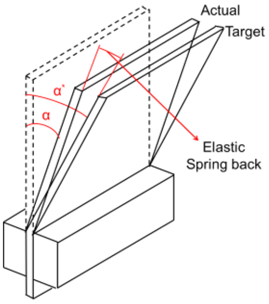

Fig. 7 Schematic showing the elastic springback

Geometrical error due to curvature at fixed end

Figure 8 depicts the schematic showing the effect of curvature at the fixed end on the actual angle of inclination of the bent section. This phenomenon is due to the moment curvature concept of the beam theory. From the figure it is evident that actual angle of inclination α_2 is greater than then the desired bent angle α_1 resulting in dimensional inaccuracy. The error in bent angle is calculated by measuring both the angles.

Error in bent angle = $\alpha_2 - \alpha_1$

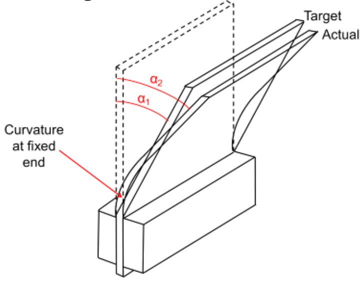

Fig. 8 Schematic showing the effect of curvature at the fixed end

Inclination of bent structure along the length

Figure 9 depicts the schematic showing the effect of inclination along the length at free end of the thin bent structure. The thin structure has maximum stiffness at the centre across the length and least at the ends. Therefore the amount of deflection at the centre is less as compared to at the edge across the length. Moving tool retraction and contact along the length in incremental bending also play a significant role in increased deflection at the edges. This results in inclination of angle 'θ' along the length at the free end of the bent structure.

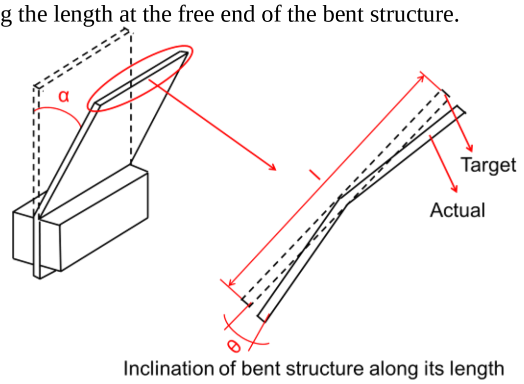

Fig. 9 Schematic showing the effect of inclination at free end

Put together, these three attributes have significant effect on overall dimensional accuracy of the bent sheet metal in incremental bending process. Process flexibility allows for the compensation of these errors by modifying the bending tool path, in order to achieve the desired free form components. Figure 10 shows the same sheet metal component bent without and with error compensation respectively. Figure 11 shows sheet metal components with complicated geometries fabricated by non-inline incremental bending process. In this, the amount of increment in each pass is varying with respect to the length of the travelled tool path.

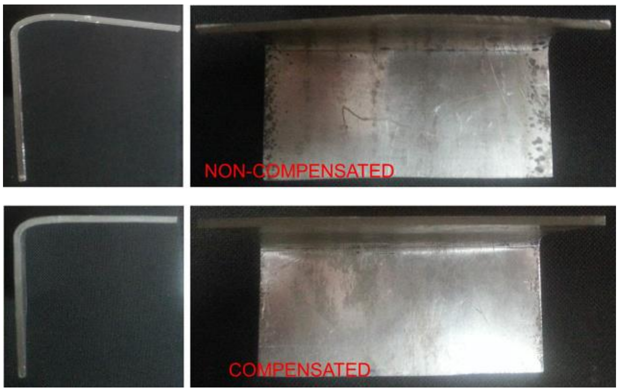

Fig. 10 Uncompensated and compensated sheet metal incremental bending

Fig. 11 Sheet metal components with complex geometries

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