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A REVIEW ON INCREMENTAL SHEET METAL FORMING

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Abstract

Incremental sheet forming (ISF) has gained significant attention from researchers due to its better formability, die less process, cost-effectiveness, and adaptability for low-volume production and prototyping. Unlike conventional forming methods, ISF offers greater flexibility and does not require costly dies. This paper provides an extensive review of the developments in incremental forming, highlighting key progressions, current challenges, and the influence of various process parameters like wall angle, step depth, spindle speed on sheet forming process. The study aims to aid engineers and industry professionals in understanding the capabilities and limitations of ISF, thereby promoting its application in commercial manufacturing.

Keywords: Incremental sheet forming, CNC Machine, Hemispherical ended tool, Process Parameter.

1. INTRODUCTION

Conventional sheet metal forming methods like stamping, stretch forming etc. requires dedicated tooling's specific to the sheet metal component being formed and hence are suitable only for mass production. For a single piece or small batch production, these processes are costly to implement. Incremental Sheet Forming (ISF) process overcomes this limitation and can be used for single or batch (prototype) production. The credit for developing the process goes to Leszek who was awarded a patent on ‘‘Apparatus and process for incremental die less forming’’ in 1967.[1] The ISF process uses a simple hemispherical ended tool to locally deform the sheet metal as shown in Figure 1. Sheet metal blank is firmly clamped in-between the backing plate and the blank holding plate. Sheet metal blank is formed into any complex shape by moving the tool in a defined tool path controlled by NC Part Program using CNC machines. The process is suffering from the limitations like long processing time, poor geometrical accuracy, not suitable for mass production, and difficult to produce the true cylindrical shape.

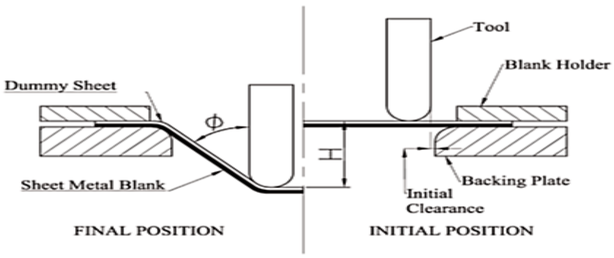

Figure 1 Schematic representation of the ISF process

The present paper represents the development in incremental sheet metal forming and its effect on its process parameters to increase the productivity.

2. TYPES OF THE ISF PROCESS:

Over a period of 20 years, different ISF processes and variants have been developed. Based on the direction of forming, the ISF process can be classified as negative forming and positive forming ISF process in negative forming, sheet metal component is formed from a larger base to the smaller base Whereas in positive forming sheet metal component is formed from a smaller base to the larger base by moving the fixture along the guidepost. If a single tool with no die support is used in the case of negative forming, the process is known as die less forming or Single Point Incremental forming (SPIF) If a single tool with female full die as shown in is used in negative forming the process is referred as two-point incremental forming (TPIF). Negative forming can also be achieved by providing coordinated motion to two tools (forming tool and counter tool to support the sheet metal blank) each operated by separate robots or custom-made machine When two tools are operated using different robots the process is called rob forming which facilitates in preparing undercuts. In the positive forming male support in the form of partial. or full die is used. In two point incremental forming the formability is better as the mode of deformation is only plane strain. Whereas in SPIF process along with plane strain biaxial mode of deformation is also present. ISF process can also be classified as symmetric incremental sheet forming (SISF) and asymmetric incremental sheet forming (AISF) process. Symmetric components are mainly produced by spinning process; however, they can also be formed by ISF process. Asymmetric components are mainly

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produced by AISF process which is generally referred to as ISF process. Moreover, in a heat-assisted ISF processes additional energy source (laser beam, electric heat, heat blower, friction-stir, and ultrasonic vibration) is used to generate localized heat which softens the material and in turn improves formability of difficult to form materials

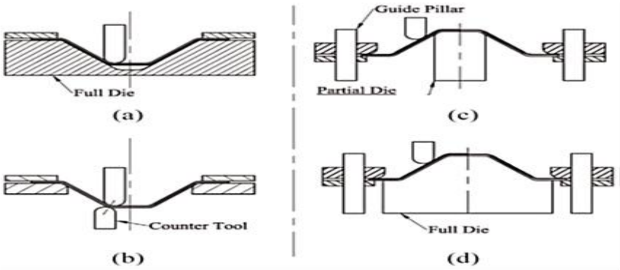

Figure 2 TPIF process (a) Negative forming with full die (b)Negative forming with double tool (c) Positive forming with partial die (d) Positive forming with full die

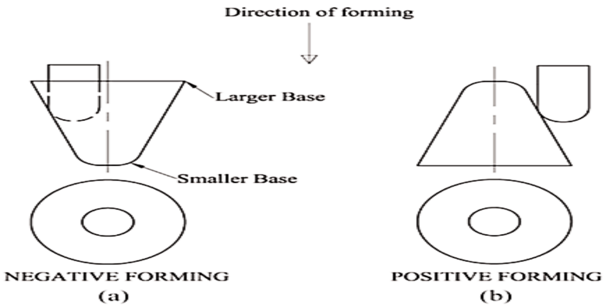

Figure 3 Negative and Positive ISF processes

3. ELEMENTS OF ISF

The parameters influencing the performance of the ISF process have been studied and classified as main elements of the ISF process as. They have been discussed in detail in the following sections.

Type of Equipment

Equipment in the ISF process provide power to move the tool along the required tool path. Researchers have used Vertical Machining Center,91,109 Horizontal Machining Centre, Single robot, Dual robots' custom made ISF machine100,143 and commercial ISF machine to carry out experiments. Machining centers are general purpose machines and can be used for variety of shapes. Though, robots provide flexibility in operation, they are not suitable where high forces are involved, high accuracy is desired and shapes with undercuts are to be formed. Commercial machines can provide high forces and can produce components with better geometric accuracy. First prototype machine dedicated to the ISF process was developed by AMINO corporation in 1996. These motors often do not use many poles in the rotor. As a result, their performance reduces at lower speeds. [9].

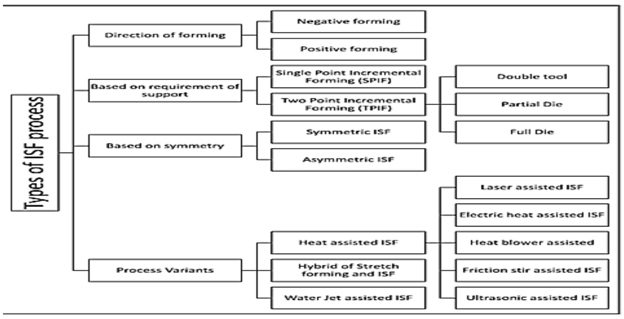

Figure 4 Types of ISF processes

4. PROCESS PARAMETERS

Forming feed. Study of the ISF process with feed rate ranging from 26.6790 to 889078mm/min has been reported in the literature. Feed rate in the ISF process affects the time of forming and in-turn energy consumption. Chezhian Babu & Senthil Kumar reported an improvement in formability at lower feed rates but with a corresponding increase in the forming time. However, Fan et al. reported adverse effect of too low (sheet metal burns) or tool high feed rate on formability of sheet metal in electric heat-assisted ISF process. Higher feed rates can be employed in friction stir assisted ISF process as compared to electric heat assisted ISF process. This contradiction suggests that forming feed is having interaction effect with other process parameters and requires to be optimized for the process under consideration. Feed rate of 100mm/ min31 and 2000mm/min167 was found successful in water jet-assisted and ultrasonic-assisted incremental forming respectively. Spindle speed. ISF process can be carried out without giving rotation to the tool or with the rotation of the tool (016,77,94,95,106,144,156,160,162 to 10000127 rpm). To have a minimum friction pure rolling condition should be set by choosing appropriate spindle speed and feed for a given tool diameter.12,16,22,137 It is observed that as the rotational speed increases the formability increases. Step-depth. Similar to rapid prototyping, in which material is added layer by layer, in ISF process also components are formed layer by layer. Distance between two successive layers is step-depth which impacts the formability and surface finish. Step-depth can be kept constant or can be variable. Researchers have studied the ISF process with step-depth in the range of 0.19 to 114mm. Increase in formability is found with an increase in step-depth while working with PLA and PVC plastic materials.159 However, formability of metals found to be decreased with the increase in step-depth20,175 or marginal effect147 of step-depth on formability. Tool path. Tool path is the trajectory along which the tool traverses to give the desired shape to the sheet metal blank. The geometry of the formed component strongly depends on the type of the tool path (Figure 5) selected. Tool path can be classified as Constant step-depth, Variable step-depth, and Helical tool path (Figure 5(b)). Constant step-depth tool path (Figure 5(a)) has been widely used by the researchers. Variable step-depth tool path results in better Figure 5. Elements of the ISF process. 4 Proc IMechE Part B: J Engineering Manufacture 00(0) formability when the slope of the component gradually decreases towards the bottom (Figure 5(c)). In such components, tool path is generated30 using constant scallop height concept to have more contours at bottom. However, scallop height is the concept of machining and more appropriate term to use is step-in (SI) for SPIF or step-out for TPIF as shown by the line 1 to 2 in Figure 5(a). By maintaining a constant step-in value, the generated tool path gives more contours at the bottom as shown in Figure 5(d) which improves the geometric accuracy. While taking the step-in motion tool leaves the contact and allows the component to spring back. However, in an experimental study Matsubara6 used a movement of the tool along an inclined line (1–7) which helps continuous contact between the tool and sheet. Tool path should be designed in such a way that the forming starts from the lower stiff area (Dai et al.3). Forming near the stiff areas (i.e., near clamped periphery) leads to splitting along the boundary. Tool path can also be classified as a single-stage and multi-stage tool path. Multi-stage tool path reduces successive thinning (Young and Jesweit18) and hence improves the formability. Multi-stage tool path facilitates the tool entry at lower angle which shifts the deformation mode from near plane strain to bi-axial strain. Tool path can also be classified as a uni-directional 75 or bi-directional tool path. The part twists about its axis under the influence of the uni-directional forming forces involved when the uni-directional tool path6 is used. Bi-directional tool path prevents twisting of the component in which direction of the tool movement reverses after each loop.

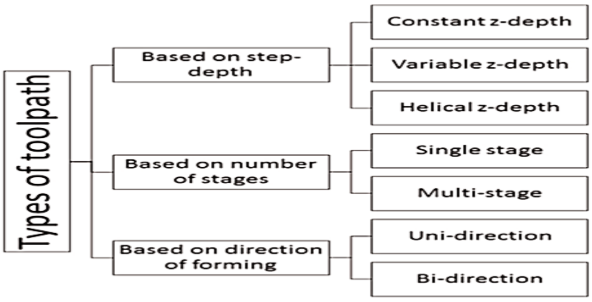

Figure 5 Types of toolpaths

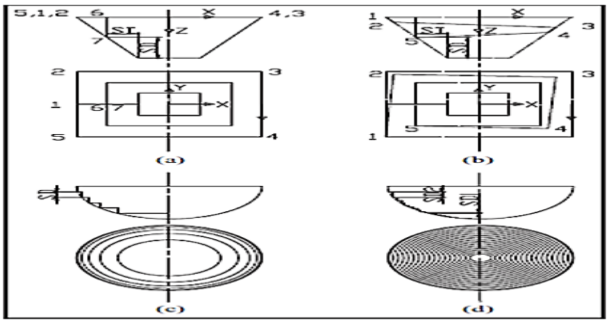

Figure 5 Tool path (a) Constant step-depth (b) Helical (c) Variable step-depth (d) constant step-in

5. PERFORMANCE PARAMETERS

Depth of forming depth (depth at which fracture occurs) achieved in the ISF process depends on input parameters like tool type and size, tool path, speed of forming, and process types. The ORB tool145 has a positive effect and laser surface textured tool118 has a negative effect on the forming depth. Helical tool path as compared to constant Z-depth tool path forms the component to the full depth. Ebrahimzadeh et al. have reported a higher formability (Forming height of cone) in TPIF process as compared to SPIF process while working on AA5083 friction stir welded blank. Forming depth can also be improved using TPIF process with two tools along with the superimposed pressure,87 laser-assisted ISF process, and Ultrasonic vibration-assisted ISF process.

Maximum draw angle Draw angle (ϕ) is used as a forming limit indicator in various research work and summarized. Maximum draw angle for square pyramid and cone has been found to be 63 and 66 while working with Aluminium alloy AA7075 T0 sheet (1mm thick).38 Vertical wall (90) formation could be possible using multi-stage forming strategy.50 Maximum draw angle have been used as a measure of formability while forming a cone with increasing wall angle as with this shape formability limit can be achieved with reduced number of trials. Maximum draw angle can be achieved by selecting a threshold value of tool radius to the blank thickness ratio (r=t0 =2110 to 2.2149). Wall angle at fracture point have been studied by Suresh et al.161 for variable wall angle conical (VWACF) and pyramidal (VWAPF) frustum having circular, elliptic, parabolic and exponential generatrix. Wall angle formed with VWAPF was less than VWACF due to higher hoop strain in corners of VWAPF components. In an analytical study performed based on membrane analysis, Silva et al.41 and Martins et al.52 attributed the formation of circumferential crack as the reason for the limited forming angles. The circumferential crack propagates due to tensile meridional stress. However, in their analytical model, authors have neglected bending moments of deforming shells to simplify the analysis. Formability enhancement can also be attributed to simultaneous bending and stretching effect under tension (BUT)56 deformation mode. This mechanism is based on continuous bending and unbending of strip of sheet due to the action of tool. To check the validity of continuous bending under tension mechanism Emmens et al.60 performed tensile testing in which elongation before fracture was observed of the order of 430% for Mild Steel material. The effect of bending in stabilizing the deformation under the action of tensile load was also established by Hades et al.84 through 2D and 3D FE simulation. Malhotra et al.94 have proposed Noodle theory considering local bending and shear effect. According to this theory local nature of deformation is responsible for earlier material instability. However, being confined to local area it doesn't lead to the fracture. Moreover, in subsequent passes this region takes up additional deformation and maximum strain is increased before fracture. Similar findings were observed by Li et al. based on FE analysis in which major strain was found to be accumulated to a large value during the deformation and minor strain was limited to a small value. The model includes bending, stretching and shearing effect and was validated by experimental work. A material having a particular thickness can be formed to a critical draw angle in a single-stage.155 Beyond this critical value, the multi-stage tool path strategy has to be used. The square pyramid was successfully formed with a wall angle of 81 using multistage. Wall angle can be measured with digital angle finder or by pre or post CAD modelling software of particular cross section.

Hardness and grain size the hardness of the formed component depends on the number of factors. In general hardness of the formed component increases as reported by Amino et al.120 (From a range of HB40-HB50 to HB70-HB80 range). Study performed by Suresh et al.161 shows that hardness of the component was found to be same as of base material (134 HV) in bending region, however, it was found to be increased in wall region (185 HV) and at the tail end (208 HV) of component. This was mainly attributed to grain elongation and strain hardening. Grain size was found to be increased from ASTM6 to ASTM5 number. Elongated grains were also observed at a distance away from the initial position.92 Increasing the tool diameter, feed rate and speed tend to elongate the grain.111 However, reverse phenomena were observed in the case of step-depth. In a study (AA2017-T3)127 performed to learn the effect of rotational speed, hardness was found to be decreased due to an increase in grain size because of heat generation (250_C). In friction-stir assisted ISF process, no change in grain size (65 mm) was observed up to 4000rpm while forming a cone of 45 with AA6082-T6 aluminium alloy.114 However, beyond 4000rpm due to dynamic recrystallization grain size reduces to 20 mm. Hardness was also observed to decrease from 103 HV to about 90 HV beyond 4000 rpm.

6. CONCLUSIONS

Over a period of time significant development have emerged in the equipment front to develop the ISF process. Initially CNC machines were used to perform the ISF process, however, the use of industrial robot either as individual equipment or in sync with other robot has improved the flexibility of the ISF process. Continuous development has also led to the realization of commercial equipment dedicated to the ISF process. To the date only a single manufacturer (AMINO) has developed dedicated ISF machine. Studies134 shows that total power consumption is highest in the AMINO machine as compared to conventional CNC machine and robot. Hence, the development of energy efficient dedicated machine is the need of the day to make the process economically viable for industrial application.

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