Incremental Sheet Forming (ISF)

Yogesh Kumar and Santosh Kumar

Abstract Incremental sheet forming (ISF) process is an advanced flexible manufacturing process to produce complex 3D products. In conventional forming process, the products are produced by dedicated tools, i.e. die and punch. However, ISF does not require any dedicated tool. A laboratory setup of single-point incremental forming machine has been developed using a motion card to control the 3 servo motors for controlling individual 3-axis and spindle movement at IIT (BHU), Varanasi. The strain distribution on the sheet over the length of deformation has been computed. The surface quality of the products is found to be good. Simple simulation has also been carried out.

Keywords Metal forming · Incremental forming · Dieless forming · Deforming tool

1 Introduction

Metal forming is the backbone of modern manufacturing industry besides being a major industry in itself. Throughout the world, hundreds of million tons of metals go through metal forming processes every year. As much as 15–20 % GDP of industrialized nations comes from metal forming industry. Besides, it fulfills a social cause by providing job opportunities to the millions of workers. Metal forming industry, in general, is a bulk producer of semi-finished and finished goods

Y. Kumar (✉) · S. Kumar (✉)
Mechanical Engineering Department, Indian Institute of Technology (BHU),
Varanasi, Uttar Pradesh 221005, India
e-mail: yogeshiitbhu@gmail.com

S. Kumar
e-mail: santoshkr.mec@gmail.com

R.G. Narayanan and U.S. Dixit (eds.), *Advances in Material Forming and Joining*,
Topics in Mining, Metallurgy and Materials Engineering,
DOI 10.1007/978-81-322-2355-9_2

and this is one reason that it is viable to undertake large-scale research and development projects because even a small saving per ton adds up to huge sums (Juneja 2013).

The incremental forming process is originated from stretch forming and metal spinning process. The ISF has been originated with partial hybridization of stretch forming process and metal spinning processes. Thus, ISF process has combined advantages of stretch forming processes and metal spinning process. In the later developments in ISF process, the process is found to be capable of producing 3D complex shapes with multiple features on it.

1.1 Elements of Incremental Forming Process

Incremental forming is a new technique for deforming sheet metals by the application of step-by-step incremental feed to a deforming tool (DT). For the production of parts by conventional sheet forming techniques, dedicated tools are required. The dedicated tools are complex 3D design and thus are expensive. The design of tooling (die and punch) for complicated shapes is very difficult and costly. In incremental forming technique, only a DT is required for deforming the sheet metals. There are four basic elements of an ISF process as shown in Fig. 1—a sheet metal, a blank holder, a single-point forming tool or DT, and CNC machine.

The shape of DT may be hemispherical. The design of DT is quite simple and economical. A CNC controller having capability for controlling individual 3 axes can be used to control the movements of the DT. The tool path needs to be optimized and a free run is taken before performing the actual manufacturing on the sheet metal in order to ensure the proper functioning of the machine.

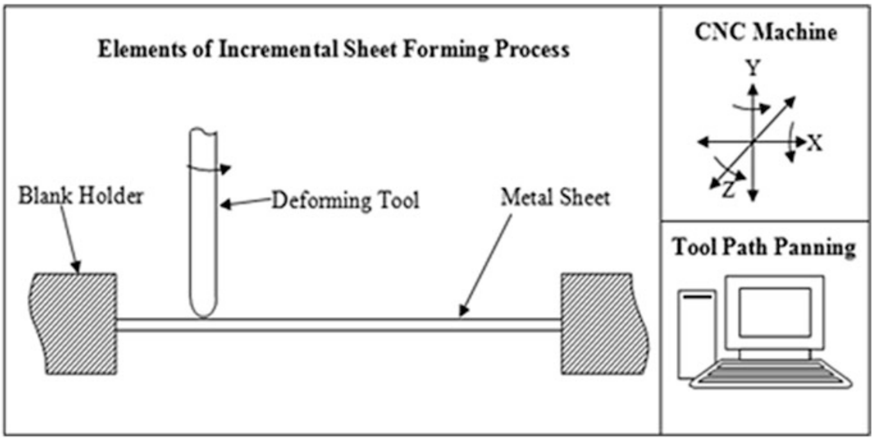


Fig. 1 Basic elements of ISF

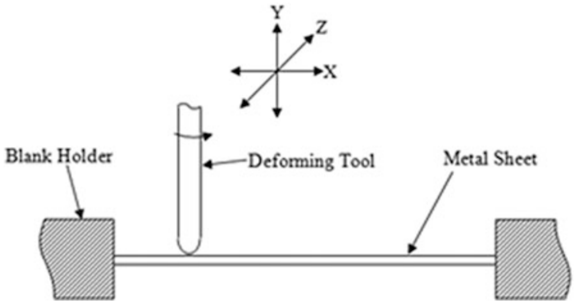


Fig. 2 Single-point incremental forming (SPIF)

1.1.1 Classification of Incremental Sheet Forming

The Incremental forming processes are broadly classified into two categories:

(i) **Conventional Incremental Sheet Forming (CISF)**:
In CISF process, generally a sheet of metal is deformed by progressive and localized plastic deformation using a simple hemispherical/ballpoint tool, and this path of the DT is controlled by a CNC machine. The DT moves over the surface of the sheet and results the final shape. There is no other tool or external pressure applied for deforming the sheets into the desired shape. The conventional incremental forming process can be further classified as follows:

(a) **Single-Point Incremental Forming (SPIF) also known as Negative Dieless Forming**:
In SPIF, only one tool moves over the surface of the sheet as shown in Fig. 2.

(b) **Two-Point Incremental Forming (TPIF) or Positive Dieless Forming**:
In TPIF, two tools, one called DT and another one supporting tool, move over the surface of the sheet as shown in Fig. 3.

(ii) **Hybrid Incremental Sheet Forming (HISF)**:
HISF processes are the modified forms of conventional incremental forming. In these processes, DT moves over the surface of sheet metals, while the another side of surface of sheet metals is supported by pressurized hydraulic fluid, partial die or full die to get the desire shape and size. Hybrid incremental forming processes are further classified as follows:

(a) ***SPIF with Hydraulic Fluid also known as Single-Point Incremental Hydro-Forming***:
In this type of hybrid incremental forming process is different from conventional SPIF process that a single tool moves over one side of the surface of the sheet metals and other side of surface of sheet metals is supported by the pressurized hydraulic fluid as shown in Fig. 4.

(b) ***TPIF with Partial Die***:
In this type of hybrid incremental forming process, a single tool moves over one side of the surface of the sheet metals and other side of surface of sheet metals is supported by a partial die to get the desire impression as shown in Fig. 5.

(c) ***TPIF with Full Die***:
In this type of hybrid incremental forming process, a single tool moves over one side of the surface of the sheet metals and other side of surface of sheet metals is supported by a full die to get the desire shape and size as shown in Fig. 6.

Fig. 3 Two-point incremental forming (TPIF)

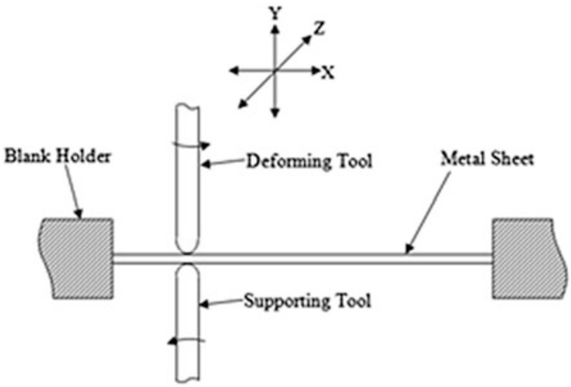
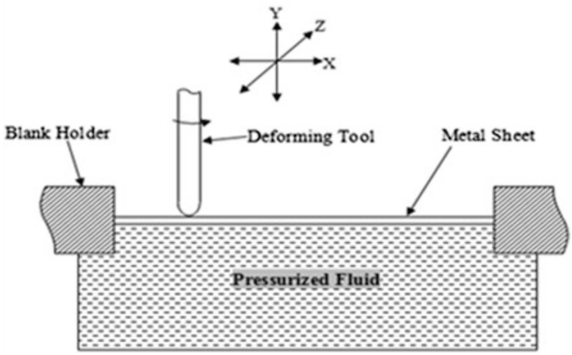


Fig. 4 Single-point incremental hydro-forming (SPIHF)



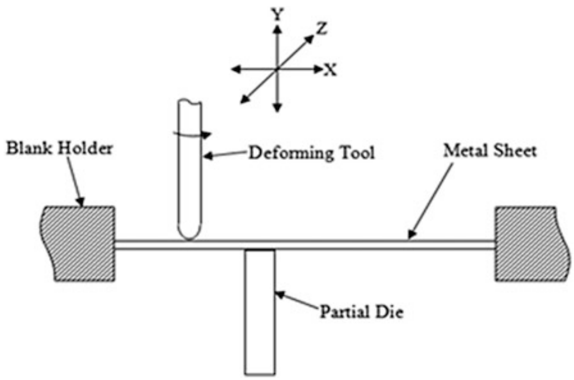


Fig. 5 Two-point incremental forming with partial die (TPIFPD)

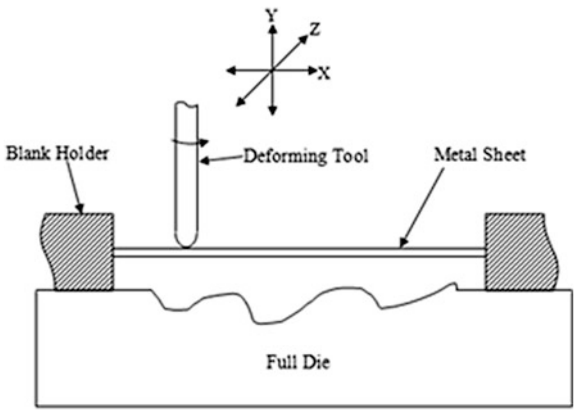


Fig. 6 Two-point incremental forming with full die (TPIFFD)

1.1.2 Advantages and Disadvantages of ISF

The advantages and disadvantages of SPIF are as follows

A. **Advantages**:

- Useable parts can be formed directly from CAD data with a minimum of specialized tooling. These can be either rapid prototypes or small volume production runs.
- The process does not require either positive or negative dies; hence, it is dieless. However, it does need a backing plate to create a clear change of angle at the sheet surface.
- Changes in part design sizes can be easily and quickly accommodated, giving a high degree of flexibility.
- Making metal rapid prototypes is normally difficult, but easy with this process.
- The small plastic zone and incremental nature of the process contribute to increased formability, making it easier to deform low formability sheet.

- A conventional CNC milling machine or lathe can be used for this process.
- The size of the part is limited only by the size of the machine. Forces do not increase because the contact zone and incremental step size remain small.
- The surface finish of the part can be improved.
- The operation is quiet and relatively noise free.

B. **Disadvantages**:

- The major disadvantage is the forming time is much longer than competitive processes such as deep drawing.
- As a result, the process is limited to small-size batch production.
- The forming of right angles cannot be done in one step, but requires a multi-step process.

1.1.3 Applications of ISF

There are a number of areas, where high precision of the products is required for the accuracy of the performance. Areas of products can manufacture by ISF are as follows:

- **Aerospace Industry**: Instrument panel, body panel, passenger seat cover, etc.;
- **Automobile**: Door inner/outer panel, hood panel, engine cover, etc.;
- **High customized products**: Denture plate, ankle support, metal helmet, etc.;
- Cellular phones;
- IC lead frames;
- Electronics;
- Health care;
- Miniature fasteners;
- Hard disk drives;
- Products of national security and defense;
- Automobiles; and
- Sensors.

1.1.4 Basic Terminology in Incremental Sheet Forming

The typical terminology in ISF can be understood from the terminologies used in the incremental sheet hydro-forming (ISHF) as shown in Fig. 7, with notations below:

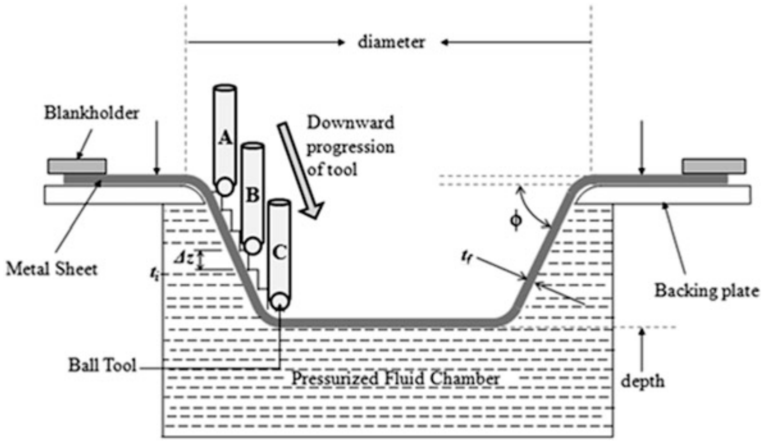


Fig. 7 Basic terminology in deformed part in ISHF

$$t_i = \text{Initial sheet thickness.}$$
$$t_f = \text{Final sheet thickness.}$$
$$\Delta z = \text{Incremental step} - \text{down size.}$$
$$\varphi = \text{Draw angle or forming angle.}$$

The incremental step-down size (step size, Δz) affects the machine time and the surface quality. Feed rate is the speed the forming tool moves around the mill bed. The angle between the un-deformed sheet metal and the deformed sheet metal is defined as forming angle (φ) as shown in Fig. 7. The forming angle can be used as a measure of material formability. The maximum angle ($\varphi_{\max}$) is the greatest angle formed in a shape without any failures. The forming angle is set within CAD software (Ham and Jeswiet 2007).

1.2 Literature Review

Single-point incremental forming (SPIF) is a sheet metal forming process that allows manufacturing components without development of complex tools in comparison with stamping process (Thibaud et al. 2012). ISF process depends strongly on the forming tool path which influences greatly the part geometry and sheet thickness distribution (Azaouzi and Lebaal 2012).

There are several issues that need separate discussion as peoples around the world are trying to optimize the ISF process the governing process parameters. The concerned issues (formability, surface quality, geometric accuracy, forming forces, etc.) are discussed briefly.

Kim and Park (2002) identified that the deformation pattern in ISF is very similar to spinning process and the sheet metals deform by shear-dominant deformation like shear spinning. They also found that the formability is improved when a ball tool of a particular size is used with a small feed rate and a little friction. The formability differs according to the direction of the tool movement because of the plane anisotropy (Kim and Park 2002). Several investigations have been done with emphasis on assessing and improving the formability in this forming method. Kim and Yang proposed the double-forming technique to improve formability, assuming that only shear deformation occurs in the material (Kim and Yang 2000). The ball tool is more effective than the hemispherical head tool in terms of formability. Little friction at the tool and sheet interface helps to improve the formability. Also, the formability increases as the feed rate decreases (Kim and Park 2002).

Filice et al. proposed the two characteristics of deformation in this forming method. One is the deformation pattern. While the tool moves straight on a horizontal plane, the deformation that occurs at the starting and ending points of the straight line is biaxial stretching. The deformation that occurs between these points is plane-strain stretching. As the curvature of the tool movement increases, the deformation turns more into biaxial stretching. The other characteristic is the formability of the deformation. As shown in Fig. 8, the forming limit curve, which depicts the formability in the major and minor strain space, is expressed as a straight line with a negative slope. Especially, for an aluminum sheet, the formability can be quantified as a scalar number of ($\varepsilon_{\text{major}} + \varepsilon_{\text{minor}}$). It is noted that formability is the greatest under plane-strain stretching, during which the minor strain is zero. Therefore, a greater deformation of a sheet metal can be achieved in the ISF (Kim and Park 2002). The ISF is characterized by a local stretching deformation mechanics which determines a forming limit curve quite different from the

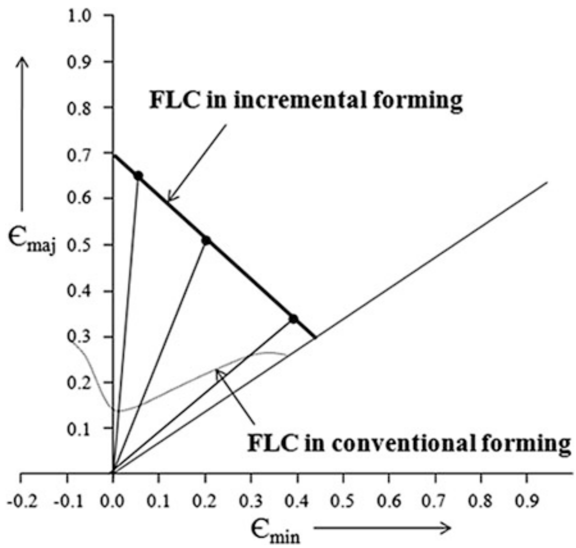


Fig. 8 A comparative plot of FLC in conventional forming and incremental forming

traditional one and such FLC has a linear shape with a negative slope in the positive $\varepsilon_{\mathrm{minor}}$ side of FLD (Filice et al. 2002).

The depth and diameter have no effect the likelihood of forming a part. Also, the material thickness, tool size, and the interaction between material thickness and tool size have a significant effect on maximum forming angle (Ham and Jeswiet 2006). The ball tool is more effective than the hemispherical head tool in terms of formability. The little friction at tool/sheet interface helps to improve the formability. They also found that formability increases with decreasing feed rate (Kim and Park 2002). The formability is enhanced while deforming the metal sheets in warm conditions, and the role of tool diameter is negligible as compared to the influence of temperature and tool depth (Ambrogio et al. 2008). The deformation mechanisms of both SPIF and TPIF are increasing stretching and shear in the radial–axial plane (perpendicular to the tool direction) and shear in the tool direction (Jackson and Allwood 2009). Hussain et al. (2007) found that the formability increases as the radius of curvature decreases. Ham and Jeswiet (2006) formalized the two designs of experiments for the forming parameters critical in SPIF and the degree to which they affect formability.

Ambrigio et al. investigate that in hot ISF, the quality of bottom surface is better as compared to the one in contact with the punch. This is due both the lower temperature reached on the bottom side that reduces oxidation phenomenon and the absence of mechanical actions on the sheet. Anyway because of low sheet thickness, the thermal gradient is very low and this reduces the difference between the two sheet sides (Ambrogio et al. 2012).

Attananio et al. optimized of the tool path in two-point sheet incremental forming, with a full die in a particular asymmetric sheet incremental forming configuration. They carried out the experimental evaluation of the tool path, which is able to reproduce an automotive component with the best dimensional accuracy, the best surface quality, and the lowest sheet thinning (Hussain et al. 2007).

The geometries produced by ISF represent some errors along the oblique walls. In particular, a sort of distortion is also obtained, generating a curvature on the expected straight sides. This phenomenon is due to elastic spring back whose effect is lower in correspondence of the edges, where the geometrical stiffness is higher than in other areas (Cerro et al. 2006; Filice et al. 2002; Ham and Jeswiet 2007). The results obtained in geometric accuracy measurements with the process model, as compared to experimental results obtained by testing in the CNC machine, are approximately same (Cerro et al. 2006). Azaouzi and Lebaal (2012) gave optimal solution provided an improvement of about 7 % regarding the sheet thickness distribution at the maximum forming depth.

Azauzi et al. (2012) found that the forming forces depend largely on the proper design of the tool path. The forming force is slightly lower than the experimental values, but results are very good (Cerro et al. 2006). Forming forces obtained by numerical simulation show good correlation with measured values. However, it was a slight underestimation of the axial forces during thinning. It is assumed the influence of grain size and softening on the material behavior (Thibaud et al. 2012).

Araghi et al. (2009) investigated that the thinning in ISF depends on the wall angle α and is given by the sine law $t_1 = t_0 \sin(90° - \alpha)$. Cerro et al. (2006) investigated that the results obtained in thickness measurements with the process model, in comparison with experimental results obtained by testing in the CNC machine, are approximately same. Increasing stretching and shear perpendicular to the tool direction account for differences between the sine law and measured wall thickness for SPIF and TPIF (Jackson and Allwood 2009). The prediction of thickness distribution is close to that obtained on the real part (Thibaud et al. 2012).

The literature review reveals that ISF method is well investigated, but there are still some issues not well understood in incremental forming like strain distribution on the sheet over the length of deformation, effect of step size, tool size, etc., in ISF.

2 Simulation of Single-Point Incremental Forming Process

In deforming sheets by incremental forming, methodology of deformation plays an important role. The current literature survey in the area of ISF has been kept into consideration in order to adopt a suitable forming methodology. To carry out a dedicated simulation study of the process, a blank holding arrangement for ISF has been prepared as shown in Fig. 9, using DEFORM 3D.

For the successful implementation of ISF, a proper forming methodology has to be followed as shown in Fig. 10. The first step in ISF is to identify need for the components. As soon as the need analysis is done, the geometrical dimensions of the product to be manufactured are decided. Based on geometrical dimensions, a 3D

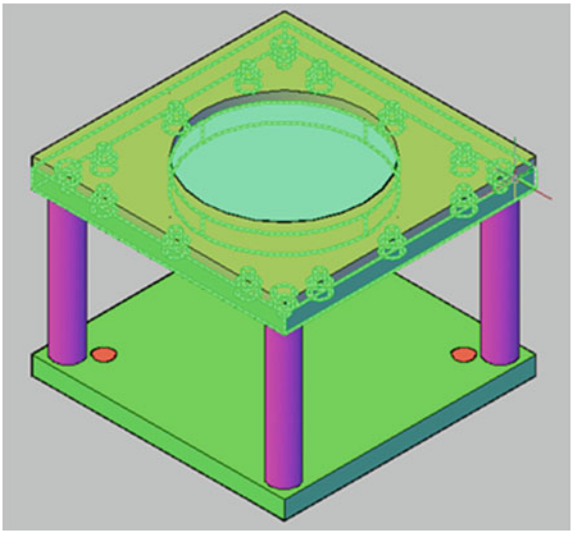


Fig. 9 Blank and blank holding arrangement

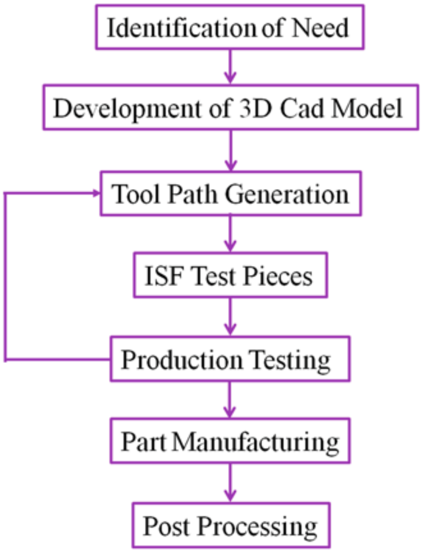


Fig. 10 Forming methodology of 3D components by ISF

CAD model of the product is developed using CAD/CAM package. Moving forward with the help of CAD/CAM package, the tool path, suitable for movement of the tool is generated. In the next step, the workpiece is held in the proper blank holding, and test pieces are produced using the generated tool path. The accuracy of test pieces is tested against the desired profile.

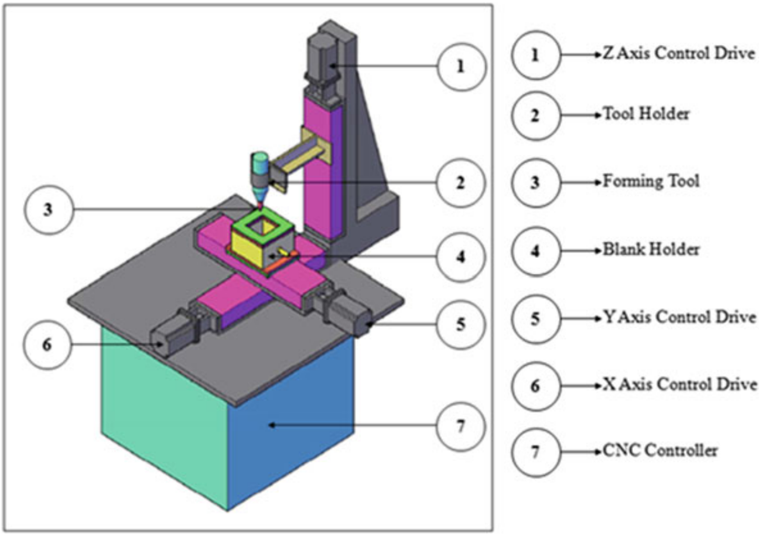


Fig. 11 CAD model of single-point ISF machine

The metals as well as alloys can be used for the implementation of ISF process. For the current investigations, the initial blank of material brass is selected for finding the capabilities of ISF process brass has good formability at room temperature. The sheet having dimensions 80 mm × 80 mm × 5 mm has been used for current case study. A CAD model of the single-point ISF can is represented in Fig. 11.

2.1 Simulation Results

Based on deforming methodology, a product as shown in Fig. 12 is produced using simulation run under ISF process. The stresses are found to be distributed in normal. The experimental results have also validated same. The effective stresses

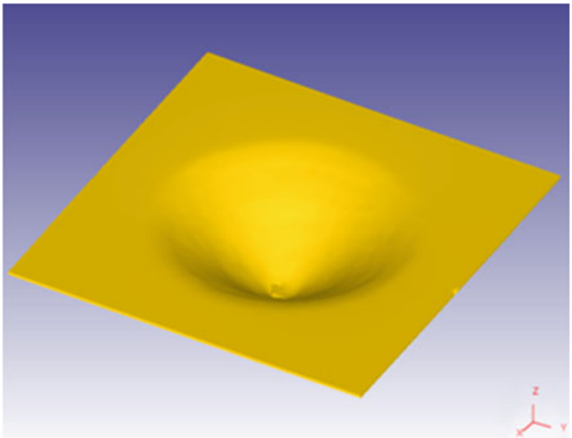


Fig. 12 Defect-free product (wall angle = 30°)

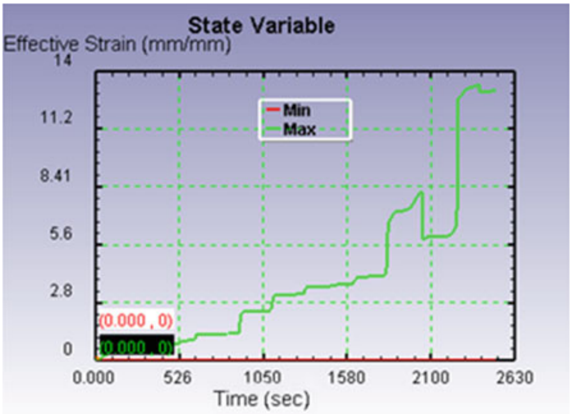


Fig. 13 Variation of effective strain with time

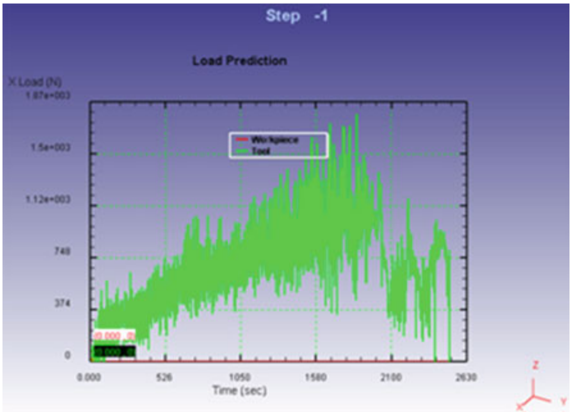


Fig. 14 Force prediction in *X*-direction

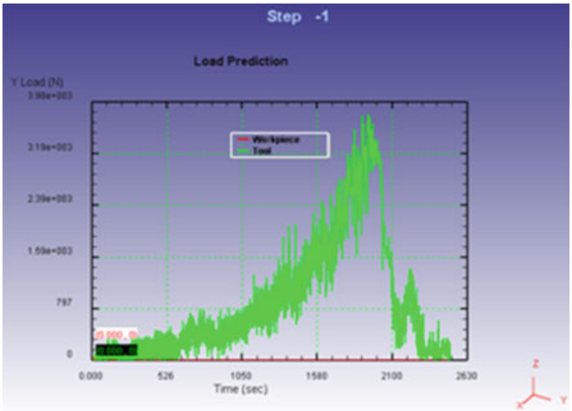


Fig. 15 Force prediction in *Y*-direction

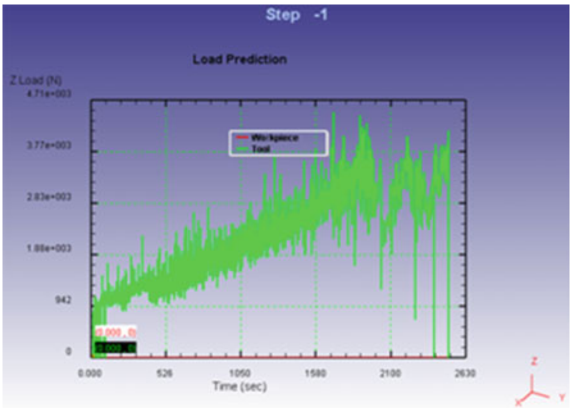


Fig. 16 Force prediction in *Z*-direction

are found increase as the DT path going to finish, i.e., the stresses increase with respect to time. This is obvious due to the strain hardening. Figure 13 shows the evolution of effective strain during the process, which is increasing with time.

The forming forces in X- and Y-direction are repetitive in nature. The forces in X- and Y-directions were also increased gradually. As the tool moves in Z-direction, the deforming force in Z-direction is found increasing. The force predicted in X-, Y-, and Z-directions are represented in Figs. 14, 15, and 16, respectively.

3 Development of Single-Point Incremental Forming Machine

The major elements of ISF are identified as follows: (i) a sheet metal blank, (ii) a blank holder, (iii) a single-point forming tool or DT, and (iv) CNC machine. The path of the DT is responsible for the shape, size and accuracy of the final product. Thus, the quality of the product depends on the proper tool path planning. The development of different parts of ISF machine has been discussed as below:

3.1 Sheet Metal Blank

The ISF machine is basically used for deforming product from metal sheets. The current research is mainly focused on the development of ISF process for light alloy. The material for metal sheets can be aluminum alloys, brass, titanium alloys, etc. For testing the machine developed at IIT (BHU), a brass sheet of blank size 100 mm × 100 mm × 0.5 mm has been used for current experimental study.

The shape, size, and accuracy of the finished product are compared with the simulation model. The shape and size of the processed model as compared to the simulation model has been found approximately same.

3.2 Blank Holder or Blank Holding Arrangement

Blank holder is the second most important element of the ISF machine. The proper blank holding arrangement is necessary for properly holding the blank sheet. A CAD model of the blank holding arrangement as shown in Fig. 11 is developed for simulation study. Also based on the simulation study, a modified blank holding arrangement and a single-point incremental forming machine have been developed as shown in Figs. 17 and 18. The metals as well as alloys can be deformed easily by ISF process. For the current investigations, the initial blank of material brass is selected for finding the capabilities of ISF process because brass is having good formability at room temperature.

Fig. 17 Blank and blank holding arrangement

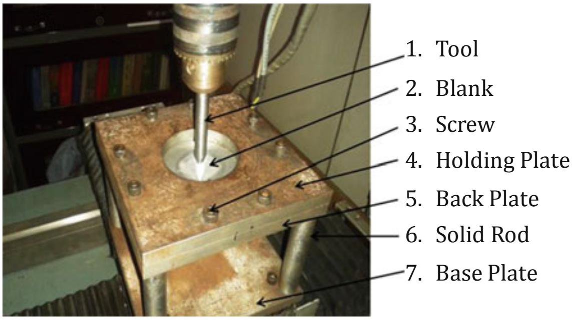


Fig. 18 Single-point incremental forming machine

3.3 Single-Point Forming Tool or Deforming Tool

The single-point forming tool also known as DTis another major element or most important element of the ISF machine. The DT may be spherical or elliptical or conical in shape. For the current research, a conical tool, having hemispherical shape at tip, has been used as shown in Fig. 17.

3.4 CNC Machine

The CNC machine is needed in order to control the tool path. A GALIL-make motion card having capability of controlling 8 independent axes has been used. A 3-axis in-house CNC machine has been developed for controlling the tool path. The completed experimental setup of single-point incremental forming machine has been represented in Fig. 18.

Fig. 19 Defect-free product (brass)

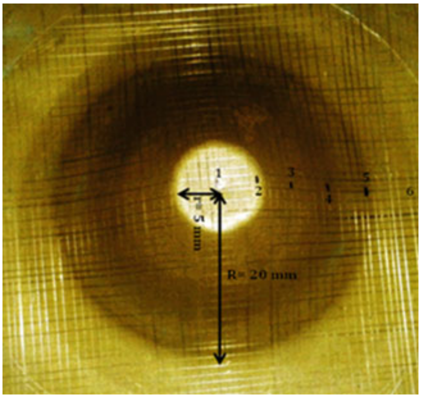


Fig. 20 Grid pattern on the bottom surface

4 Experimental Results

In order to investigate the strain distribution in the deformed product, the grid pattern was prepared on the bottom surface of sheet as shown in Fig. 20 having resolution of 1 mm. The metal sheet was divided into the 5 portions. Each portion is having 5 grids, i.e., 5 mm in length. The cone having top circle radius $R = 20$ mm and bottom circle radius = 5 mm has been successfully produced by ISF (Fig. 19).

For the analysis of strain distribution in the sheet deformed by ISF process, the following 5 regions were identified on the deformed sheet:

Region A: Starting from center point (Point 1) of bottom circle next 5 grids (Point 2) were identified as the region A.

Region B: Starting from Point 2 of next 5 grids, i.e., up to Point 3 were identified as the region B.

Region C: Starting from Point 3 of next 5 grids, i.e., up to Point 4 were identified as the region C.

Region D: Starting from Point 4 of next 5 grids, i.e., up to Point 5 were identified as the region D.

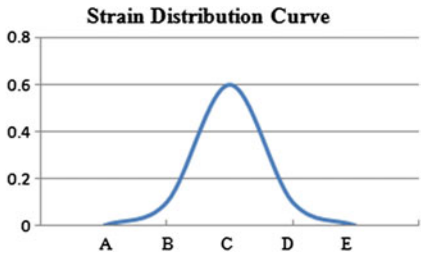


Fig. 21 Strain distribution

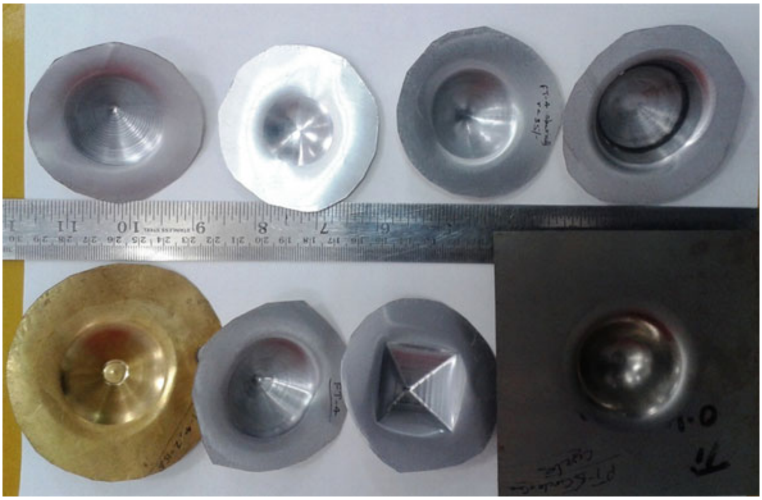


Fig. 22 Product formed by dieless forming machine (*top row* all aluminum and *bottom row* from *left* to *right* 1st brass, 2nd and 3rd aluminum, and 4th titanium)

Region E: The portion beyond Point 5 was identified as the region E.

The strain was found to be distributed normally as shown in Fig. 21.

Based on the simulation study, the experiments were carried out to get the defect-free products as shown in Fig. 22.

5 Conclusions

The ISF process is a flexible forming process, and it can be easily used for producing 3D complex shapes. The process can be used for larger forming angles with proper forming methodology. The laboratory setup of single-point ISF machine has been developed using motion card to control the 3 servo motors giving capability of individual 3-axis controlling. The defect-free products of brass, aluminum, and titanium have been produced using the ISF. The strain distribution over the length of deformation has been computed, and it has been found to be distributed over the length of the deformation.

Acknowledgments The authors acknowledge the help in running the simulation at IIT Kanpur.

References

Ambrogio G, Filice L, Manco GL (2008) Warm incremental forming of magnesium alloy AZ31. CIRP Ann Manuf Technol 57:257–260

Ambrogio G, Filice L, Gagliardi F (2012) Formability of lightweight alloys by hot incremental sheet forming. Mater Des 34:501–508

Araghi BT, Manco GL, Bambach M, Hirt G (2009) Investigation into a new hybrid forming process: incremental sheet forming combined with stretch forming. CIRP Ann Manuf Technol 58:225–228

Azaouzi M, Lebaal N (2012) Tool path optimization for single point incremental sheet forming using response surface method. Simul Model Pract Theor 24:49–58

Cerro I, Maidagan E, Arana J, Rivero A, Rodriguez PP (2006) Theoretical and experimental analysis of the dieless incremental sheet forming process. J Mater Process Technol 177:404–408

Filice L, Fratini L, Micari F (2002) Analysis of material formability in incremental forming. CIRP Ann Manuf Technol 51(1):199–202

Ham M, Jeswiet J (2006) Single point incremental forming and the forming criteria for AA3003. CIRP Ann Manuf Technol 55(1):241–244

Ham M, Jeswiet J (2007) Forming limit curves in single point incremental forming. CIRP Ann Manuf Technol 56(1):277–280

Hussain G, Gao L, Hayat N, Qijian L (2007) The effect of variation in the curvature of part on the formability in incremental forming: an experimental investigation. Int J Mach Tools Manuf 47:2177–2181

Jackson K, Allwood J (2009) The mechanics of incremental sheet forming. J Mater Process Technol 209:1158–1174

Juneja BL (2013) Fundamental of metal forming processes. New Age International (P) Limited, Delhi

Kim YH, Park JJ (2002) Effect of process parameters on formability in incremental forming of sheet metal. J Mat Process Technol 130:42–46

Kim TJ, Yang DY (2000) Improvement of formability for the incremental sheet metal forming process. Int J Mech Sci 42:1271–1286

Thibaud S, Hmida RB, Richard F, Malécot P (2012) A fully parametric toolbox for the simulation of single point incremental sheet forming process: numerical feasibility and experimental validation. Simul Model Pract Theor 29:32–43

http://www.springer.com/978-81-322-2354-2

Advances in Material Forming and Joining
5th International and 26th All India Manufacturing Technology, Design and Research Conference, AIMTDR 2014
Narayanan, R.G.; Dixit, U.S. (Eds.)
2015, XV, 382 p. 237 illus., 148 illus. in color., Hardcover
ISBN: 978-81-322-2354-2