International Journal of Mechanical and Production
Engineering Research and Development (IJMPERD)
ISSN (P): 2249-6890; ISSN (E): 2249-8001
Vol. 8, Issue 3, Jun 2018, 921-932

ANALYSIS OF PRESSURE ASSISTED INCREMENTAL SHEET FORMING PROCESS THROUGH SIMULATION

YOGESH KUMAR & SANTOSH KUMAR

Department of Mechanical Engineering, Indian Institute of Technology (BHU),

Varanasi, Uttar Pradesh, India

ABSTRACT

Incremental sheet forming (ISF) process is a flexible manufacturing process to produce complex 3D products at reasonable manufacturing cost. In addition to a single point, incremental sheet forming pressure has been applied to the back side of sheet surface in order to provide support to the sheet surface and improve process efficiency. In the current work, a comparative analysis of ISF & pressure assisted ISF process through CAE simulation have been done to predict the forming forces, energy requirements, effective stresses, etc. The forming forces in ISF as well as pressure-assisted ISF is very low when as compared to forming forces in traditional forming processes. The pressure-induced ductility has resulted in the reduction of forming forces with pressure assisted ISF. The energy required in pressure assisted ISF is slightly higher than the ISF process. An increment in effective stresses is observed in pressure assisted ISF, which is a due application of force on both sides of the sheet. However, these stresses are local and very small when as compared to traditional forming processes.

KEYWORDS: Incremental Sheet Forming, Die-Less Forming & Pressure Assisted Incremental Sheet Forming

Received: Apr 29, 2018; **Accepted:** May 19, 2018; **Published:** Jun 12, 2018; **Paper Id.:** IJMPERDJUN201898

INTRODUCTION AND LITERATURE REVIEW

Incremental sheet forming (ISF) is a flexible process for the manufacturing of small series and single products. The formability of ISF is much higher than traditional sheet forming processes. Kumar and Kumar (2016) identified one of such hybrid incremental sheet forming in which one side of the sheet is deformed by moving the tool over the sheet surface while the other side is supported by pressurized fluid. This Innovation is recorded as Incremental Sheet Hydro-Forming (ISHF) [Figure 1].

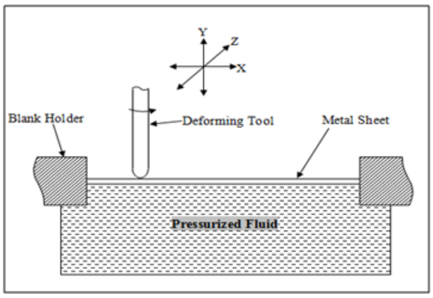

Figure 1: Single Point Incremental Hydro-Forming (SPIHF)[Kumar et al., 2015]

Kumar et al., 2018 carried out the analysis of incremental sheet forming process through simulation have been done to predict the forming forces, energy requirements, effective stresses, and total forming forces on the sheet. The geometrical accuracy of the product was found to be satisfactory [Figure 2].

Len et al. (2013) carried out the comparative analysis of ISF process other metal forming processes. Furthermore, this study would be the basis for determining the development of equipment necessary to carry it out. Panty (2014) has developed a new adaptive tool path control algorithm at process level to bypass fracturing due to localized thinning.

Bambach et al. (2014) investigated the process limits of incremental hole flanging and proposes two new approaches aiming to reduce deficits. The first one is an adaptive blank holder that acts in the vicinity of the forming tool and reduces unwanted secondary deformation that would lead to deviations from the target geometry.

Belchior et al. (2014) applied Process/Machine coupling approach to Robotized Incremental Sheet Forming (RISF) for Finite Element Analysis (FEA) of the process with an elastic modeling of the robot structure to improve the geometrical accuracy of the formed part. Lu et al. (2013) presented a new feature-based tool path generation algorithm for incremental sheet forming process in which tool paths are generated according to the specified critical edges to improve geometric accuracy. Wang et al. (2017) found that the enhanced CDM-based Lemaitre model can be used for ductile fracture of AA 7075 aluminum alloy in TPIF with a hemispherical shape. Bagudanch et al. (2014) concluded that the Marlow and the rule of mixture material models could be used to describe viscoelastic and softening and permanent set effects, respectively, to predict the behavior of a part formed by ISF.

Lu et al. (2015) investigated that by employing two forming tools on each side of the sheet, DSIF process can provide additional process flexibility, compared to the conventional single point incremental forming (SPIF) process, therefore to produce complex geometries without the need of using a backing plate or supporting die. Shrivastava and Tandon (2015) performed experiments on samples heat treated at different temperatures and hence, different grains to evaluate the effect of forming forces. Cui et al. (2016) developed a new method denoted as electromagnetic incremental forming combined with stretch forming is proposed, which was adopted for manufacturing large-size and thin-walled ellipsoidal parts. Bansal et al. (2017) developed a modified analytical model to accurately predict formed component thickness, contact area and forming forces during single and multi-stage incremental forming. Araghi et al. (2009) presented the positive impact of this hybrid process on the process limits.

The main influencing factors in pressure assisted incremental sheet forming are material formability, forming an angle, single-stage / multi-stage, sheet thickness, and pressure applied. All these factors are put together in the Fishbone diagram of pressure assisted ISF [Figure 2].

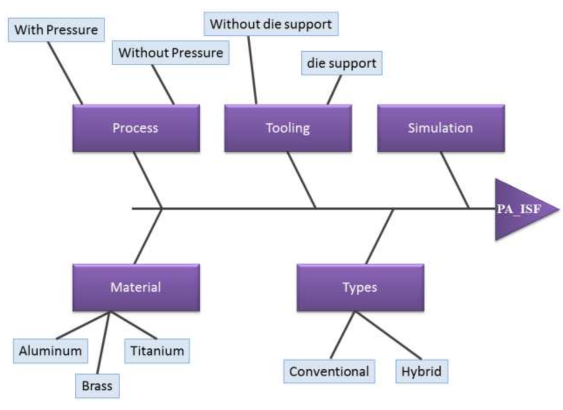

Figure 2: **Fishbone Diagram of Incremental Sheet Forming**

COMPUTATIONAL ANALYSIS OF PRESSURE ASSISTED INCREMENTAL SHEET FORMING PROCESS

The CAE engineers create the simulation test models for a given deformation system. The physical model idealizes the real engineering problems and abstracts to comply with some physical theory with some assumptions. The main elements of the Incremental sheet forming process are: (1) Sheet Metal Bank (2) Blank holding arranging (3) Forming Tool, (4) CNC Machine (5) Pressure inducing device.

CAE Simulation Procedure

This study applies commercial finite element code; the basic equations are as follows:

Equilibrium Equation:

$$\sigma_{ij,j}=0 \tag{1}$$

Compatibility and incompressibility equations

$$\dot{\varepsilon}_{ij} = \frac{1}{2}(u_{ij}+u_{ji}), \dot{\varepsilon}_v = u_{ij} = 0 \tag{2}$$

Constitutive Equations:

$$\sigma^{o}_{ij}=\frac{2\bar{\sigma}}{2\dot{\bar{\varepsilon}}}\dot{\varepsilon}_{ij}, \bar{\sigma} = \sqrt{\frac{3}{2}\acute{\sigma}_{ij}\acute{\sigma}_{ij}}, \dot{\bar{\varepsilon}} = \sqrt{\frac{3}{2}(\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij})} \tag{3}$$

Boundary Conditions

$$\sigma_{ij}n_i = F_j on S_F, u_i = U_i on S_U \tag{4}$$

Where σ_{ij} and $\dot{\varepsilon}_{ij}$ are the stress and the strain rate, respectively, $\bar{\sigma}$ and $\dot{\bar{\varepsilon}}$ are the effective stress and the effective strain rate, respectively, F_j is the force on the boundary surface of S_F, and U_i is the deformation velocity on the boundary surface of S_U.

The weak form of rigid- plastic FEM can be determined by applying the variational method to Equations (1) – (4), i.e.

$$\int_V \bar{\sigma}\delta\dot{\bar{\varepsilon}}dv + K\int \dot{\varepsilon_V}\,\delta\dot{\varepsilon_V}\,dV - \int_{S_F} F_i\,\delta u_i\,dS = 0 \tag{5}$$

Where *V* and *S* are the volume and the surface area of the material, respectively, and *K* is the penalty constant. The most important and crucial part of simulation in software is the selection of appropriate material models. DEFORM-3D contains various material models (for elastic-plastic, rigid-plastic and porous material), and each model has different suitability, so selection of correct material model as per the requirement is the prime necessity to get the accurate results.

Most of the material models require detailed material properties such as young's modulus of elasticity, strain hardening exponent, and strength coefficient, etc., as input to pre-processor before running the solver. In addition to material properties, pre-processor also require the input of detailed process parameters such as friction coefficient, blank holding force, sheet thickness, etc. Yielding criteria that is used for solving of following problem is Von Mises (in the Deform3D): Equations. (6) and (7) show effective strain and effective stress respectively.

$$\bar{\varepsilon} = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_1-\varepsilon_2)^2 + (\varepsilon_2-\varepsilon_3)^2 + (\varepsilon_3-\varepsilon_1)^2} \quad (6)$$

$$\bar{\sigma} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2} \quad (7)$$

Where ε_i and σ_i are principle strain and principle stress in the direction i respectively.

The following Elasto-Plastic constitutive equation for isotropic material is adapted to model the deformation behavior of the sheet.

$$\tilde{\tau}_{ij} = D^{ep}_{ijmn}\dot{\varepsilon}_{mn} \quad (8)$$

Where

$$D^{ep}_{ijmn} = D^{e}_{ijmn} - \frac{D^{e}_{ijkl}D^{e}_{uvmn}(\partial f/\partial\sigma_{kl})(\partial f/\partial\sigma_{uv})}{D^{e}_{kluv}(\partial f/\partial\sigma_{kl})(\partial f/\partial\sigma_{uv})+\acute{H}(\sigma_{uv}(\partial f/\partial\sigma_{uv})/\bar{\sigma}} \quad (9)$$

and D^{ep}_{ijmn} Represents the coefficient of Elasto-plasticity, D^{e}_{ijmn} is the coefficient of elasticity, $\tilde{\tau}_{ij}$ the Jaumann rate of Kirchhoff stress, $\dot{\varepsilon}_{ij}$ The rate of deformation, which is the symmetric part of the velocity gradient $L_{ij} = (\partial v_i/\partial X_j)$, X_j the fixed spatial Cartesian coordinates, σ_{ij} The Cauchy stress, $\acute{H}$ The strain-hardening rate, f the yield condition of rate-independent strain-hardening plasticity and $\bar{\sigma}$ The effective stress.

The equation for virtual work can be made discrete. The updated Lagrangian formulation (ULF) in a framework of the application of an incremental deformation for the metal forming process (bulk forming and sheet forming) has been used practically applied to describe the incremental properties of plastic flow. The current configuration according to ULF at each stage of deformation is used as a reference state to evaluate the deformation during a small time interval *t*, such that the first-order theory is consistent with the required accuracy. The rate equation for virtual work written as an updated Lagrangian equation is

$$\int_V (\tilde{\tau}_{ij} - 2\sigma_{ik}\,\dot{\varepsilon}_{kj})\,\delta\dot{\varepsilon}_{ij}\,\mathrm{dv} + \int_V \sigma_{jk}\,L_{ik}\,\delta L_{ij}\,\mathrm{dv} = \int_{S_f} \dot{t}_i\,\delta v_i\,\mathrm{dS} \quad (10)$$

In which v_i is the velocity, $\dot{t}_i$ the rate of the nominal traction, and V and S_f Represent the material volume and the surface on which the traction is prescribed.

In Elasto-Plastic material definition of Young's modulus and Poisson’s ratio is very important and equation No.11 has been suggested:

$$\bar{\sigma} = c\bar{\varepsilon}^n\dot{\bar{\varepsilon}}^m + y \quad (11)$$

Where n and m are strain hardening and strain rate hardening respectively. It is accurate for y=0 to be equal to the initial yield stress. If y=0, the initial yield stress will be poorly represented. The function of material which is used has to have the strain rate at different temperature.

The general procedure of the proposed CAE process is shown in Figure 3. To conduct CAE, simulation, it is the first step to represent the geometrical detail / geometry content. Therefore a CAD model, in a suitable CAD modelling package, is developed for the metal forming simulation systems.

The mathematical model specifies the mathematical equations, such as the differential equations on FEM analysis along with detailed boundary and initial conditions and their constraints. The numerical model describes the element type, mesh density and solution parameters. Usually, most CAE packages have part of built in content of these models, but users still need to prepare and input most of the model information into a CAE system.

The CAE simulation process consists of four main steps (1) pre-processing (2) simulation analysis, (3) post processing and (4) result analysis and evaluation. After the simulation, the simulation results need to be analyzed and evaluated. If the results and solutions are satisfactory, then changes and modifications may be suggested for the metal forming system (part design, tooling design, process configuration and material selection) which can be made for the next round of the simulation study. The process is therefore, iterative in nature [Fu et al. (2007)].

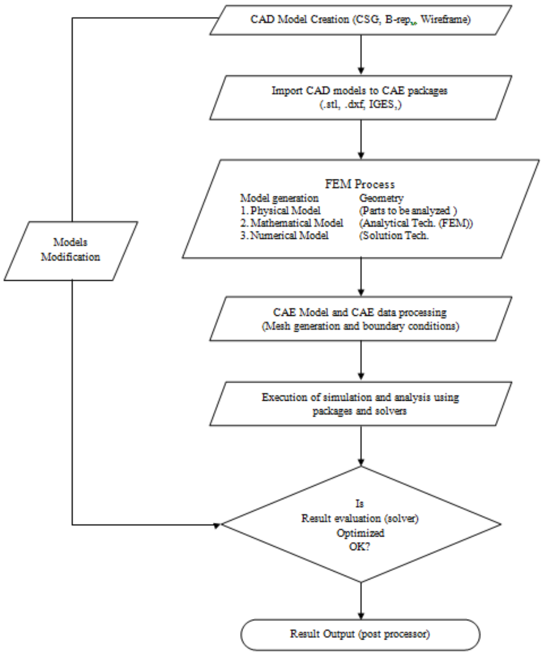

Figure 3 : Implementation of CAE Process, [Fu et al. (2007)]

The simulation process consists of following five steps:

- **Initial Geometry:** In this step CAD model of work piece, blank holding arrangement and deforming tool are converted into STL files. These STL files are imported in into the pre-processor of the simulation package.
- **Material Data and Meshing:** In this step, already existing material and their material properties are assigned to the previously imported products. Also, there is a provision for defining new materials. The circular sheet blank, 125 mm diameter with 2 mm thickness of Aluminum-1080A, has been chosen to carry out simulation analysis. Meshing can be done with the use of tetrahedral elements.
- **Defining Boundary Conditions:** Different types of boundary conditions such as back pressure, blank holding

pressure or force, coefficient of friction, tool movement are applied. The back pressure applied to 0.02 MPa was on the back side of the sheet. Finally a database file (.DB) is generated. This file is run in the simulation engine.

- **Simulation Engine**: Performs the numerical analysis and writes the resulting information in the database file.
- **Post-Processing**: This is used to extract the information from the data base file. In this step different typed of defects, load requirement and effective stresses are studied. This step gives the modifications required in geometry or boundary conditions to get the optimum deformation.

Process Parameters and Material Data

The following process parameters and material data have been used for simulation:

- **Tooling Setup**

Blank Diameter (mm) = 125 mm

Blank thickness (mm) = 2 mm

Initial temperature (°C)= 20°C

Blank Material= Aluminum-1080A

- **Material Properties**

Young modulus E (GPa) = 68

Ultimate Strength (MPa) = 74 to 140

Yield Strength (MPa) = 17 to 120

Poisson ratio (ν) = 0.33

Friction coefficient (μ) = 0.02

- **Pre-Processor & Simulation Setting**

Simulate Solver = Lagrangian Incremental (Deformation Model only)

Simulation Steps = 27500 Steps

Per step time increment= 0.5 seconds.

Remesh Criterion = 0.7 (Relative interference)

Iteration= (Solver = Sparce, & Method = Newton-Raphson)

Inter-Object Relationship = Tool & Workpiece Coulomb friction = 0.02, Workpiece & blank holder Shearing friction = 0.02.

Tolerance limit = 0.0002 mm

Number of Meshes= 1,00,000

Mesh type= Tetrahedron

Total Run Time= 360 hrs.

SIMULATION RESULTS

The simulation analysis is done by Deform 3D simulation tool and it took approximately 360 hours to complete the simulation. The simulation results obtained are (1) load prediction, i.e. the forming forces, (2) Energy requirements, (3) Effective stresses, etc. The same are discussed in the current section.

Load Predictions

The forming forces (load) have been predicted from simulation results. The load predicted in X, Y and Z-direction in shown in Figure 4-9. The forming force requirement is very low. It increases at very-2 slow rate due to strain – hardening effect on the sheet. The forces observed in X-direction is plotted in Figure 4 & 5 for incremental sheet forming and pressure assisted ISF. A slight decrease in forces in X-direction is observed in pressure assisted ISF.

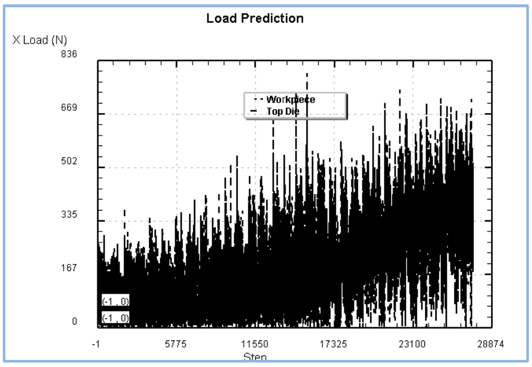

Figure 4: X-Load in ISF [Kumar et al., 2018]

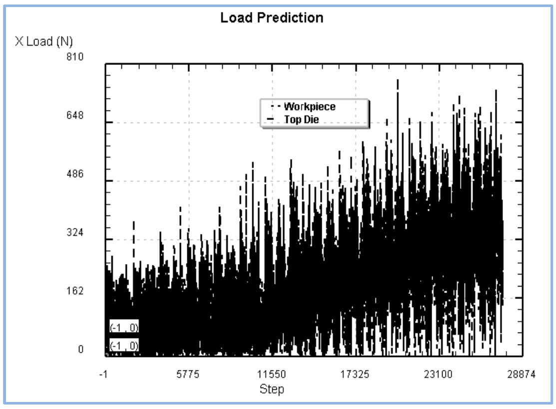

Figure 5: X-Load in Pressure Assisted ISF

The forces observed in Y-direction is plotted in Figure 6 & 7 for incremental sheet forming and pressure assisted ISF. A slight decrease in forces in Y-direction is observed in pressure assisted ISF.

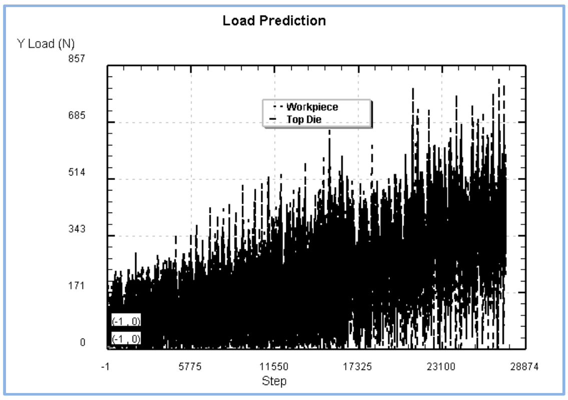

Figure 6: Y-Loading ISF [Kumar et al., 2018]

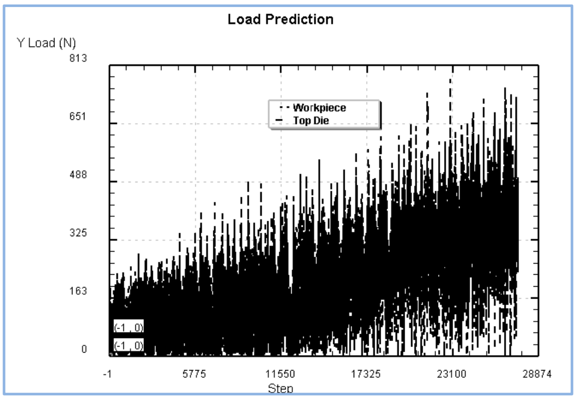

Figure 7 : Y-Load in Pressure Assisted ISF the Forces Observed in Z-Direction are plotted in Figure 8 & 9 for Incremental Sheet Forming and Pressure Assisted ISF. A Slight Decrease in Forces in Z-Direction is Observed in Pressure Assisted ISF

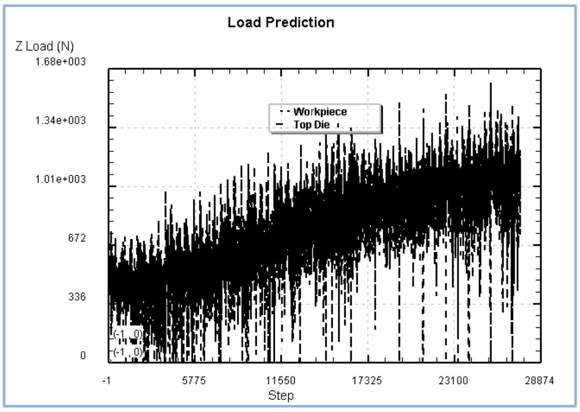

Figure 8: Z-Load in ISF [Kumar et al., 2018]

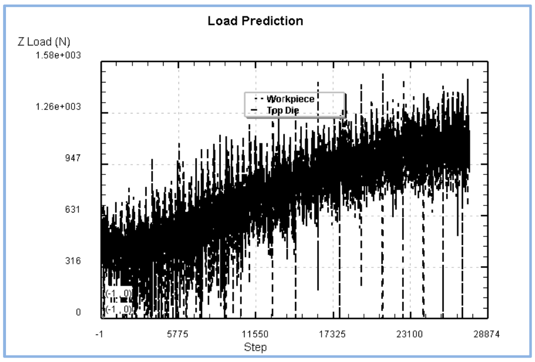

Figure 9: Z-Load in Pressure Assisted ISF

The forming forces in ISF as well as pressure assisted ISF are very low when as compared to forming forces in traditional forming processes. The forming forces in pressure assisted ISF are slightly reduced. The main reason for reduction in forming forces may be pressure induced ductility.

Energy Requirements

The total energy requirement predicted in ISF as well as in pressure assisted ISF is shown in Figure 10 & 11. The energy requirement is linearly increasing with time. The energy required in pressure assisted ISF is slightly higher than the ISF process. However, it is very low when as compared to traditional forming processes.

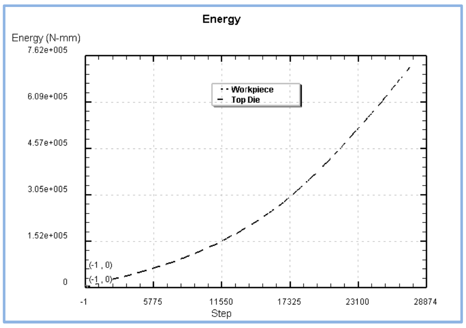

Figure 10: Energy Requirement in ISF [Kumar et al., 2018]

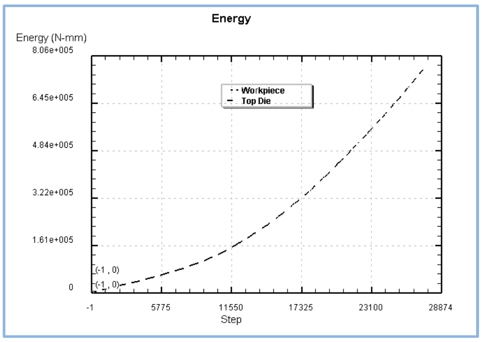

Figure 11: Energy Requirement in Pressure Assisted ISF

Effective Stresses

The effective stresses predicted in ISF as well as in pressure assisted ISF are shown in Figure 12 & 13. The effective stresses are found to increase with time both at ISF as well as in pressure assisted ISF. Slight increment is effective stresses is observed in pressure assisted ISF, which is due application of force on both sides of a sheet.

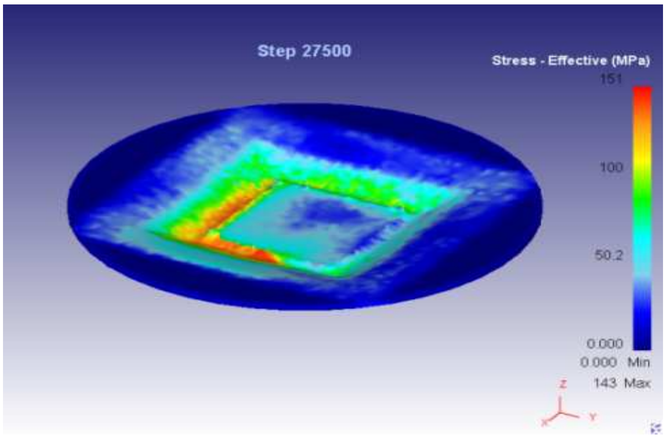

Figure 12: Effective Stresses in ISF [Kumar et al., 2018]

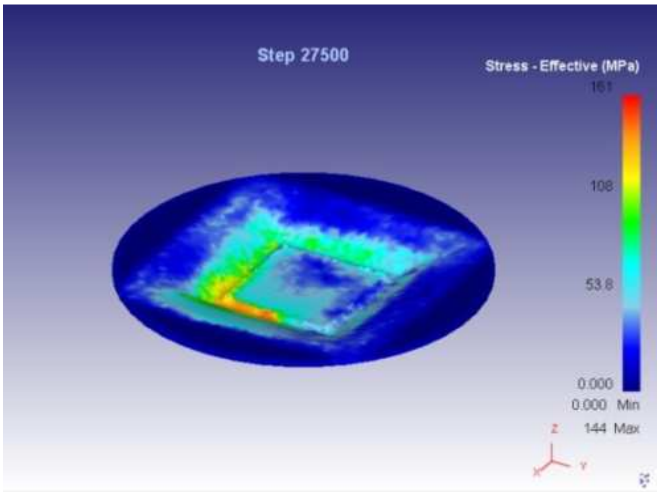

Figure 13: Effective stresses [Pressure assisted ISF]

CONCLUSIONS

- The forming forces in ISF as well as pressure assisted ISF are very low when as compared to forming forces in traditional forming processes. The pressure induced ductility has resulted in reduction of forming forces with pressure assisted ISF.
- The energy required in pressure assisted ISF is slightly higher than the ISF process.
- An increment in effective stresses is observed in pressure assisted ISF, which is due application of force on both sides of a sheet. However, these stresses are locally and very less when as compared to traditional forming processes.
- The CAE simulation results have guided in the development of Incremental sheet hydro-forming machine.

ACKNOWLEDGEMENTS

The authors express their gratefulness to IIT Kanpur and DRDL Hyderabad for their help & support to carry out this research work.

REFERENCES

1. *Araghi, B. T., Manco, G., Bambach, M., Hirt, G., 2009. Investigation into a new hybrid forming process: Incrementalsheet forming combined with stretch forming. CIRP Annals 58 (1), 225 – 228.*
2. *Bagudanch, I., Martnez-Romero, O., Elas-Ziga, A., Garcia-Romeu, M. L., 2014. Identifying polymeric constitutive equations for incremental sheet forming modelling. Procedia Engineering 81, 2292 – 2297, 11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014, Nagoya Congress Center, Nagoya, Japan.*
3. *Bambach, M., Voswinckel, H., Hirt, G., 2014. A new process design for performing hole-flanging operations by incremental sheet forming. Procedia Engineering 81, 2305 – 2310, 11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014, Nagoya Congress Center, Nagoya, Japan.*
4. *Bansal, A., Lingam, R., Yadav, S. K., Reddy, N. V., 2017. Prediction of forming forces in single point incremental forming. Journal of Manufacturing Processes 28, 486 – 493, sI: NAMRC 45.*
5. *Belchior, J., Leotoing, L., Guines, D., Courteille, E., Maurine, P., 2014. A process/machine coupling approach: Application to robotized incremental sheet forming. Journal of Materials Processing Technology 214 (8), 1605 – 1616.*
6. *Cui, X., Mo, J., Li, J., Xiao, X., Zhou, B., Fang, J., 2016. Large-scale sheet deformation process by electromagnetic incremental forming combined with stretch forming. Journal of Materials Processing Technology 237, 139 – 154.*
7. *M. W. Fu, M. S. Yong, K. K. Tong & T. Muramatsu (2007) A methodology for evaluation of metal forming system design and performance via CAE simulation, International Journal of Production Research, 44:6, 1075-1092, DOI: 10.1080/00207540500337643.*
8. *Kumar, S., Kumar, Y., Aug. 31 2016. Incremental sheet hydroforming machine. IN Patent App. 3312/DEL/2,014.*
9. *Kumar, Y., Kumar, S., 2015. Incremental Sheet Forming (ISF). In: Advances in Material Forming and Joining. Springer, New Delhi, pp. 29–46.*
10. *Kumar, Y., Kumar, S., 2018. Analysis of incremental sheet forming process through simulation. International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) 8 (3), 145–152.*
11. *D. Srikanth, M. V. S. Murali Krishna & P. Usha Sri, 2018. Impact of Injection Timing and Injection Pressure on Performance Parameters and Combustion Characteristics of High Grade Semi Adiabatic Diesel Engine with Cotton Seed Biodiesel, International Journal of Mechanical and Production Engineering Research and Development (IJMPERD), 6 (1), 1-14.*
12. *Len, J., Salcedo, D., Ciurriz, C., Luis, C., Fuertes, J., Puertas, I., Luri, R., 2013. Analysis of the influence of geometrical parameters on the mechanical properties of incremental sheet forming parts. Procedia Engineering 63, 445 – 453, the Manufacturing Engineering Society International Conference, MESIC 2013.*
13. *Lu, B., Chen, J., Ou, H., Cao, J., 2013. Feature-based tool path generation approach for incremental sheet formingprocess. Journal of Materials Processing Technology 213 (7), 1221 – 1233.*
14. *Arul Manij, Nagarajan P, Swaminathan G, Vignesh K & Saravana Bhavan, 2018. International Journal of Research in Engineering & Technology (IMPACT: IJRET), 5 (4), 11-12*
15. *Lu, B., Fang, Y., Xu, D., Chen, J., Ai, S., Long, H., Ou, H., Cao, J., 2015. Investigation of material deformationmechanism in double side incremental sheet forming. International Journal of Machine Tools and Manufacture 93, 37 – 48.*
16. *Paniti, I., 2014. Adaptation of incremental sheet forming into cloud manufacturing. CIRP Journal of Manufacturing Science and Technology 7 (3), 185 – 190.*

17. *Shrivastava, P., Tandon, P., 2015. Investigation of the effect of grain size on forming forces in single point incremental sheet forming. Procedia Manufacturing 2, 41 – 45, 2nd International Materials, Industrial, and Manufacturing Engineering Conference, MIMEC2015, 4-6 February 2015, Bali, Indonesia.*

18. *Wang, C., Daniel, W. J., Lu, H., Liu, S., Meehan, P. A., 2017. Fem investigation of ductile fracture prediction in two point incremental sheet metal forming process. Procedia Engineering 207, 836 – 841, international Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom.*