Analyzing the effect of Forming Force in Single Point Incremental Forming (SPIF) of Polycarbonate Sheets

[1]Prashant Khanna

[1]Assistant Professor
[1]Department of Mechanical Engineering
[1]Parul Institute of Technology, Parul University, Vadodara, India.

Abstract: Due to the demand of complex products, the development in the CAD/CAM programs is increasing. Various processes requiring CAD/CAM cycle also needs to be improved in order to justify the increasing complexity. In the field of sheet metals, the development of prototype needs to be faster, cheaper and better. Since all the sheet metal processes require expensive tooling, machinery and labor, the process of incremental sheet metal forming is developed to improve rapid prototyping of the complex parts. Incremental sheet metal forming (ISMF) is a looming sheet metal process, which does not demand any given die for action. It is a flexible process and its simplicity is to produce complex shapes using just a round tipped tool, a clamping device and a CNC machining center. In this paper, the main focus is kept on using a force model for predicting the forming force developed during SPIF of polycarbonate sheets. The theoretical force values are coming out to be in good agreement with the experimentally obtained force values with an overall error of 8.29%. In addition to this work, the effect of 4 major incremental forming parameters (i.e. wall angle, sheet thickness, tool diameter, and step depth) on the forming force is analyzed. It is observed that the step depth and the sheet thickness have major influence on the forming forces.

Index Terms **– Incremental forming, force analysis, forming force, polycarbonate sheets.**

I. INTRODUCTION

All Incremental sheet metal forming (ISMF) is a flexible process which uses a round tipped tool for producing a variety of shapes of new or replacements parts. By this process, parts can be formed directly from CAD model with very less and inexpensive specialized tooling; therefore, it is having a high potential for rapid prototyping and economically producing small quantity of various applications. In its earlier stage, Allwood et al. (2005) [1] identified the potential applications of ISMF technology. Ambrogio et al. (2005) [2] produced a customized ankle support successfully with high accuracy. Micari et al. (2007) [3] demonstrated that ISMF can be utilized for manufacturing automotive body parts. However, due to lack of proper analysis of deformation mechanism occurring in ISMF, its further development was inhibited.

In particular, a model which is based on the deformation mechanics is required to get a better understanding of forming forces, failure criteria and material behavior. Silva et al. (2008) [4] analyzed the ISMF by considering membrane strains. An analytical model was developed which provided a view for explaining the principle behind the material fracture and the raised formability of ISMF.

Emmens and Boogaard (2008) [5] concluded that bending of sheet under the tensile load plays a critical role in the localized deformation of the ISMF process. Using finite element (FE) simulations, Smith et al. (2013) [6] described the fracture mechanics in SPIF and connected it with accumulative dual- sided ISMF. Lu et al. (2014) [7] claimed that through- thickness-shear which is caused by friction is the main cause for increased formability in ISMF. By experiments, Jackson and Allwood (2009) [8] outlined that the fracture structure in ISMF is a sequence of shear in the plane perpendicular to the tool motion in the path of the tool and stretching. However, Eyckens et al. (2011) [9] proposed that the fracture structure depends mainly on individual forming parameters (e.g. wall angle, tool diameter, step-down size and spindle rotation speed).

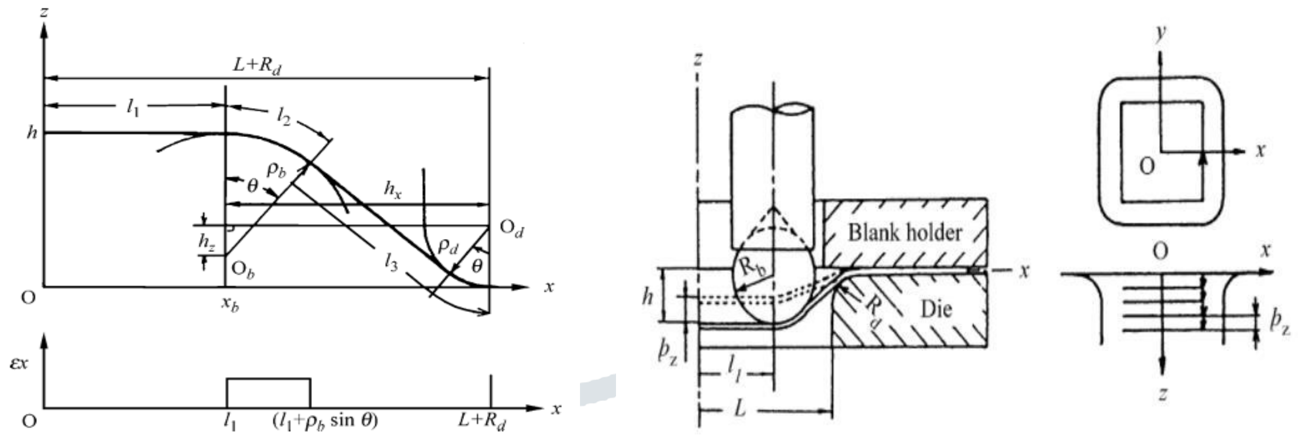
Many authors have studied the forming force behavior of ISMF. Duflou et al. (2007) [10] observed that the force of forming increases with the increase in step size, tool diameter, wall angle and thickness of sheet. Ambrogio et al. (2006) [11] found that the force gradient after the peak could be considered effectively as an indicator to prevent fracture of work piece. Filice et al. (2006) [3] considered forming force mainly for on-line control and optimization. Ingarao et al. (2012) [12] found the energy consumption required for the ISMF process based on the measured force data providing guidance for sustainable development of the process. Due to the localized fracture and extensive tool path in ISMF, force prediction with FE models is highly time-consuming. Smith et al. (2013) [6] presented a simulation time of around 24 days for single point ISMF process of a truncated cone shape. To overcome the above problem, Iseki (2001) [13] found the forming forces in ISMF using an approximated deformation analysis based on a plane-strain deformation model. Aerens et al. (2010) [14] studied the incremental forming of truncated cones with other materials applying statistical and experimental analysis. Also, formulae were proposed using regression analysis to forecast the forming forces from input variables having wall angle, initial thickness, tool diameter, and vertical step size. Since the axial force is the actual force component in the plastic work during ISMF, so it is mainly concerned to the deformation process.

II. ANALYTICAL MODEL FOR FORCE PREDICTION

The Basic assumptions

1. Bending stresses and frictional forces are neglected.
2. Deformation follows the plain strain condition.
3. Force variation is steady state in nature.

Fig. 1 shows the proposed model along with the strain distribution along x-axis [16].



(a) (b)

Fig. 1 a) Incremental forming using ball tipped tool b) Plain strain deformation model

Where, θ is the contact angle between tool and the sheet; R_b is the radius of the ball/tool; R_d is the shoulder radius of the die or backing plate; ρ_b is the extended length of tool radius on the sheet; ρ_d is the extended length of die radius on the sheet; 2L is the distance between opposite sides of the die; t_0 is the initial thickness of the sheet; h is the incremental height of a step; x_b is the location of the center of the tool.

With the help of extended contact length l_2, the uniform logarithmic strain ε_t on the deformed sheet along x-axis is given by:

$$\varepsilon_x = -\varepsilon_t = ln\left[\frac{l_2}{L+R_d-l_1-l_3}\right] \quad (1)$$

According to the plain strain deformation model, the tensile force T is given by:

$$T = BT\sigma \quad (2)$$

Where, $B=2R_b$ is the projected width of the deformed sheet; t is the sheet thickness ($=t_0$) and σ is the stress generated due to stretching. Considering the strain hardening law for any material, the value of σ is given by:

$$\sigma = K\varepsilon^n \quad (3)$$

Where K is the strength coefficient; n is the strain hardening index; and ε is the engineering strain. The engineering strain in terms of true strain or logarithmic strain is given by:

$$\varepsilon_t = ln(1+\varepsilon) \quad (4)$$

After substituting all the above values, we get:

$$T = 2R_b t_0 K(|e^{-\varepsilon_x} - 1|)^n \quad (5)$$

Considering the equilibrium between tensile force 'T' and forming force 'F' as shown in Fig. 2, the two components of forming force i.e. axial force F_z and tangential force F_x are given by:

$$F_x = T(1-\cos\theta),\ F_z = T\sin\theta \quad (6)$$

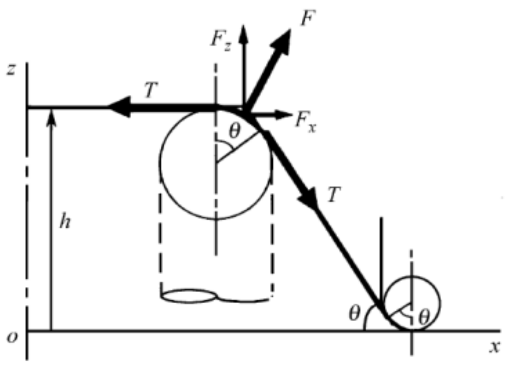


Fig. 2 Equilibrium of tensile and forming forces

With the help of the above equations, an approximate idea about the amount of forming force developed during incremental forming of any material of sheet can be obtained.

III. Experimental work

To prove the concept of SPIF, different shapes were formed on the CNC router using different parameters. The effect of various parameters i.e. tool diameter, step size, sheet thickness, and wall angle on the axial forming force is analyzed.

3.1Sheet Material

The material of the sheet used for ISMF is polycarbonate. It is a durable material with high impact resistance and good ability to be formed. Due to excessive spring back action of the polymeric sheet, the final products are deviated from the initial shape. The sheets are bought in three different thicknesses of 1.5mm, 2mm, and 3mm. The sheets are then cut into square sections of 150×150mm considering the maximum size which the setup can clamp. The polycarbonate mechanical properties are given in Table3.1.

TABLE 3.1 Mechanical properties of polycarbonate

PROPERTIES	VALUE
Young's modulus	2.2 Gpa
Elongation at break	80-150%
Compressive strength	>75Mpa
Poisson's ratio	0.37
Coefficient of friction	0.31
Strain hardening coefficient (K)	62 Mpa
Hardening index (n)	0.22

3.2 Experimental Setup

For measuring the forming force, Kistler 9257B dynamometer along with multichannel charge amplifier is installed directly below the clamping setup. The dynamometer is clamped to the table of the CNC router TR-203 as shown in Fig. 3. The parts are made in the shape of a frustum with depth of 20mm as shown in Fig. 4. Other shapes are also formed using the same process parameters. Fig. 5 shows different shapes formed by using SPIF.

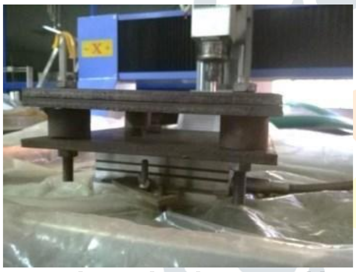


Fig. 3 Dynamometer clamped to the CNC table along with setup

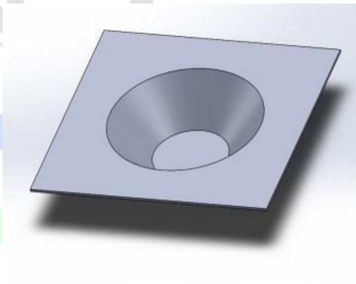
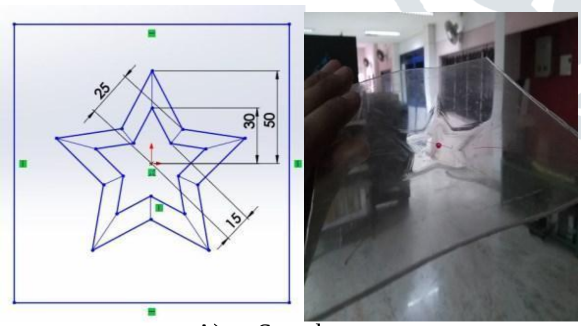
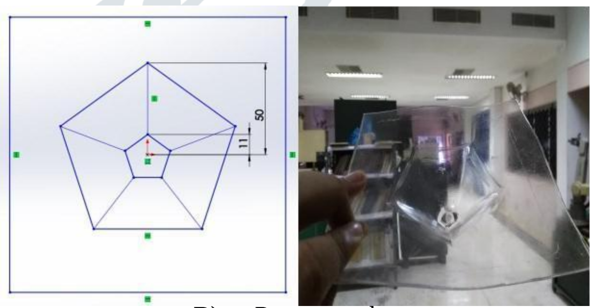


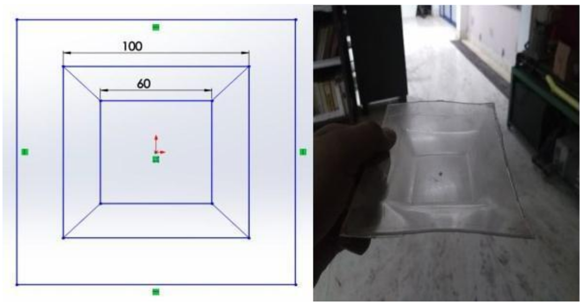
Fig. 4 Geometry of the formed part



A) Star shape



B) Pentagon shape



C) Rectangular shape

Fig. 5 Different shapes formed from SPIF

3.3. Experimental parameters

All experiments are performed on the CNC router TR-203. Results are analyzed for 9 experiments with different process parameters as given in Table II.

TABLE 3.2.Process parameters used for incremental forming

Experiment number	Tool diameter (mm)	Step depth (mm)	Sheet thickness (mm)	Wall angle (°)
1.	10	1	2	45
2.	12	1	2	45
3.	16	1	2	45
4.	12	0.5	2	45
5.	12	1.5	2	45
6.	12	1	1.5	45
7.	12	1	3	45
8.	12	1	2	30
9.	12	1	2	60

IV. RESULTS AND DISCUSSIONS

4.1. Comparison of Force values

The output from the dynamometer is in the form of data points in large numbers. The forces obtained from the experiments are plotted in the form of graphs with respect to time. The trend of the force is irregular which have many peaks and valleys as shown in Fig. 6. In order to get the steady state force value, the root mean square (rms) value of the forces is taken. The occurrence of peaks and valleys is majorly due to the localized deformation of sheet. Due to the excessive springback of the polycarbonate sheets, sometimes there are portions of the sheet left undeformed by the tool. So when the next contour is traced, the step depth becomes more due to which the tool has to penetrate more into the sheet causing irregular behavior in the force.The calculations are done using Excel. The obtained force values along with the theoretically calculated values are shown in Fig. 7. The overall error obtained is 8.29% which is in good agreement with the theoretical model as shown in Table 4.1.

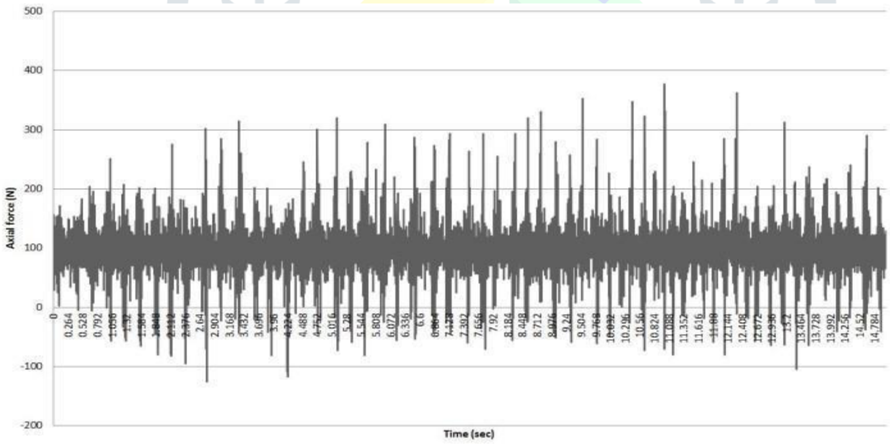


Fig. 6 Unsteady nature of axial force obtained

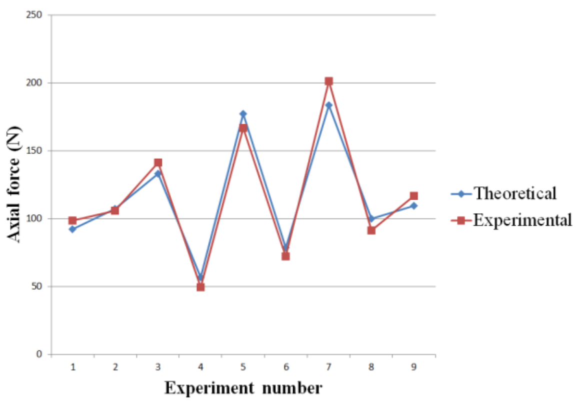


Fig. 7 Comparison of theoretical and experimental results

TABLE 4.1.Comparison of theoretical and experimental force

Sl.No	Tool diameter (mm)	Step depth (mm)	Sheet thickness (mm)	Wall angle (°)	Theoretical Fz (N)	Experimental Fz (N)	Error %
1.	10	1	2	45	92.342	98.52338	-6.69
2.	12	1	2	45	107.29	105.8183	1.372
3.	16	1	2	45	133.16	141.2613	-6.08
4.	12	0.5	2	45	56.93	49.4595	13.12
5.	12	1.5	2	45	177.26	166.9017	5.84
6.	12	1	1.5	45	78.712	72.3695	8.05
7.	12	1	3	45	183.65	201.1596	-9.53
8.	12	1	2	30	99.93	91.3129	8.26
9.	12	1	2	60	109.69	116.9551	-6.623
	Overall error %						8.29

4.2 Influence of tool diameter

It is found that increasing the tool diameter increases the forming force. The main reason behind this trend is due to the increased localized contact of the tool with the sheet. The tool with 16mm diameter has more area of contact compared to 12mm diameter tool and so do the 10mm diameter tool. So a large amount of forming force is required in order to locally deform the sheet. The effect is shown in Fig. 8.

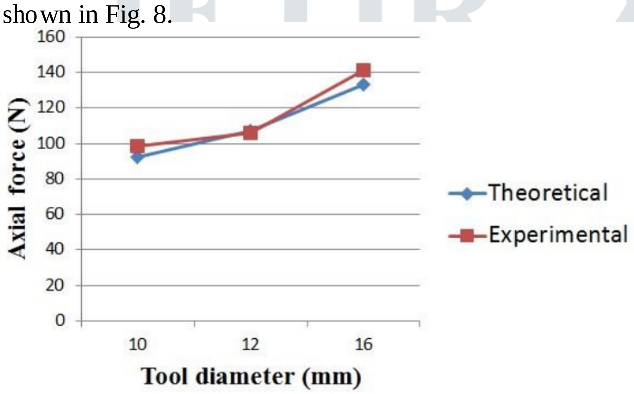


Fig. 8 Effect of tool diameter on forming force

4.3 Influence of step size

Step size has a major influence on the forming force. Increasing the step size increases the forming force but on the other hand decreases the overall time for forming. The increase in the force with the increased step size is because the tool has to move more into the sheet for tracing a contour causing excess work hardening due to large deformation, thus requiring higher forming force. Since when the step size is increased, the number of contours to be traced for a given depth is reduced. So more material is deformed at a time due to which the force value increases. Fig. 9 shows the effect of step size.

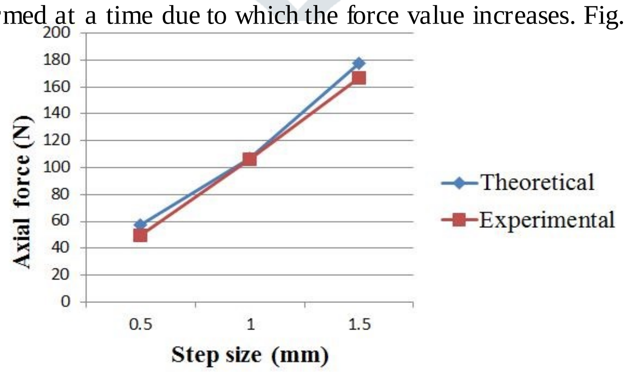


Fig. 9 Effect of step size on forming force

4.4. Influence of sheet thickness

Increasing the sheet thickness makes more material to be deformed at a time due to shear thinning phenomenon which increases the force required for forming. On the other hand, increasing the sheet thickness increases the accuracy of the parts. The main reason for this is because thicker sheets have less spring back compared to thin sheets. The deformation in the thicker sheets is more plastic in nature due to which it is easier to form accurate shapes. But increasing the sheet thickness greatly increases the forming forces. So due to this, the maximum sheet thickness value is restricted to intermediate. Fig. 10 shows the effect of sheet thickness.

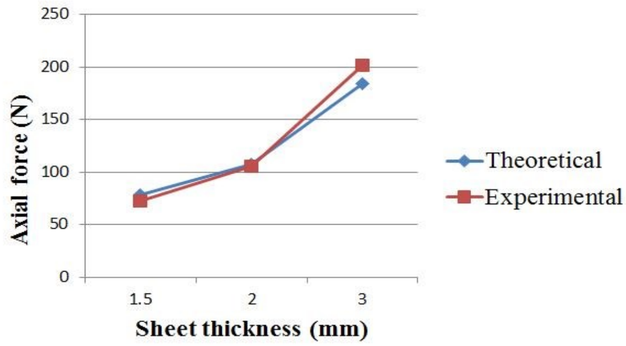


Fig. 10 Effect of sheet thickness on forming force

4.5. Influence of wall angle

The wall angle does not have much significant effect on the forming force. For a particular step size, the wall angle decides the forming force required to deform the material. This is generally because for a given step size, wall angle is used to calculate the actual material depth (slant depth) which needs to be deformed. Based upon this forming force seems to slightly increase with the increase in the wall angle. Fig. 11 shows the effect of wall angle.

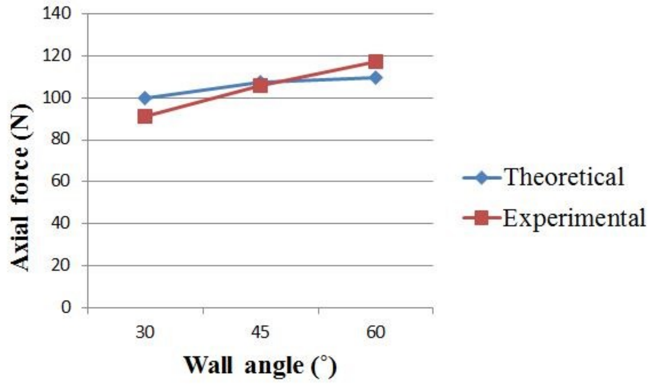


Fig. 11 Effect of wall angle on forming force

V. CONCLUSION

The forming force is mainly dependent on two material properties i.e. strain hardening index 'n' and strength coefficient 'k'. The experimental results came out to be in good agreement with the theoretical model. The forming force is mainly dependent on two material properties i.e. strain hardening index 'n' and strength coefficient 'k'. All other factors are based up on the geometry of the setup and the shape of the required final product. The overall obtained error is 8.29% which justifies the modelling. The maximum force obtained is 201.159 N for 12mm tool diameter, 1mm step size, 45° wall angle, and 3mm sheet thickness. From the experiments, it is found that the forming force increases with the increase in tool diameter, step size, sheet thickness, and wall angle. The most influencing parameters are the step size and the sheet thickness since the variation in the forming forces is very high for increase in the value of step size and sheet thickness. While tool diameter and wall angle have less influence on the forming force, still they are important factors affecting part accuracy.

All the experiments and results are strictly for polycarbonate sheets. Although the results are satisfactory, but still there is a lot of scope for improving the process.

REFERENCES

[1] Allwood, J.M., King, G.P.F., Duflou, J., 2005, A structured search for applications of the incremental sheet-forming process by product segmentation, ‖ Proc. Inst. Mech.Eng, Part B, J. Eng. Manuf., 219, pp.239 – 244.

[2] Ambrogio, G., De Napoli, L., Filice, L., Gagliardi, F., Muzzupappa, M., 2005, Application of incremental forming process for high customised medical product manufacturing, ‖ J. Mater. Process. Technol., 162 – 163, pp.156–162.

[3] Filice, L., Ambrogio, G., Micari, F., 2006, On-line control of single point incremental forming operations through punch force monitoring, ‖ CIRP Ann. Manuf. Technol., 55, pp.245 – 248.

[4] Silva, M.B., Skjoedt, M., Martins, P.A.F., Bay, N., 2008, ―Revisiting the fundamentals of single point incremental forming by means of membrane analysis, ‖ Int. J. Mach.Tools Manuf., 48, pp.73 – 83.

[5] Emmens, W.C., Boogaard, A.H., 2008, An overview of stabilizing deformation mechanisms in incremental sheet forming, ‖ J. Mater. Process. Technol., 209, pp.3688－3695.

[6] Smith, J., Malhotra, R., Liu, W.K., Cao, J., 2013, Deformation mechanics in single-point and accumulative double-sided incremental forming, ‖ Int. J. Adv. Manuf. Technol., 69, pp.1185－1201.

[7] Lu, B., Fang, Y., Xu, D.K., Chen, J., Ou, H., Moser, N.H., Cao, J., 2014, Mechanism investigation of friction-related effects in single point incremental forming using a developed oblique roller-ball tool, ‖ Int. J. Mach. Tools Manuf., 85, pp.14－29.

[8] Jackson, K., Allwood, J., 2009, The mechanics of incremental sheet forming, ‖ J. Mater. Process. Technol., 209, pp.1158－1174.

[9] Eyckens, P., Belkassem, B., Henrard, C., Gu, J., Sol, H., Habraken, A.M., Duflou, J.R.,Van Bael, A., Van Houtte, P., 2011, Strain evolution in the single point incremental forming process: digital image correlation measurement and finite element prediction, ‖ Int. J. Mater. Form. 4, pp.55－71.

[10] Duflou, J., Tunc¸ kol, Y., Szekeres, A., Vanherck, P., 2007, Experimental study on force measurements for single point incremental forming, ‖ J. Mater. Process. Technol., 189, pp.65－72.

[11] Ambrogio, G., Filice, L., Micari, F., 2006, A force measuring based strategy for failure prevention in incremental forming, ‖ J. Mater. Process. Technol., 177, pp.413－416.

[12] Ingarao, G., Ambrogio, G., Gagliardi, F., Di Lorenzo, R., 2012, A sustainability point of view on sheet metal forming operations: material wasting and energy consumption in incremental forming and stamping processes, ‖ J. Cleaner Prod., 29－30, pp.255－268.

[13] Iseki, H., 2001, An approximate deformation analysis and FEM analysis for the incremental bulging of sheet metal using a spherical roller, ‖ J. Mater. Process. Technol., 111, pp.150－154.

[14] Aerens, R., Eyckens, P., Van Bael, A., Duflou, J.R., 2010, Force prediction for single point incremental forming deduced from experimental and FEM observations, ‖ Int. J. Adv. Manuf. Technol., 46, pp.969－982.

[15] Martins P.A.F., B.N., Skjoedt M., Silva M.B, 2008, Theory of Single Point Incremental forming, ‖ Journal of Strain Analysis, 43, pp.15-35.

[16] Skjoedt M., H.M.H., Bay N., 2007, Creating Helical Tool Paths for Single Point Incremental Forming in Key Engineering Materials, ‖ 37,pp.583-590.

[17] Prashant Khanna, R.Manu, 2016, Analysis of forming force and part accuracy in incremental forming of polycarbonate sheets, ‖ ICONDM' 16 IIIT Kancheepuram, IJEST' 2017, pp.xxx-xxx.