Feature based assessment of forming force behavior in Incremental Sheet Forming

Satwik Priyadarshi
PDPM Indian Institute of Information Technology, Design and Manufacturing Jabalpur, Jabalpur-482005, Madhya Pradesh, India
satwik.p@iiitdmj.ac.in

Prashant K. Jain
PDPM Indian Institute of Information Technology, Design and Manufacturing Jabalpur, Jabalpur-482005, Madhya Pradesh, India
pkjain@iiitdmj.ac.in

J. J. Roy
Centre for Design & Manufacture, Bhabha Atomic Research Centre, Trombay-400085, Mumbai, Maharashtra, India
jjroy@barc.gov.in

M.K.Samal
Reactor Safety Division Bhabha Atomic Research Centre, Trombay-400085, Mumbai, Maharashtra, India
mksamal@barc.gov.in

Debanik Roy
Board of Research in Nuclear Sciences Bhabha Atomic Research Centre, Trombay-400085, Mumbai, Maharashtra, India
deroy@barc.gov.in

Puneet Tandon
PDPM Indian Institute of Information Technology, Design and Manufacturing Jabalpur, Jabalpur-482005, Madhya Pradesh, India
ptandon@iiitdmj.ac.in

ABSTRACT
Forming forces and their behavior plays an important role in defining the mechanism of any sheet metal forming process. In Incremental sheet forming, due to inherent complexities, study of forming force behavior is a challenging task. In absence of geometry independent techniques, only studies specific to certain axisymmetric and planer symmetric geometries are available. Present work deals with development of a novel methodology for the study of behavior of forming forces in geometries with multiple features by mapping components of forming forces obtained with dynamometer readings to spatial coordinates of tool path coordinates. Techniques such as Nearest Neighbor Search, RANSAC and calculation of l_2 norm are employed for this very purpose.

Keywords
Incremental Sheet Forming, Forming Forces, Point cloud, Nearest Neighbor Search, RANSAC

1. INTRODUCTION
Incremental Sheet Forming (ISF) is a novel sheet forming process which allows user to produce sheet metal components directly from CAD models using a CNC milling center with nil or minimum part specific tooling. Unlike, conventional forming processes which requires costly part specific dies; it allows a single set-up without specialized tooling to produce a variety of geometries in different shapes and sizes. Immense flexibility in implementation and reduced requirement of part specific and process specific tools makes ISF an ideal choice for rapid prototyping of sheet metal components and production of components in small batches [1].

1.1 Introduction to Incremental Sheet Forming
ISF is performed using a CNC controlled hemispherical tool following a tool path of normally finishing operation which when indented on a metal sheet clamped at periphery produces highly localized plastic deformation. This deformation when dragged along the path of CNC controlled tool progresses incrementally. In due course, this progression of incremental deformation results in formation of desired contour or geometry on the sheet. Most common and simple set-up for ISF is known as Single Point Incremental Forming (SPIF) as shown in figure 1. Here, sheet is deformed at a single point of contact by the tool.

Most significant of the parameters which governs the ISF process are wall angle (α),vertical step size (Δz),forming depth (h), tool diameter (d), etc. as shown in Figure 2.

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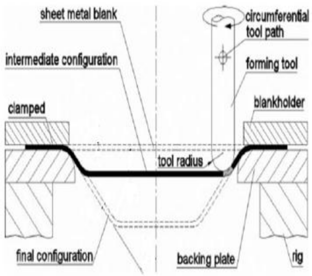

Figure 1.Incremental Sheet Forming [1]

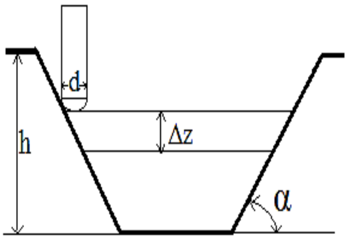

Figure 2.Schematics of ISF Parameters

In ISF, the angle subtended by the wall of the component with horizontal plane is referred as wall angle (α) as shown in Figure 2. Wall angle is formed by the tool while it follows a predefined tool path. Step size (Δz) is the distance moved by the tool, in vertical direction per revolution of the tool for helical tool path. Forming depth (h) means the maximum depth achievable through ISF for a given geometry with given material and process conditions. Tool diameter (d) is the diameter of the forming tool being used. Generally, hemispherical tipped tools are used in ISF. Tools transfers deformation force to sheet at tool-sheet contact to facilitate the desired local deformation.

1.2 Background

In the existing literature, study of forming force is limited to only simple axisymmetric geometries like truncated cone, truncated pyramid etc. [2]. These studies, utilized the rate of force change obtained from measuring devices such as tool dynamometers and then correlated them with increasing forming depth [3].

Although, parameters like wall angle and step depth are sufficient to describe behavior of forming [4], [5], [6]; complex shaped geometries presents challenges in explaining the force behavior through traditional methods.

A complex geometry may comprise multiple features of different wall angles. Further, in case of adaptive tool path [7]; step depth may differ with change in depth.

In both the aforementioned cases, behavior of forces can't be explained by a single value of wall angle or step depth. Local geometry i.e. geometry at a given depth and plane or tool position must be involved in assessing and forecasting forming forces and their behavior for providing a more generalized view. Sometimes, due to constraints on machine, material, tooling or geometry; forming forces above certain level are undesirable. By incorporating the effect of tool position on forming force the effect of local geometry can be easily approximated. Here by visualizing forming forces in relation with tool positions one can plan a corrective strategy by using forming at elevated temperature, multi pass ISF [8] or any other technique to bring down the intensity of the forming forces to the desired level.

Several geometries have been studied for incremental sheet forming applications, but literature indicating force behavior for geometries involving multiple features are scarce. In the present work, force data from ISF was configured to obtain the spatial variations occurring during the forming process and the force change pattern was observed on a complex shaped geometry.

The present work discusses a methodology which can be used to map and visualize forming forces to tool positions and geometrical features.

2 METHODOLOGY

A computational tool is developed to establish mapping between spatial coordinates and components of forming force. A special purpose NC code, an In-house tool and an open source solution forms the basic constituent of the tool box utilized in the present investigation. The proposed methodology comprises of tool path generation, acquisition of forming force data, mapping between forming force components and coordinates of tool path points. The resulting point cloud of tool paths points with force components as scalar fields can be segmented in sub-clouds of different shapes and features to facilitate feature based assessment of forming forces.

2.1 Test geometry

Since, the proposed methodology is a geometry based technique, preparation of a 3D CAD model of the desired geometry is the first step required. As a case study, test geometry is necessary which comprises of multiple features and can be formed easily. Hence, an Irregular Hexagon was chosen as test geometry because of its unsymmetrical shape and presence of multiple features such as flat, concave and convex surfaces with fillets and sharp corners. A uniform wall angle was kept for all faces. Wall angle of the geometry was taken at 55° to ensure complete formation of geometry. 55° is a safe wall angle as most of the sheet metal alloys allows achievement of considerable forming depth with it.

Dimensions of the geometry are chosen according to the constraints of available machine tools and fixtures.

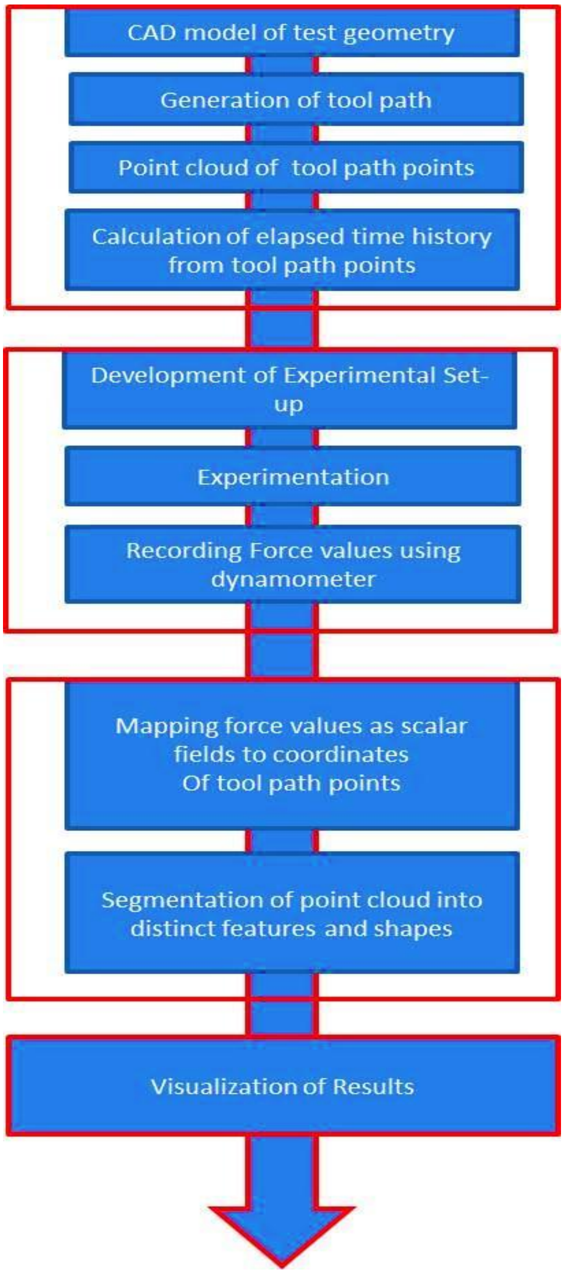

Figure 3.Methodology

Figure 4 shows the test geometry. Various faces of the test geometry are named as shown in Figure 4. Dimensions of the geometry is described in Figure 5 and Table 1.

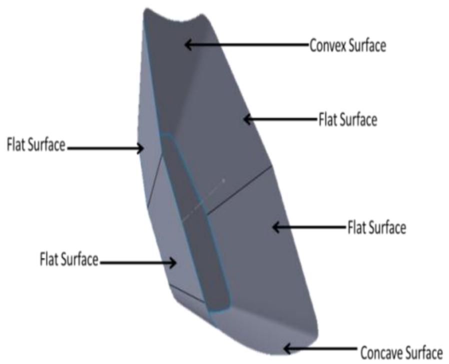

Figure 4.Test Geometry

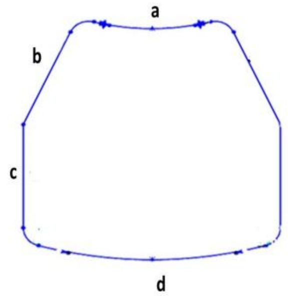

Figure 5.Various Faces of Test Geometry

Dimensions	
Radius of Convex Surface (a)	10 mm
Length of flat Surface (b)	56.47 mm
Length of flat Surface (c)	57.49 mm
Radius of Concave Surface (d)	10 mm
Depth	30 mm
Wall Angle	55°

Table 1.Dimension of the test geometry

2.2 Generation of Tool path

The test geometry in STL format is sliced into planer contours which are used for producing helical tool path as discussed by Malhotra et al. [9] and Zhu et al[7]. Here, STL model when sliced in Z direction results in generation of "n" number of contours separated by incremental depth of tool path in negative Z direction. Number of slices from a STL model depends on geometry of the component and desired incremental depth. By interpolating a helical

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curve on points of the contours; the tool path is generated.

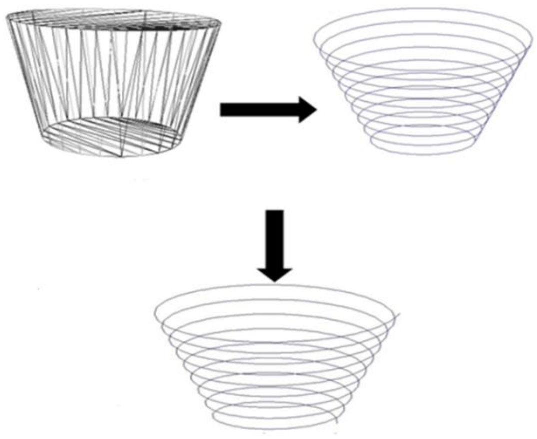

Figure 6.Generation of tool path

The set of points on the tool path can also be considered as a 3 dimensional point cloud. Figure 7 shows a point cloud formed using tool path points of the test geometry. Since, the point cloud being analyzed is synthetically produced; it is completely devoid of outliers and noise. Although, base of the geometry fails to get captured, it is not a matter of concern as the base lies un-deformed and detached from the forming process.

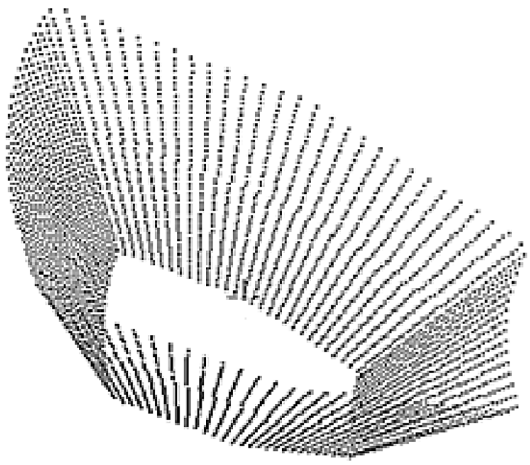

Figure 7.Point cloud formed using tool path points

2.3 Calculation of elapsed time between tool positions

As calculation of elapsed time between tool positions is required to facilitate mapping of tool position to force data, the NC code was prepared with linear interpolation and circular interpolation was completely avoided. Feed rate was chosen as constant at 2000 mm/min.

Tool path generated only through linear interpolation at constant feed rate allows the tool path to be considered as a polyline comprising of multiple straight line segments. The coordinates of the points on tool path can also be considered as coordinates of tool's position while forming.

By taking l2 norm, distance between the two consecutive tool path points were calculated in 3 dimensional space which leads to calculation of elapsed time while tool moves between the given consecutive points. Therefore, complete time history of the tool movement can be calculated in this manner.

2.4 Experimental set-up & Experimentation

An experimental campaign was undertaken to form geometry through SPISF. An Experimental set-up was developed and experiments were performed to record force data using a tool dynamometer.

All experiments were performed using a 3-axis milling center. Fixtures and clamping mechanism were developed in-house. Fixtures were developed according to the test geometry and clamping plates were designed as per the external periphery of the test case. The design was realized by fabricating mild steel plates of 10 mm thickness. Provision for setting a tool dynamometer in the fixture was also included. Figure 8 shows the experimental set up with tool dynamometer.

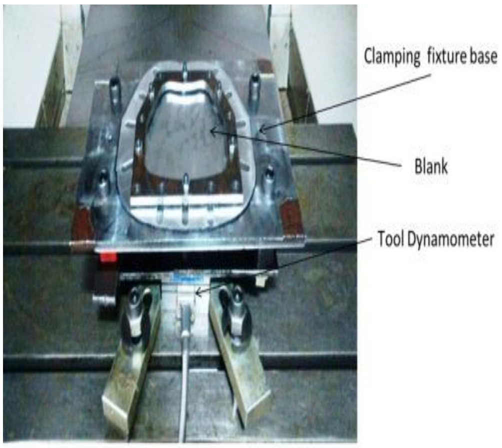

Figure 8.Experimental setup with dynamometer

Experiments were conducted using set-up described in the preceding section. Irregular Hexagons were formed through SPISF. Al 1050 sheets with 0.95 mm thickness were used as blank material. The process parameters selected for the experiment are described in Table 2. The process parameters were chosen arbitrarily as their effects are not a point of concern for the present investigation.

Process Parameter	Selected Value
Feed Rate	2000 mm/min
Step Depth	0.5 mm
Tool speed	1000 rpm

Table 2.Process Parameters

2.5 Recording force values by a Tool Dynamometer

For measuring numerical values of forming in x, y and z axes a Kistler tool dynamometer has been used. It is a Piezoelectric Quartz based three-component dynamometer used for measuring the three orthogonal components of a force. The dynamometer consists of four three-component force sensors fitted under high preload between a baseplate and a top plate. Each sensor contains three pairs of quartz plates, one sensitive to pressure in the z direction and the other two responding to shear in the x and y directions respectively. The force components are measured practically without displacement. The outputs of the four built-in force sensors are connected inside the dynamometer in a way to allow multicomponent measurements of forces and moments to be performed [10]. Figure 9 shows a Kistler Multicomponent tool dynamometer.

Figure 9.Kistler Multicomponent tool dynamometer

Dynamometer was mounted below a base plate on the outer corner of which four holes were drilled to accommodate the desired fixture. Base plate rested on the upper surface of the dynamometer while the fixture stood on the base plate by using four pegs of desired length. Set-up of dynamometer also consists of a Personal Computer or workstation and a controller to acquire and record data. Figure 4 shows arrangement of dynamometer in the experimental set-up.

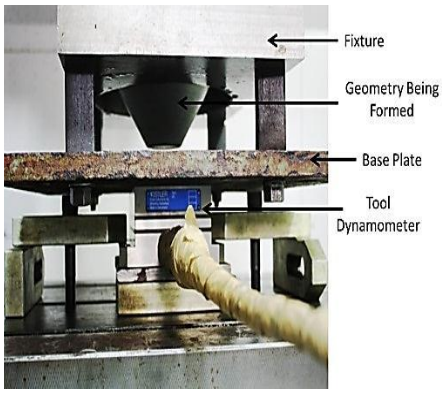

Figure 10.Arrangement of dynamometer in experimental set-up

Force components in x, y and z axes i.e. F_x, F_y and F_z were considered for the present investigation and were recorded in newtons. 10 Samples per second were recorded and saved in a csv file. Forming force vs. forming time plot with interval of 0.1 seconds is shown in Figure 11.

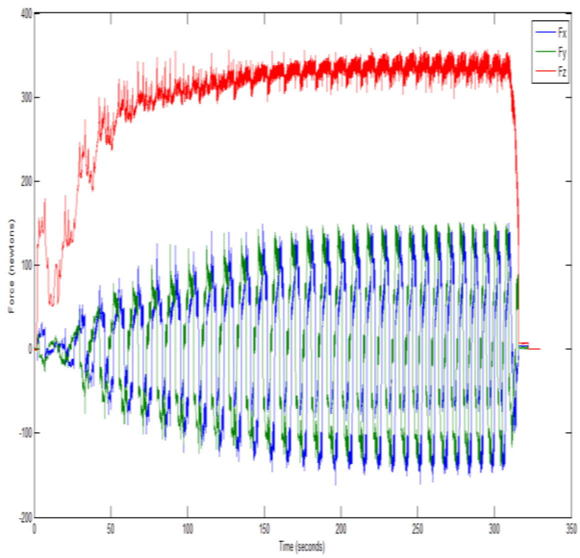

Figure 11.Plot of forming force vs. forming time

2.6 Mapping force values to coordinates of tool path points (tool positions)

A Nearest Neighbor Search (NNS) algorithm [11] was used to obtain the mapping of the time history of values to the spatial coordinates during the forming

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operation. Initially, for every value of elapsed time in time history calculated from the tool path; a nearest neighbor was searched in the array of elapsed time values recorded by the dynamometer.

As it can be seen form Figure 12, a linear NNS algorithm was utilized for the very purpose. For any given data point in Time History calculated from the Tool path a nearest neighbor can be searched in the array of Elapsed time calculated using the dynamometer. Linear NNS returns the index value of the identified nearest neighbor. For example, as shown in Figure 12 at 17 second after the initiation of forming, i.e., at time = 17 second in time history calculated from the tool path the Nearest Neighbor in the array of Elapsed time calculated using the dynamometer is 17.82 sec with index value of 3.

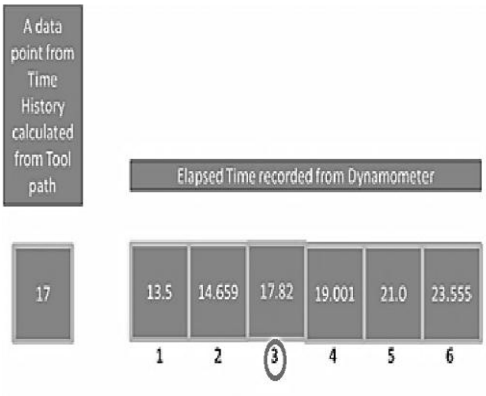


Figure 12.Linear NNS at T= 17 seconds

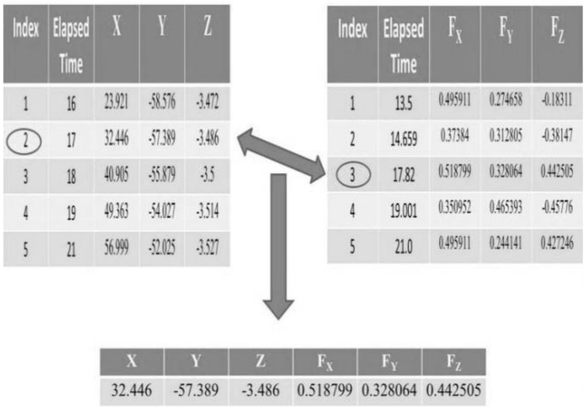
By calling all the values corresponding to index 3 in the array of Elapsed time calculated using the dynamometer and values corresponding to index of query point (i.e., 17); a new array can be generated with both spatial coordinates and force components. This is shown in Figure 13.

Force components can be considered as 3 dimensional scalar fields corresponding to the respective tool position points in the point cloud.

2.7 Segmentation of features from the point cloud

Collection of tool path points can also be considered as a 3 dimensional point cloud. Figure 7 showed a point cloud formed using tool path points of the test geometry. Force components can be considered as 3 dimensional scalar fields corresponding to the respective tool position points. Since, the point cloud being analyzed is synthetically produced it is completely devoid of outliers.

General point cloud segmentation techniques can easily be applied to such points to generate sub-clouds representing individual features. Sub-clouds can be generated from the original point cloud of tool path coordinates through implementation of a commonly available technique known as Random Sample Consensus (RANSAC) Shape Detection.



Index	Elapsed Time	X	Y	Z
1	16	23.921	-58.576	-3.472
2	17	32.446	-57.389	-3.486
3	18	40.905	-55.879	-3.5
4	19	49.363	-54.027	-3.514
5	21	56.999	-52.025	-3.527

Index	Elapsed Time	F_X	F_Y	F_Z
1	13.5	0.495911	0.274658	-0.18311
2	14.659	0.37384	0.312805	-0.38147
3	17.82	0.518799	0.328064	0.442505
4	19.001	0.350952	0.465393	-0.45776
5	21.0	0.495911	0.244141	0.427246

X	Y	Z	F_X	F_Y	F_Z
32.446	-57.389	-3.486	0.518799	0.328064	0.442505

Figure 13.Mapped data

In the present work a variant of RANSAC developed by Schnabel et al. [12] is used. It was selected over other techniques such as Hough Transform [12] and MLESAC [12] as it is a simple and general technique with potential for wide applicability. Further, complex shaped geometries can easily be processed.

This operation can be performed using Cloud Compare (CC), an open source solution for point cloud analysis [13]. Cloud Compare uses the same implementation as introduced by Schnabel et al. and just provides a simple user interface on top of it.

Parameters selected for the segmentation operation are given as shown in Table 3. For the given test geometry, minimum number of support points per primitive was manually selected at 500. Even though minimum points required per primitive are 3, 4, 3 and 4 respectively for Plane, Sphere, Cylinder and Cone; a much larger set of points was used as the features inherent to test geometry were large themselves with high density of points. Furthermore, as it is visually evident that the test geometry has lack of toroid features; Plane, Sphere, Cylinder and Cone were the only primitives chosen. Number of maximum iterations is automatically computed by the Cloud Compare software.

Using data obtained from experimentation described in the previous section, the proposed methodology was implemented. Sub-clouds for various features were generated. The original geometry was divided into 5 different types of features. Figure 14 depicts the sub-clouds generated from the original point cloud using RANSAC.

Now, individual points with spatial co-ordinates of tool position and scalar values of forming force components corresponding to position are ready to be analyzed for drawing required inferences.

Parameters for segmentation	
Primitives	Plane, Sphere, Cylinder, Cone
Minimum support points per primitive	500

Table 3.Parameters for segmentation

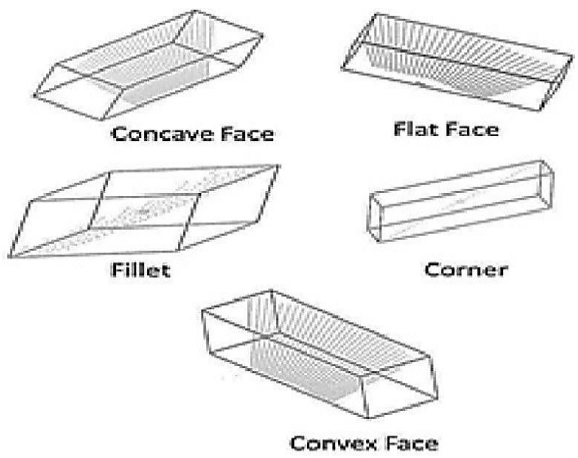


Figure 14.depicts the sub-clouds generated from the original point cloud

2. 3 ASSESSMENT OF FORCE BEHAVIOR FEATURE-BY-FEATURE

After the implementation of the proposed methodology, sub-clouds for various features were assessed for force behavior. After segmentation, Force Vs. time graphs for each feature was plotted separately, and the trends in all the three components of force values were observed. Histograms were used for quantitative description of the spatial force behavior.

3.1 Force vs. time graphs

Force vs. time graphs are shown in Figure 15 and Figure 16. Figure 15 shows graphs of force behavior at the faces. A common trend in force behavior was observed. Figure 16 shows graphs of force behavior at the corners and fillets. Graphs for corners and fillets too show similar trends.

It is the number of spatial points in features which results in differences visible in graphs; as the number of sample points varies across the features. Otherwise, force behavior is almost same across the features due to all features being at a constant wall angle.

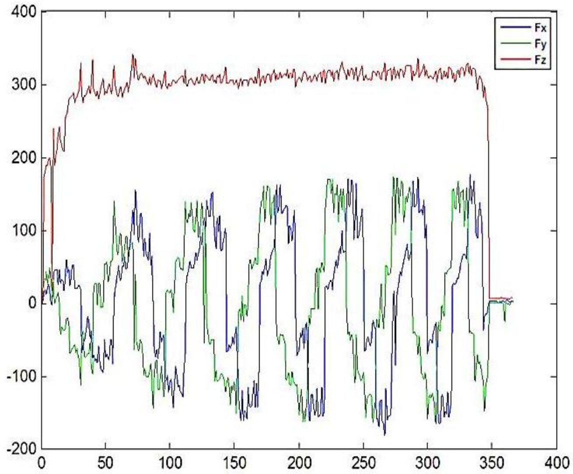


Figure 15 (a).Plot of forming force vs. forming time for flat surface

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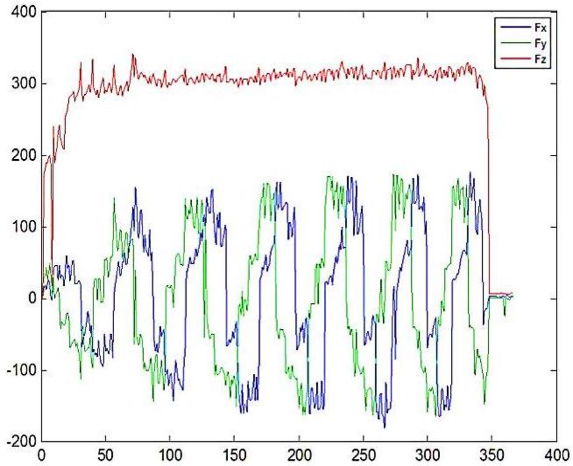

Figure 15 (b).Plot of forming force vs. forming time for convex surface

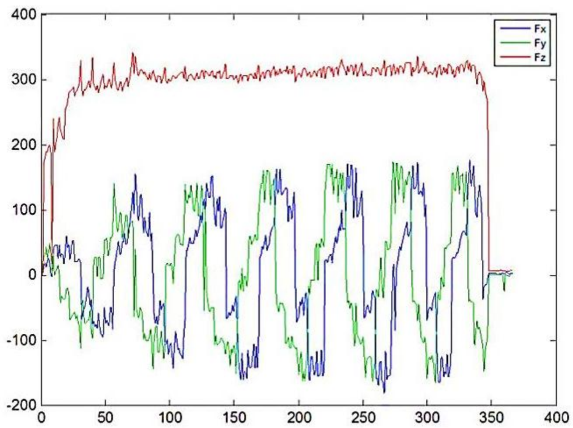

Figure 15 (c).Plot of forming force vs. forming time for concave surface

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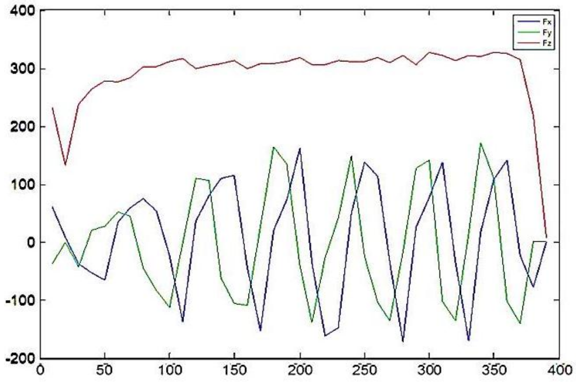

Figure 16 (a).Plot of forming force vs. forming time for a corner

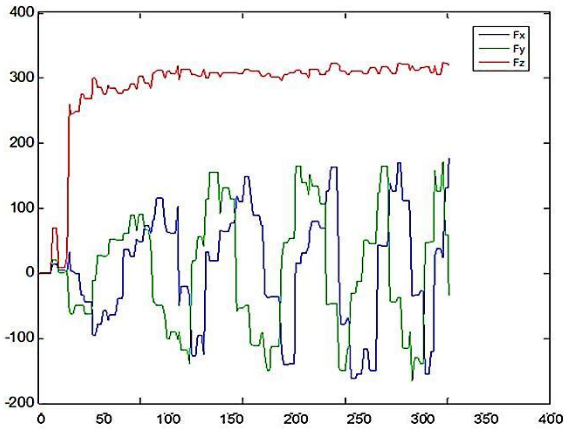

Figure 16 (b).Plot of forming force vs. forming time for a fillet

3.2 Quantitative analysis of the forces

Apart from the graphs shown in the preceding section a quantitative description of the force behavior is also required.

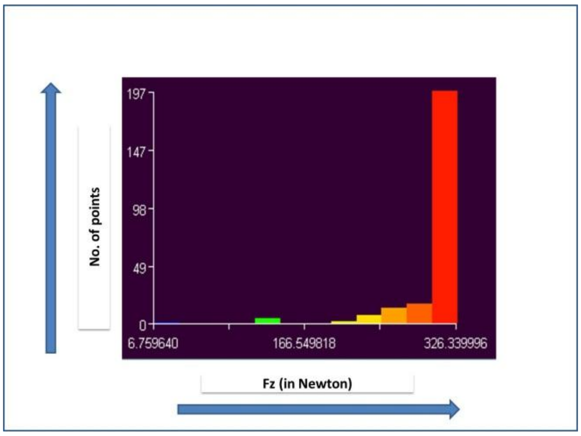

Figure 17 Histogram of Fz from point cloud of a fillet with values of Fz mapped as a scalar field

After mapping force components with spatial coordinates, quantitative variation in forming forces is shown with the help of a Histogram as Shown in Figure 17.

4 RESULT & DISCUSSION

As presented in the previous sections, the methodology for spatial assessment of the forming forces in Incremental Sheet Forming was successfully developed and tested on the selected test geometry.

Force vs. time graphs were plotted for individual features by segmenting the point clouds mapped with force components as scalar fields. Histograms for individual features were plotted to gauge the spatial variation in forming forces in a quantitative manner.

Based on the visualizations and spatial assessment of forming forces it is now possible to take corrective actions to bring forming forces to the desired levels.

In future, present work can be extended by integrating the spatial assessment with corrective actions as a single solution.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] Jeswiet, J., Micari, F., Hirt, G., Bramley, A., Duflou, J., Allwood, J. Asymmetric single point incremental forming of sheet metal. CIRP Annals - Manufacturing Technology 54, 88–114, 2005

[2] Petek, Aleš, Karl Kuzman, and J. Kopac. "Deformations and forces analysis of single point incremental sheet metal forming." Archives of Materials science and Engineering 35.2 (2009): 35-42.

[3] Li, Yanle, et al. "Efficient force prediction for incremental sheet forming and experimental validation." The International Journal of Advanced Manufacturing Technology 73.1-4 (2014): 571-587.

[4] Duflou, J. and Tunçkol, Y. and Szekeres, A. and Vanherck, P., "Experimental study on force measurements for single point incremental forming", Journal of Materials Processing Technology, 2007.

[5] Petek, A. and Kuzman, K. and Kopac, J., "Deformations and forces analysis of single point incremental sheet metal forming", Archives of Materials science and Engineering, 2009

[6] Henrard, C. and Bouffioux, C. and Eyckens, P. and Sol, H. and Duflou, J.R. and Van Houtte, P. and Van Bael, A. and Duchêne, L. and Habraken, A.M.,

"Forming forces in single point incremental forming: prediction by finite element simulations, validation and sensitivity", Computational Mechanics, 2011

[7]Hu Zhu, Zhijun Liu, Jianhui Fu. Spiral tool-path generation with constant scallop height for sheet metal CNC incremental forming. Int J Adv Manuf Technol 2011, 54:911–919.

[8] Kim, T.J., Yang, D.Y. Improvement of formability for the incremental sheet metal forming process. International Journal of Mechanical Sciences 2000 42, 1271–1286.

[9] Rajiv Malhotra, N. V. Reddy, Jian Cao. Automatic 3D Spiral Toolpath Generation for Single Point Incremental Forming. Journal of Manufacturing Science and Engineering, 2010, Vol. 132 / 061003-1.

[10] Kistler Multicomponent tool dynamometer Manual

[11] Nene, Sameer A., and Shree K. Nayar. "A simple algorithm for nearest neighbor search in high dimensions." Pattern Analysis and Machine Intelligence, IEEE Transactions on 19.9 (1997): 989-1003.

[12] Schnabel, Ruwen, Roland Wahl, and Reinhard Klein. "Efficient RANSAC for Point Cloud Shape Detection. "Computer graphics forum.Vol. 26.No.2. Blackwell Publishing Ltd, 2007.

[13] Girardeau-Montaut, D. Cloudcompare, a 3D point cloud and mesh processing free software. Technical Report, EDF Research and Development, Telecom ParisTech. http://www. danielgm. net/cc/ (accessed 19.03. 2015).

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