Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Double Sided Incremental Forming: Capabilities and Challenges

To cite this article: N V Reddy and R Lingam 2018 *J. Phys.: Conf. Ser.* **1063** 012170

IOP Conf. Series: Journal of Physics: Conf. Series **1063** (2018) 012170 doi:10.1088/1742-6596/1063/1/012170

Double Sided Incremental Forming: Capabilities and Challenges

N V Reddy, R Lingam

Department of Mechanical and Aerospace Engineering,
Indian Institute of Technology Hyderabad, Kandi, Telangana, 502285, India

E-mail: nvr@iith.ac.in

Abstract. Incremental Sheet Forming (ISF) is gaining importance because of its flexibility to form customized/low volume sheet metal parts. Out of different variants of ISF, Double Sided Incremental Forming (DSIF) is most flexible variant which uses two tools, one to form the geometry and the other to provide local support. Complex geometries with features on both sides of sheet can be formed in single setup by changing the roles of forming and supporting tools based on the geometrical characteristics. This article presents the evolution of DSIF process, machines, methodologies and strategies to form complex geometries and their prediction. A multi-stage methodology is attempted to enhance the accuracy of large components is presented. Results show that the accuracy of a 250 mm × 250 mm size conical component is enhanced by 50% (maximum error reduced from 2.9 mm to 1.4 mm) using two-stage forming.

1. Introduction

Incremental Sheet Forming (ISF) is gaining importance because of its flexibility to form customized/low volume sheet metal parts [1, 2, 3, 4, 5]. Advantages of ISF are forming complex parts with simple tools, higher formability compared to conventional forming, low forming forces, less lead time and suitable for low volume production. Leszak [6], was the first one to propose the concept of incremental sheet forming. Since then many variants of ISF are developed. Some of them are, Single Point Incremental Forming (SPIF) using milling machine [7], Two-Point Incremental Forming (TPIF) with partial or full support [8], Double Sided Incremental Forming (DSIF) [9, 10, 11].

Double sided incremental forming is the most flexible variant of incremental sheet forming. It uses two independently controlled tools, one on either side of sheet, to form the geometry. At any instant, one tool will be forming the geometry while the other provides local support that enhances the accuracy of components. The role of tools (forming or supporting) can be changed to form complex three-dimensional parts having features on both sides of sheet and/or multiple features.

This paper presents evolution of DSIF process, machines, forming strategies, feature recognition and geometry prediction methodologies. A multi-stage methodology is attempted to enhance the accuracy of large components formed using DSIF. While forming large components, compliance of scaled-up DSIF machines results in either loss of support tool contact or squeezing of sheet material. Proper contact of support tool is achieved by using force controlled support tool.

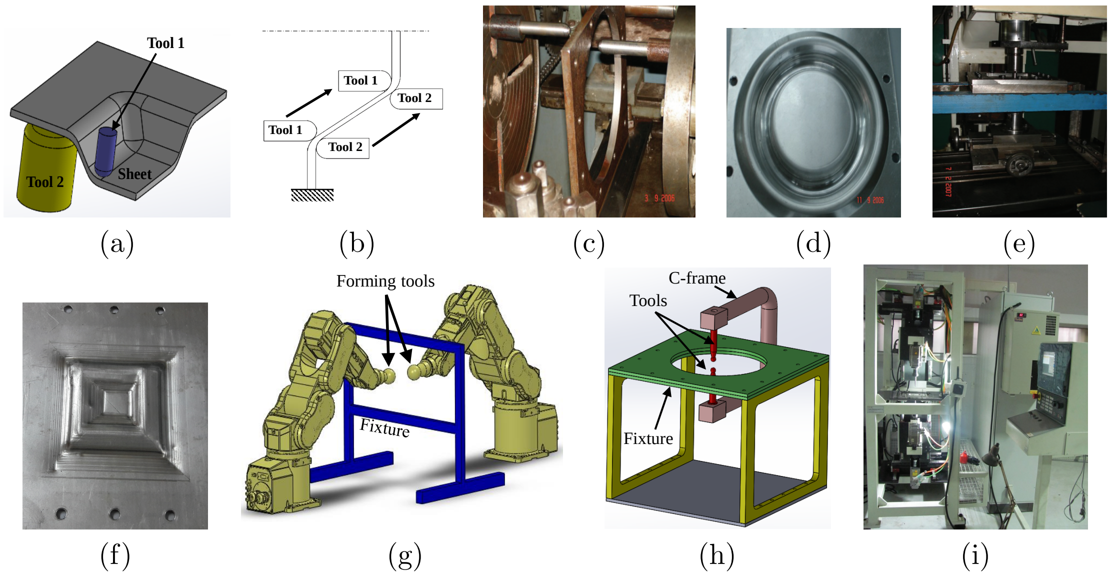
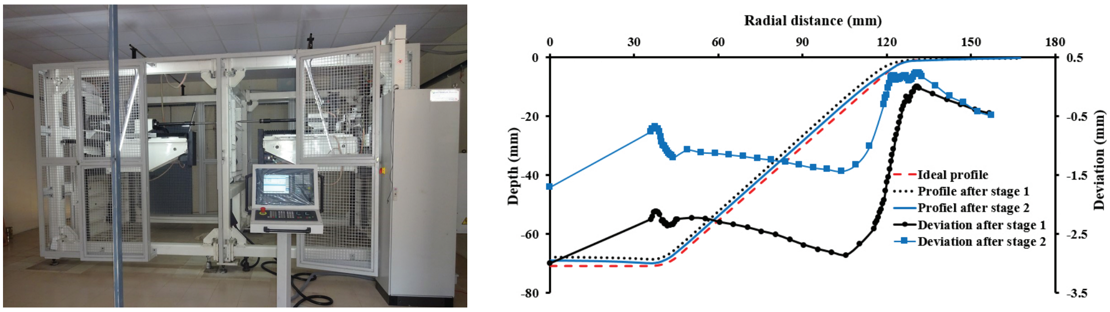


Figure 1. DSIF evolution (a) Incremental forming using two tools [12] (b) DSIF schematic (synchronized tool motion) (c) DSIF on turning machine (IIT Kanpur, 2006) (d) torus component made using DSIF on turning machine (e) DSIF on milling machine (IIT Kanpur, 2007) (f) asymmetric component formed using DSIF (g) DSIF using robots (Ruhr-Universit,2011 [13]) (h) DSIF using C-clamp (Northwestern university, 2008 [14]) (i) custom built DSIF machine (IIT Kanpur, 2010 [15])

2. DSIF: State of the Art

Machines: Yoshikawa et al. [12] have performed incremental forming using two tools as shown in figure 1 (a) in the year 1999. They used a large tool with flat base to provide support at component opening and deformation is achieved using small spherical ended tool. In 2006, an attempt is made at Indian Institute of Technology Kanpur (IITK) to form torus geometry using synchronized tools (figure 1 (b)) on a turning center as shown in figure 1 (c) [16, 17]. It can be clearly seen that features on both sides of sheet can be formed in single setup without pattern support (figure 1 (d)). In 2007, Meier et al. [9] used two industrial robots to form components using two tools as shown in figure 1 (g). They used large flat ended tool as support at the component opening and a small spherical ended tool to form the geometry, similar to that of Yoshikawa et al. [12]. In 2007, concept of DSIF to form asymmetric components is tested at IITK on a milling machine by adding a manually controlled three axis positioning system to control second tool (figure 1 (e)) [16, 17]. In 2008, DSIF using C-frame as shown in figure 1 (h) is performed at North-western university to achieve synchronized motion of forming and support tools and studied the effect of squeezing [14]. Once the concept is proved, a dedicated DSIF machine with two independently controlled tools is designed and developed at IITK in 2010 (figure 1 (i)) [15]. Similar DSIF machine is developed at Northwestern university in 2011 [10]. A DSIF machine using two hexapod manipulators is developed and patented by Ford USA in 2012 [18]. A scaled-up DSIF machine (figure 2 (a)) is design and development at Indian Institute of Technology Hyderabad (IITH) (designed by November, 2014 and comissioned by May, 2016), that can form components up to 1150 mm $\times$ 1150 mm, to study the effect of scaling-up and take the process to industrial usage. This machine has displacement and force control options for both the tools. Ford, USA has also developed a DSIF machine to form large components up to 1500 mm $\times$ 2000 mm [19].



(a) (b)

Figure 2. (a) Scaled-up DSIF machine (IITH) (b) Measured profiles and error during two stage forming of cone (wall angle 30°, fixture opening 340 mm × 340 mm, component opening diameter 250 mm)

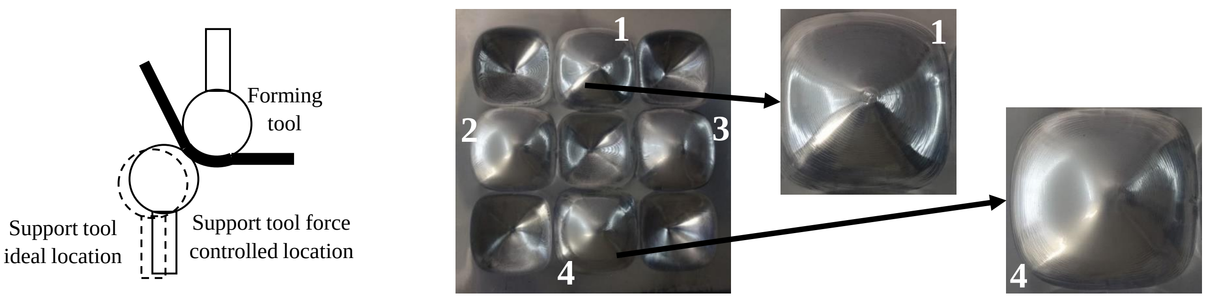
Small components (up to 150 mm × 150 mm opening): Meier et al. [13] performed DSIF using two industrial robots by synchronizing their motion and force control for support tool. They showed that higher formability and enhanced accuracy can be achieved by applying pressure in deformation zone using force controlled support tool [13]. Malhotra et al. [10] used squeezing between tools to enhance the accuracy of components formed using DSIF and maintain continuous contact of support tool. Here, squeeze factor is defined as the ratio of tool gap to thickness predicted using sine-law. Geometric accuracy of conical component, with 65°wall angle, increased when squeeze factor of 0.9 is used. However, with higher squeeze factor (0.85) accuracy reduced, which is attributed to higher spring-back. Moser et al. [20] considered in-plane curvature in thickness prediction which enhanced the support tool contact while forming a component with convex and concave in-plane curvatures. Lingam et al. [11] developed a mechanics based methodology to predict and compensate the tool and sheet deflections during DSIF to enhance the accuracy of components. They formed several components with complex geometries using Al5052 sheets with maximum error of 0.5 mm between measured and ideal profiles.

Malhotra et al. [21] introduced accumulative-DSIF (ADSIF), in which tools are moved outward from the center of component and the same concept is patented by Ford, USA [22]. In ADSIF support tool tip is in a plane parallel to initial plane of sheet and maintining contact with the sheet. Relative position between forming and support tools is varied to achieve desired wall angle [23]. Zhang et al. [24] used ADSIF followed by DSIF to form a pyramid geometry with pockets. ADSIF is used to maintain support tool contact, whereas DSIF with squeeze is used to enhance the accuracy.

Sheet spring-back and tool deflection due to forming forces causes deviation in the part dimensions. Asghar et al. [25] developed mechanics based methodology to predict component thickness as well as forming forces during SPIF and used the same to compensate the tool and sheet deflections caused by forming forces. Lingam et al. [11] have developed mechanics based compensated tool paths for DSIF by extending the work of Asghar et al. [25] for SPIF; to maintain contact of support tool without arbitrarily selecting the squeeze factor and formed variety of components with opening size up to 150 mm × 150 mm with good accuracy (maximum error is 0.5 mm). Thin plates and shell theory used to calculate sheet deflection is valid only when sheet length to thickness ratio is in between 10 and 100 [26]. Hence, for large components, above methodology cannot be used as sheet length to thickness ratio becomes very high.

Large components: In the present work, a multistage methodology is attempted to enhance the accuracy of large components. A conical component with 30° wall angle and 250 mm opening diameter is formed in two stages. Aluminium alloy 5052 sheet of 0.8 mm thickness, tool diameter of 12.7 mm and fixture opening of 340 mm × 340 mm are used to form the component. Tool path is generated by applying only tool radius compensation (neglecting tool and sheet deflections) to the contact points on the geometry obtained by slicing. Component is formed using displacement control for both forming and support tools. After first stage, error between measured and ideal profiles ranged between 2.3 mm to 2.9 mm in component wall region (figure 2 (b)). In the second stage, component is formed with same tool path as that of first stage after which error between measured and ideal profiles reduced by 50% (1.2 mm to 1.4 mm). During second stage, the contact area and forming force is very less as tool is moving along already formed geometry resulting in less tool and sheet deflections. Hence, component accuracy improved without any additional compensations. However, support tool did not maintain contact with the sheet. Work is in progress to develop mechanics based methodologies to enhance the accuracy of large components.

In scaled-up DSIF machine designed and developed at IITH, spindle weight causes the machine frame to deflect due to its compliance, resulting in relative displacement between two tools even when they are programmed to move same distance. Hence, support tool may lose contact or squeeze the sheet material while forming components. Proper contact of support tool, without squeezing the sheet, can be achieved using force control for support tool. In force control strategy, support tool is first programmed to move to ideal tool path location (with predicted thickness and tool radius compensation) and then it is moved towards the center of forming tool (figure 3(a)) till specified load is applied. Note that displacement control is used for forming tool. A component with multiple pockets (figure 3(b)) is formed to demonstrate the effect of force control. Component shown in figure 3(b) has four pockets (numbered 1 to 4) with opening in to the plane of paper and five pockets with opening out of plane of paper. Pocket 1 is formed using force controlled support tool and pocket 4 is formed using displacement control. Support tool marks are seen on pocket-1, which is formed using force controlled support tool (figure 3(c)). Whereas, no marks are seen on pocket-4, which is formed using displacement controlled support tool (figure 3(d)). Further work is in progress.

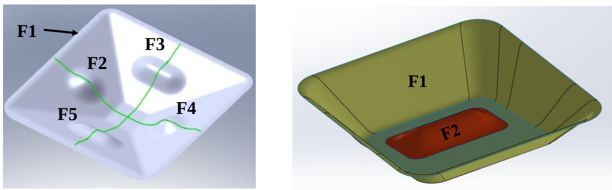


(a) (b) (c) (d)

Figure 3. Demonstration of force control (a) schematic of force controlled support tool (b) component with multiple lobes (c) support tool marks on the lobe formed using force control (d) no support tools marks on the lobe formed using displacement control

3. Feature recognition and geometry prediction for DSIF

A sheet metal components with complex geometries can have regions (features) that need to be formed by different tools of DSIF and/or proper sequence and appropriate forming strategy has to be used based on geometrical characteristics. For example, geometry shown in figure 4 (a)



(a) (b)

Figure 4. Geometries with multiple features

has a pyramid with four pockets on it. Here, pyramid feature has to be formed first and then the pockets. Geometry shown in figure 4 (b) has two features, in which F1 has to be formed by top tool and F2 has to be formed by bottom tool.

Lingam et al. [27] used silhouette of surfaces to identify saddle points and splitting loops on free-form geometries. In case of multiple-surface models, boundary representation information is used to recognize features. Relation between features and their loops is used to sequence them. As a thumb-rule, forming feature in out-to-in sequence is suggested when a feature is surrounded by other feature. When features are distributed over the sheet, larger features have to be formed first. They developed three slicing strategies namely, horizontal, inclined and offset-slicing to generate tool paths based on feature characteristics. Agbor et al. [28] performed slicing and feature recognition simultaneously. In their strategy, component geometry is sliced using planes parallel to initial plane of sheet. Loops obtained in consecutive slices are projected on to a plane to check whether a loop is surrounded by the other. Features are recognized by grouping loops based on their relations. Boundary representation based methodology of Lingam et al.[27] will recognize five features (four pockets and a pyramid) for the geometry shown in figure 4 (a). Whereas Agbro et al. [28] methodology will recognize it as single feature.

Tool and sheet deflection due to forming forces effect the accuracy of components [25]. In addition, forming sequence of features also effect the accuracy of components [29]. Predicting the formed geometry helps in deciding the right forming sequence. Lingam et al. [30] developed a mechanics based methodology to predict geometry of components formed using DSIF by combining thickness and force prediction (Bansal et al. [31]), tool and sheet deflection prediction (Asghar et al. [25], Lingam et al. [11]) and multi-stage profile prediction ([32]) methodologies.

In incremental forming, component is formed gradually by series of local deformations and the process is asymmetric even for a symmetric geometry. Hence, time taken for finite element simulations is very high. Even for small geometries of 100 mm $\times$ 100 mm, FEA simulation of DSIF takes three to six weeks. Work is in progress to develop prediction methodologies for scaled-up components.

4. Challenges

Double Sided Incremental Forming is a cost effective process to form customized low volume products. However, the following aspects need to be studied throughly to exploit DSIF capabilities.

(1) Compensations for multi-stage strategy.
(2) Process design for achieving required mechanical and metallurgical properties.
(3) Reduce computational resources required for prediction.
(4) Development of mechanics based models for prediction.
(5) Post processing treatment for enhancing the properties.

5. Conclusion
Double sided incremental forming is the most flexible variant of ISF. Developments in DSIF technology in recent past shows that DSIF is gaining attention for forming low-volume functional/customized parts. However, scaling-up the process to form large components with good accuracy, forming complex geometries and studying the mechanical and metallurgical properties are the gaps that need to be addressed to take DSIF in to industrial use. Multi-stage strategy used to form large conical component with 250 mm $\times$ 250 mm opening, enhanced the accuracy by 50% from first stage to second stage (error less than 1.4 mm). Proper contact of support tool achieved using force control can be exploited to enhance the accuracy.

6. Acknowledgments
This work is supported by SERB, Department of Science and Technology, New Delhi, India. Sanction no. EMR/2015/000286

References
[1] Jeswiet J, Micari F, Hirt G, Bramley A, Duflou J and Allwood J 2005 *CIRP Ann: Manu. Techno.* **54** 88–114
[2] Cao J, Huang Y, Reddy N, Malhotra R and Wang Y 2008 *International Conference on Technology of Plasticity, Gyeongju, Korea* 751–752
[3] Reddy N V, Lingam R and Cao J 2014 *Handbook of Manufacturing Engineering and Technology* 411–452
[4] Emmens W, Sebastiani G and Van den Boogaard A 2010 *J. Mate. Process. Techno.* **210** 981–997
[5] Behera A K, de Sousa R A, Ingarao G and Oleksik V 2017 *J. Manu. Process.* **27** 37–62
[6] Leszak 1967 *United States Patent Office* Patent no. 3,342,051
[7] Iseki H, Naganwa T and Kato K 1992 *Transactions of Japan Society of Mechanical Engineers* **59** 3147–3155
[8] Matsubara S 1994 *Journal of Japan Society for Technology of Plasticity* **35** 1311–1311
[9] Meier H, Smukala V, Dewald O and Zhang J 2007 *Key Eng. Mate.* **344** 599–605
[10] Malhotra R, Cao J, Ren F, Kiridena V, Cedric Xia Z and Reddy N 2011 *J. Manu. Sci. Eng.* **133** 061019
[11] Lingam R, Amit S and Reddy N 2016 *J. Manu. Sci. Eng.* **138** 091008
[12] Yoshikawa T, Nakamura K, Ueno K and Shima A 1999 Study on incremental sheet metal bulging using tool bar (1) *Japanese Spring Conference on Technology of Plasticity* p 305
[13] Meier H, Magnus C and Smukala V 2011 *CIRP Ann: Manu. Techno.* **60** 327–330
[14] Wang Y, Huang Y, Cao J and Reddy N Experimental study on a new method of double sided incremental forming *ASME International Manufacturing Science and Engineering Conference* pp 601–607
[15] Koganti M 2011 *M.Tech thesis, Indian Institute of Technology Kanpur*
[16] Reddy N V and Dixit P M 2007 *Department of Science and Technology, Government of India* Project no. SR/S3/MERC–37/2007
[17] Cao J and Reddy N V 2007 *National Science Foundation, USA* Project no. 0727843
[18] Johnson C F, Kiridena V S, Ren F and Xia Z C *United States Patent Office* Patent no. US 8,322,176
[19] Kiridena 2016 *https://energy.gov/*
[20] Moser N, Zhang Z, Ren H, Zhang H, Shi Y, Ndip-Agbor E E, Lu B, Chen J, Ehmann K F and Cao J 2016 *Ann: Manu. Techn.* **65** 265–268
[21] Malhotra R, Cao J, Beltran M, Xu D, Magargee J, Kiridena V and Xia Z 2012 *CIRP Ann: Manu. Techno.* **61** 251–254
[22] Kiridena V S and Xia Z C *United States Patent Office* Patent no. US 8,302,442
[23] Ren H, Moser N, Zhang Z, Ndip-Agbor E, Smith J, Ehmann K F and Cao J 2015 *J. Manuf. Sci. Eng.* **137** 051008
[24] Zhang Z, Ren H, Xu R, Moser N, Smith J, Ndip-Agbor E, Malhotra R, Xia Z C, Ehmann K F and Cao J 2015 *J. Manuf. Sci. Eng.* **137** 051007
[25] Asghar J, Lingam R, Shibin E and Reddy N V 2014 *Proc. Instn Mech. Engrs, Part B: J. Eng. Manu.* **228** 1027–1035
[26] Timoshenko S 1964 *2nd edn. McGrawHill, New York*
[27] Lingam R, Prakash O, Belk J and Reddy N 2017 *Int. J. Adv. Manu. Techno.* **88** 1639–1655
[28] Ndip-Agbor E, Ehmann K and Cao J 2018 *J. Manuf. Sci. Eng.* **140** 031004
[29] Lingam R, Kishan I, Harikrishnan C and Reddy N 2015 *ASME Int. Manu. Sci. and Engg. Conference*
[30] Lingam R, Bansal A, Prakash O and Reddy N V 2018 *J. Manuf. Sci. Eng.* **140** 021016
[31] Bansal A, Lingam R and Reddy N V 2017 *J. Manu. Process* **28** 486–493
[32] Lingam R, Bansal A and Reddy N 2016 *Int. J. Mate. Form.* **9** 395–404