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Design and validation of a fixture for positive Incremental Sheet Forming

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Abstract

Incremental sheet forming (ISF) is an emerging manufacturing technique in which sheet metal is formed into desired shape through the application of localized force using a hemispherical tool. Potential advantages of the process are its relatively low cost and small lead times have to be balanced against the disadvantages of low dimensional accuracy and a limited understanding of the process's internal mechanics.

ISF system can be classified as positive, or negative, depending on whether the sheet material is progressively deformed onto a protrusion or a cavity. In negative systems the work piece is held on a static fixture, whereas in positive ISF the fixture must be incrementally lowered onto a protruding die. Although the vertical movement of positive ISF fixtures is easily illustrated schematically, its implementation is challenging; if the descent is actuated the motion has to be carefully coordinated with those of the forming tool; if free sliding on vertical columns the rig must move without jamming or rocking. This paper reports the development and testing of a positive ISF fixture design that uses nylon sleeve bushes. Symmetric and asymmetric components were formed using the designed fixture, modular wooden dies and a rotating tool with multiple diameters and the results are discussed.

Keywords: Incremental sheet forming, Fixture design, Sheet thickness, Sheet strains.

1) Introduction

Incremental Sheet Forming (ISF) is a family of processes where the movement of a spherical tool causes highly localized deformation of material in the surrounding area [1]. Typically a multi-axis CNC machine with a hemispherical tipped tool and sheet clamper is used for ISF [2]. Although frequently referred to as being a die-less process [3]such configurations are the exception rather than the rule [4]. More generally dies are used and ISF process can be categorized by the convexity of tooling used [Figure 1] [5]. In contrast to other sheet forming processes (e.g. spinning and shear forming) ISF can create both symmetric and asymmetric shapes [6]. ISF is not limited to one-offs, but can also be regarded as a low volume production method [7] whose productivity and cycle time are affected by the size of the forming tool [8], the geometry of the part being formed [9] and the type of surface finish that is desired [10].

Frequently ISF capability is determined by the size of the fixture that can be mounted on the worktable of the CNC milling machine (the most common arrangement) [11]. The fixture is usually composed of a base plate and a top plate, which holds the sheet clamped round the edges by a series of threaded fasteners [12]. Forming is caused by the pressure created by the forming tool as it follows a path generated by CAM software [13] that generates localized stresses that cause the material to yield and deform [6]. ISF process evolution and validation are discussed in greater detail in next section of the paper.

In positive ISF processes the sheet is progressively deflected onto a protrusion whereas in negative ISF processes the sheet moves into a cavity. In both cases the design of the fixture is important in determining the success of the process. However the fixture used for positive ISF must combine vertical movement with sufficient stiffness to ensure the twisting moments caused by forming operations do not cause significant deflections.

This paper details the process of designing and assessing a fixture for positive ISF that uses nylon bushes to create a sheet mounting frame that is free to move vertically while resisting horizontal twisting. A series of component parts, produced on the prototype fixture, are used to assess if the structure’s deflections impact on the geometry of the formed components.

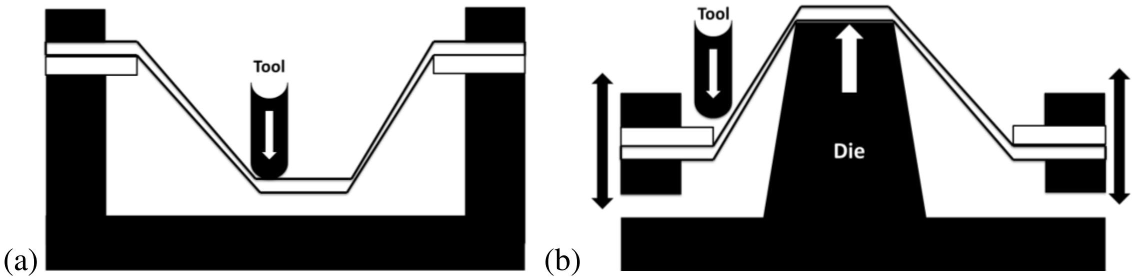


Figure 1: Types of Incremental Sheet Forming Fixtures ; (a) Positive, (b)Negative.

The rest of the paper has the following structure: Section 2 briefly reviews the literature with particular emphasis on the design of fixtures, section 3 outlines the design methodology while section 4 validates the results and section 5 discusses the limitations of the work and draws some conclusion.

2) Literature

The emergence and evolution of the modern ISF process can be summarized as occurring in three distinct stages [14]:

Stage 1 **Emergence**: The historical origins of modern ISF systems progress from the automation of artisan 'panel beating' processes to CNC system over a period between 1700 and 1996. During this period several companies were involved in developing various single point sheet forming technologies. Initial the focus was on variations of spinning processes (see Berghahn [15] and Leszak [16] 1967 patents) however in 1978 Mason's published a paper which is widely regarded as the origin of the modern ISF process. Mason analyzed different forming processes and identified the processes which are most suitable for low volume batches. He also clearly describes the fundamentals of the ISF process in which a tool follows the contours of the geometry in three dimensional space [17]. The large contribution of Japanese researchers to ISF started with the work of Iseki et. al [18] during 1989 when (aware of Mason's work) he developed a sheet manufacturing system using a contour following tool.

Stage 2 **Fundamentals**: Most of the early research into the fundamental engineering science of the ISF process was done by Japanese automotive companies who filed several significant patents between 1993 and 2000. For example Matsubara [19] patented both Two-Point Incremental forming in 1994 and an extension describing the downward movement of an inclined blank in 1997.

Stage 3 **Development:** From 2000 onward interest and knowledge of the ISF process spread beyond the Japanese automotive industry. Motivated by the simplicity of the ISF process researchers in Europe and American started reporting significant work in areas such as wall angles[20], feed rates [21], path optimization [22], process simulation [23], microstructure [24], springback [25], accuracy [26], applications [27, 28] and equipment design. Interest from the aerospace industry resulted in several well-funded research programs and in 2003 Jeswiet et. al published a comprehensive review of ISF technology [1]. Since 2000 researchers have report using an increasing range of different methods and technologies for ISF process [9, 29-34].

However despite significant academic work compared to other sheet forming technologies (e.g. spinning, shear forming) the study of incremental sheet forming process is at a much earlier stage and the process's behavior still needs accurate mathematical models for different conditions and specific materials to be developed [35]. There are several different aspects of ISF technology being researched by different groups around the world. One of these research areas is the design of equipment to perform ISF processes. Broadly speaking incremental sheet forming processes can be classified as one of the following: bespoke purpose built machines, adapted CNC machine tools and adapted robots [Figure 2]. The following sections describe each of these categories:

2.1 Purpose built ISF machines:

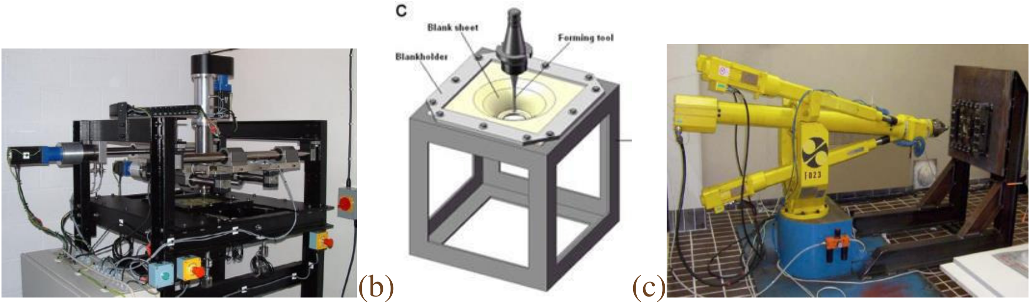
Several groups have created dedicated ISF machines. For example Powell created a machine to support experimental work on titanium sheet [36]. Similarly, Allwood et al [35] reported the design of a machine, at Cambridge University, specifically for ISF process research [Figure 2a] that incorporates load cells to acquire forming force data as the tool moved in X, Y and Z axis. Matsubara [19, 37] further contributed to bespoke ISF equipment with several patents which described fixtures for single point incremental sheet forming that incorporates guiding and supporting bars for used with CNC machines. The vertical movement in Matsubara's fixture was actuated with two servo motors. Kitazawa reported work carried out on a rotating blank using a CNC machine [38]. Motivated by the needs of automotive manufacturers Amino's [3] company developed a commercial system for ISF. Another specialist machine for the ISF process was built for University of Saarbrucken by a Japanese company [39, 40].

2.2) Adapting CNC milling machines for ISF:

However dedicated machines are the exception rather than the rule and most research on ISF has been performed using conventional CNC machines [41-45] adapted with suitable tools and fixtures [Figure 2b] [43]. Use of CNC machines is an attractive approach because of their availability and low cost (compared to other methods). A good example of this approach is the system reported by Thibaud et al. that consist of a fixed die support, a modular die, a sheet holder and attachment screws. The ISF tool is mounted on the CNC machine and a 4-axis dynamometer is used to find forces and torque during the process [46]. Similar equipment has been used by both Ambrogio et al. [47] and Duflou et al. [48]. Although the vertical movement of positive ISF fixtures is easily illustrated schematically its implementation is challenging because of the need to create a structure that is both rigid (i.e. does not tilt horizontally) and compliant (i.e. free to move vertically as the sheet deforms).

2.3) Robots ISF systems:

Rather than moving a forming tool with a CNC machine other researchers have used multi-axis robots to generate forces and paths. Meier et al for example reports the use of industrial robots, shown in Figure 2c to form rectangular sheets into standard geometries (cones, hemispherical, pyramids). The system supported the forming 200X200mm sheets (with a thickness between 0.5 and 1 mm). The machine consists of fix clamper, a forming tool and a supporting tool. Both tools are mounted on industrial robots which move through a programmed series of movements [49]. KU Leuven and IWU Fraunhofer Institute of Machine Tools and Forming Technology designed and manufactured a vertical table with clamping system for use in robot based ISF process [50]. A coolant supply was integrated with a 6-axis robot that was used to perform an ISF process (a similar arrangement is described by Callegari et.al [51]). A summary of the ISF systems reported in the literature is shown in Table 1.



(a) (b) (c)

Figure 2: Fixture Design; (a) Purpose built [35], (b) for CNC milling machine, [43](c) Robots [49].

Table 1: Reported ISF Machines.

Machine Type	**Custom made**		**Industrial Robot**			**CNC Machine**	
System	Allwood [35]	Amino [3]	Meier [49]	KU Leuven and IWU [50]	Callegari [51]	Jesweit [6]	Thibaud [46]

Comment	Force sensors on tool	Commercial system	Supporting die feature	Sheet clamped vertically & formed with robotic arm	Sheet clamped vertically & formed with robotic arm	Conventional ISF process	Micro forming
Work piece area (mm)	300x300	Variable Custom made	200x200	Not provided	180x180	300x300	34x34

2.4) Sheet Material

The experiments used to validate the fixture design reported later this paper use both plastic and metal sheet to verify different aspects of the rigs kinematics and mechanical properties. A fundamental aspect of this approach to the design's functional validation was to understand the parameters of these materials behavior in the context of an ISF process. This was done by review of the literature.

For example S. Le et al [52] discusses the relationship between tool, step size, feed rate, spindle speed and formability of thermoplastic sheets. Different polymers were studied to and their appropriateness for the ISF process established by considering: springback, ductility, cost and aesthetics. High formability of plastic sheet was achieved through cold forming (ISF). Yonan et.al discussed plastic flow and failure in Single Point Incremental

Forming (SPIF) for conical and pyramidal shaped parts. Linear strain loading paths were applied to empirically demonstrate an analytical framework's conditions [53]. Martins et al analyzed several polymers for ISF process and established that certain polymers have particular material properties that make them suitable for ISF. For instance, polyethylene terephthalate exhibits high formability, similarly polyamide can also attain high formability if twisting is prevented. Polycarbonate (PC) keeps its transparency after deformation and Polyvinyl chloride displays minimum springback [54]. However wrinkles appeared in all the parts formed from plastic sheet regardless of the composition. The literature confirmed that it was feasible to use a heated polymer sheet to test the fixture's kinematics (i.e. vertical movement) in the absence of unbalance forming loads (see section 4).

A much large literature exists on the ISF of different metals. For example Meelis et. al. conducted a study to quantify the forces involved in an ISF process that used aluminum. He also concluded that there are accuracy problems in ductile materials such as steel and aluminum due to spring back [55]. Ham and Jeswiet also discussed the accuracy of the ISF process for aluminum [56]. Robert et. al. discussed the manufacturing of large components with steel using an ISF process and discussed it with respect to kinematics of the tool. He used wide but shallow geometries with low wall angles to perform his study taking around two hours to make each part. He concluded that the parts had greatest springback at the center, similar results were reported by Muftooh et. al. [11, 57]. Researchers also performed a study on the influence of forming strategy on the main strains [58], thickness reduction [59, 60] and strain hardening [61] during ISF process for sheet metal. He used a spiral contour and stepped tool paths to conduct his study and concluded that spiral path is the optimum one [58]. Because the creation of the ISF fixture is motivated by an ongoing investigation in the ISF of titanium sheet the literature provide the basic design parameters of loads and deflections (see section 3) and also provide insight in to the details of the experimental validation (e.g. a spiral tool path was used to check the response to unbalanced loads). Similarly Petek et. al. performed a force analysis while using ISF to form steel sheets [62] and so this value was adopted (with an additional factor of safety) for the fixture's specification.

3) Fixture Design Methodology

The authors adopted Pugh's methodology for engineering design [63] that describes a systematic process which progresses through stages of requirements generations, specification, concept generation, concept selections, prototyping, testing, detail design and assessment. Subsequent sections briefly describe each of these stages.

The requirement for an ISF fixture arose from an ongoing project to develop ISF processes for titanium sheet on CNC machines. The breadth of the investigation meant that the fixture had to be capable of supporting both positive and negative ISF operations while being sufficiently ridged to ensure the deflecting forces remained vertical.

3.1 Fixture Requirements: Deformation forces and forming depth

The crucial parameter in the design of an ISF system (i.e. sheet fixture and tool) is the magnitude of localized force applied to the sheet. Part of this force is transferred to the structure of the equipment while rest is used to deform the sheet itself. A study of force developed during the ISF of a steel DC05 sheet by Petek et. al. reported that the maximum force was just under 2kN [62]. Because the objectives is a fixture to support the investigation of ISF processes for titanium and aluminum sheets the design must support load and forming depth typically needed to deform the material. These are estimated as a force of 5kN which if applied through a 16.5mm diameter tool, will create a pressure of 333 MPa. Pressure on tool and sheet will increase if the tool tip has a smaller diameter.

Forming depth is also an important design parameter for an ISF fixture. It was observed by the authors through initial experiments and the literature review that maximum forming depth attained for geometries (of this particular sheet size) are around 27mm for cold forming titanium sheet using SPIF [57]. This forming depth (27mm) could vary depending upon temperature, sheet thickness, surface finish, tool pitch and sheet size.

Given the above it was concluded that the design specification for an ISF fixture was that it had to accommodate maximum deformation of 100mm in vertical direction, enable the forming of sheets with a 110mmx110mm cross-sectional area and have a useable area of around 70mm x 70mm. Ideally this area should be able to increase to 300mmx300mm with useable area up to 250mm x 250mm by scaling up size of the fixture. On the bases of these parameters five conceptual designs were generated and analyzed.

3.2 Fixture Design Concepts

The following concepts for a fixture to support ISF were generated and numbered:

1. Springs: Four thin pillars with tension springs pulling sheet holder down.
2. Servo: Servo motor controlling vertical movement on ball screws.
3. 4 pillars: Four pillars serving as guide rails and fixture free to move vertically.
4. Scissors: Scissors design takes sheet holder down with pin in the middle.
5. 3 pillars: Three pillars serving as guide rails for vertical movement.

Table 2 shows design selection matrix for all the concepts considered and the criteria used to assess their relative strength.

Table 2: Concept selection matrix.

Concepts	**1** **Spring**	**2** **Servo**	**3** **4 pillars**	**4** **Scissors**	**5** **3 pillars**
Assessment Criteria					
Ease of Manufacturing	1	-1	1	1	1
Ease of use	0	-1	0	1	1
Efficiency	1	0	1	1	1
Durability	1	-1	1	0	1
Stability	-1	1	1	-1	1
Accuracy	0	0	0	1	1
Stuck	-1	1	-1	1	1

Modular design	-1	-1	1	1	1
Total	0	-2	4	5	8

As a result of qualitative ranking in the design matrix two concepts (4 and 5) were chosen for quantitative analysis. 3D CAD models were created for each of the three concepts. After part modeling, all the components were assembled using so called dynamic features that defined kinematic properties of an assembly (for e.g. pin joints and sliders) associated with the CAD package Creo. This enabled authors to visualize strengths and weaknesses of various concepts while analyzing their movement. Several changes to the original concept were made during modeling as assembly problems became apparent. Scissors and 3 pillars concepts are shown in Figure 3.

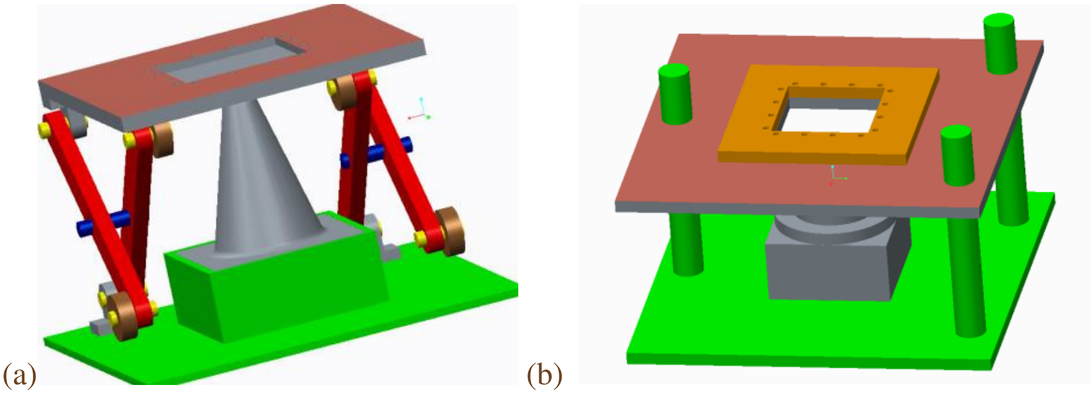


Figure 3: 3D CAD of fixture concepts; (a) Concept 4: scissors, (b) Concept 5: 3 pillars.

3.3) Prototype assessment

Concept 4 was prototyped to check the stability of the design for ISF process. Mojo® 3D printers were used to make joints between base/holder and links. Prototype was made at full scale as shown in Figure 4. Four rollers move along a straight path and let the sheet holder change its vertical position while keeping its horizontal position constant.

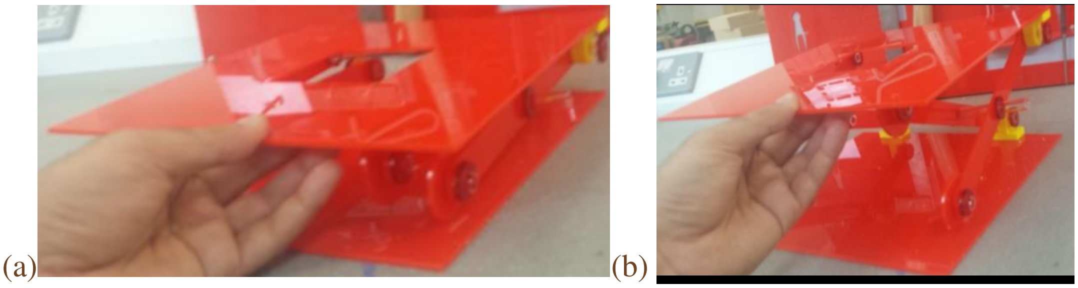


Figure 4: Scissor concept prototype at different levels (a) lowest, (b) highest.

Inspection of the concept 4 prototype suggested that there were issues with its lateral stiffness. Although several modifications to the initial design were made these changes only reduced, rather than eliminated, the lateral movement, or play, in the fixture. These trails concluded that concept 4 had inherently lower stiffness in the lateral direction, thus it was decided that concept 5 would be developed further.

4) Detailed design and validation

After detailed design a functional prototype of the ISF fixture based on Concept 5 was created. Steel and wooden dies with different forms were manufactured to check the kinematic and mechanical behavior of the concept 5 prototype. These dies [Figure 6c] are modular and can be replaced easily for forming symmetric and asymmetric shapes. [14]. The steel die used to form the polymer sheet is 93.3mm high with diameter of 10.99mm at the top and 38.84mm at the bottom. The wooden die used to form the Aluminum sheet is 25mm high with diameter of 11.46mm at the top and 37.07mm at the bottom [Figure 5]. Indeed 3D printed polymer dies could also be used with the fixture. Nylon bushes (rather than linear rolling element bearing) were used to enable free movement of fixture on the three columns. These bushes were selected because they have high stiffness coupled with low friction rate.

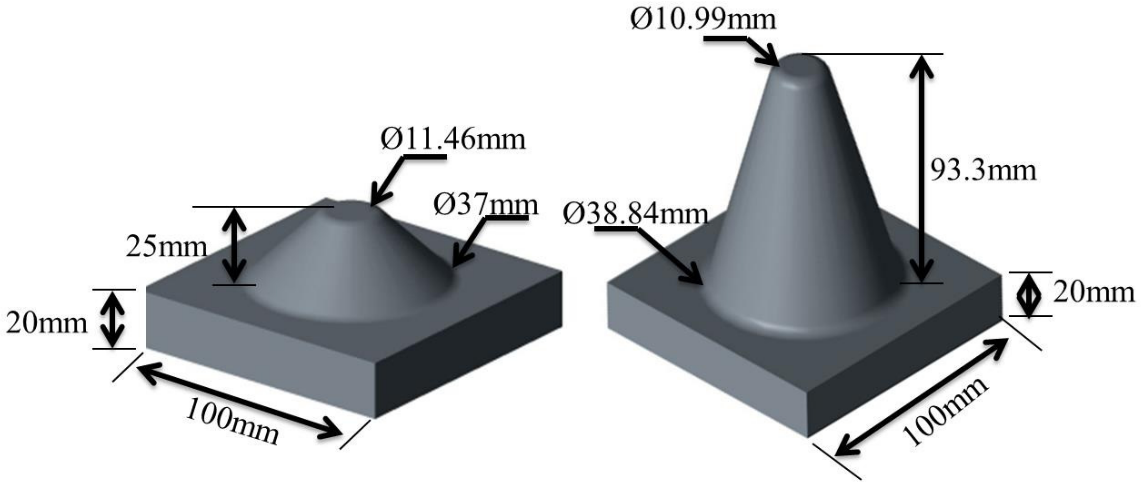


Figure 5 Wooden and steel dies used for forming the parts.

There are different types of materials used to manufacture polymer bushes including teflon, nylon, phenolics and delrin. Due to current load and environmental conditions nylon was selected for bush material. Nylon is self-lubricating, resist to abrasion and has a low wear rate. Several polymers absorb water from atmosphere and thus are hygroscopic [64]. With relative humidity of 40-65%, i.e. at normal environmental conditions, moisture content in nylon will hover around 1.5-2% by weight, consequently the possibility of expansion has to be considered [65]. Typically the increase in size can equal 0.5-0.6% in an unfilled nylon 6/6 at room temperature [65-68]. However many processors will purposely condition their nylon parts as they are being molded to shortens the time frame required for the part to reach equilibrium from weeks, or even months, to a couple of days. Because of which polymers have very low capacity to absorb further moisture at room temperatures [66].

Given the compliment nature of nylon 6/6 [69], the environment of the machine shop and the fact similar bushes have been employed successfully in analogous machine designs [70-73] any effects of moisture on the nylon bush bearings were judged to be negligible.

4.1) Kinematic assessment

The fixture was initially tested on a hard polymer (Acrylic) sheet to check its vertical kinematics. The polymer sheet was placed between the upper and lower holders and secured with nuts and bolts as shown in the Figure 6a. A hand held heater was used to simulate the vertical movement associated with the ISF process in the absence of an unbalanced force. The heater was revolved around the cone of the die to simulate ISF tool path. Heated air flow directed at a localized area increased the temperature of the polymer sheet to 148.8℃. This increase in temperature and the fixture weight forced sheet to deform into shape of die. Figure 6a shows the initial position of the sheet when sheet started deforming and Figure 6b shows final deformed part. This test validated the ability of fixture to move vertically and was considered successful since no jamming or rocking effects were observed. Although this experiment was successful but it did not include any lateral forces and did not check for stiffness and torsional resistance of the structure subjected to the loads required for an ISF process. To check fixture for these conditions further tests were performed on aluminum sheet using rotary tool.

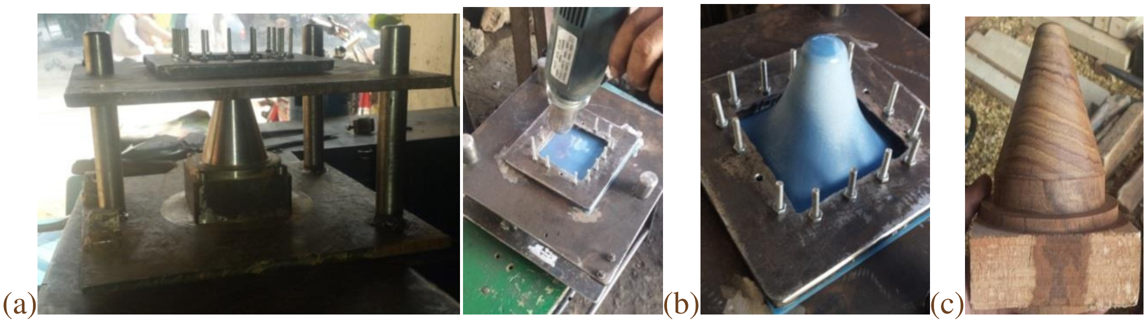


Figure 6: Testing on polymer sheet; (a) Start, (b) Finish, (c) Wooden die.

4.2) Mechanical Assessment

Several tests using metallic sheets were performed using the flexible fixture to check its stability, alignment, stiffness, torsional resistance and freedom of movement. The rotating tool and a wooden die were used to perform these experiments. The rotational speed of the tool depends upon the relative velocity between the tool and the metal sheet. Thrust bearings are used to align and hold the tool stick while its rotating Figure 7a. Rotation is helpful in reducing friction between the metal sheet and the tool. Sheets were formed until the point of fracture (maximum depth) to check the behavior of fixture under extreme operating conditions. This was done because all three components of force increase in magnitude with the forming depth and the force applied to the sheet and the fixture reaches a maximum just before fracture. Three of these tests are reported in current study. The fixture and tool were mounted on a 3-axis CNC milling machine as shown in Figure 7 and an ISF process was carried out an on an Aluminum sheet (AA 1050). Material properties, acquired through tensile tests of Aluminum sheets used in testing fixture are given in Table 3 .

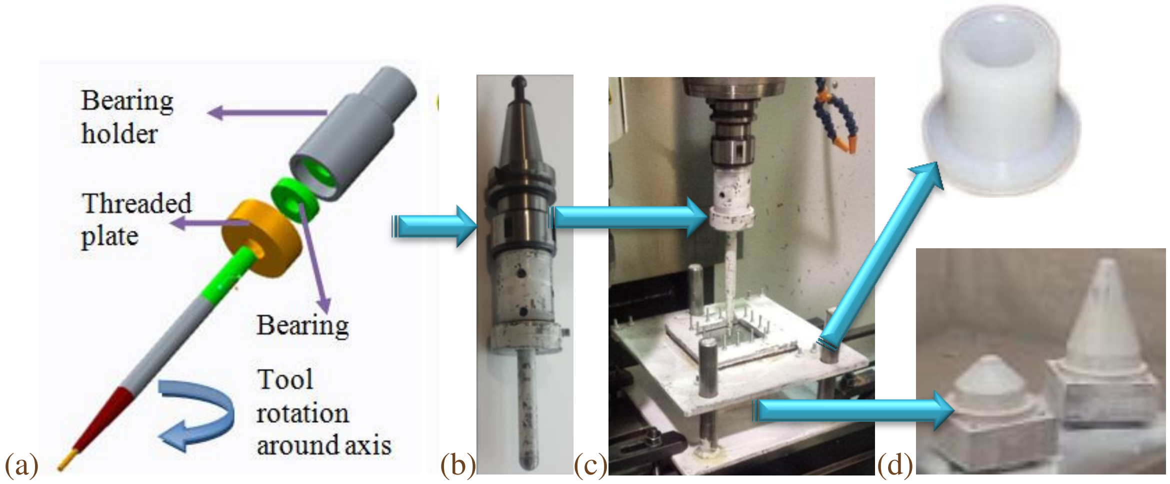


Figure 7: ISF equipment; (a) CAD model of rotating tool (4.5mm Dia), (b) Rotating tool (16.5mm Dia), (c) Equipment mounted on CNC, (d) Nylon bushes and wooden Dies.

Table 3. Material properties Aluminum used in the Fixture Assessment.

Yield Strength (MPa)	**UTS (MPa)**	**% Elongation**	**r**	**n**	**K (MPa)**	**u**
30.12	122	45	0.55	0.289	151.4	0.37

Where r is a measure of plastic anisotropy, u is Poisson's ratio, K is stiffness and n is strain hardening coefficient. Working area of the Aluminum sheet is 70mmx70mm although the total area is 130mmx130mm because of the margin used to clamp the sheet in the fixture. Figure 7 shows the fixture mounted on a CNC machine while performing the ISF process. The tool moves in a spiral path around the truncated coned to form the part. Figure 8a shows the output of the CNC milling simulation where the tool starts from a smaller diameter and moves towards bigger diameter. With the help of a positive wooden die a convex surface was produced. The value of pitch used for the test was 0.5mm and feed rate was 1000mm/min. A milling process simulation with tool is shown in Figure 8c, where material is being removed from a block.

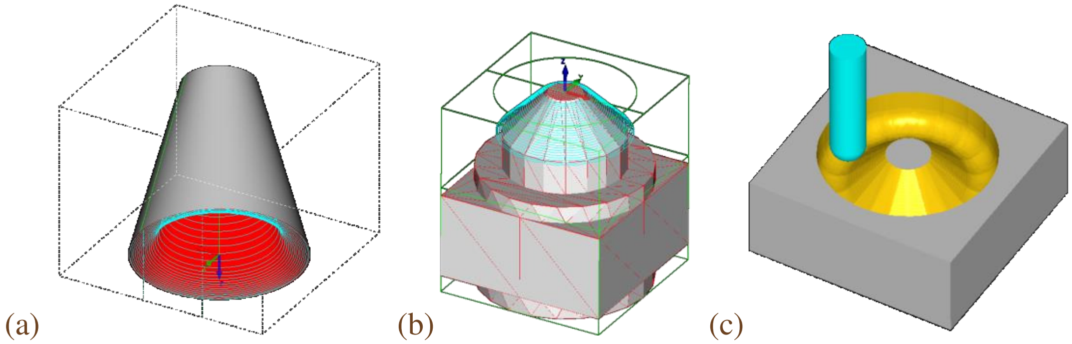


Figure 8: Tool path of ISF Process; (a) Surface of inward-out movement, (b) tool path over a die, (c) Milling process simulation.

Three different tests (Case A, B and C) were used to check the fixture's stiffness and movement under different load conditions and forming parameters (i.e. tool size and die geometry). Cases A and C are axi-symmetric geometries while case B is asymmetric geometry. Most of the parameters for these three cases are the same. Varying parameters are listed below and the resulting parts are shown in Figure 9.

- Case A: Tool size: 4.5mm, Die at center of Al sheet.
- Case B: Tool size: 16.5mm, Die off-center of Al sheet.
- Case C: Tool size: 16.5mm, Die at center of Al sheet.

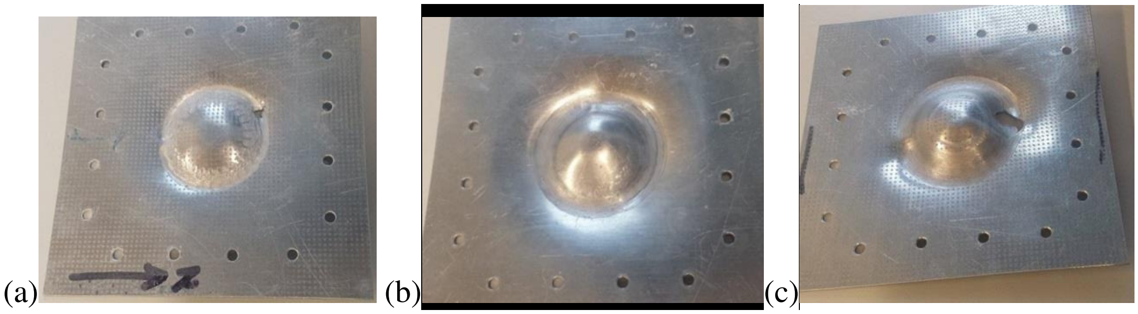


Figure 9: Final Aluminum sheets; (a) CASE A, (b) CASE B, (c) CASE C.

4.2.1) Part thickness and profile assessment

Different parameters of the ISF manufactured geometry were measured optically using a GOM ATOS Tripple Scan III scanner as shown in Figure 10. Because Aluminum is an extremely reflective material a thin layer of paint (Ardox) was applied to eliminate any specular reflection and acquire robust and continuous data from the 3D scanner. The resulting point cloud was polygonized, smoothed and processed to get final useable data.

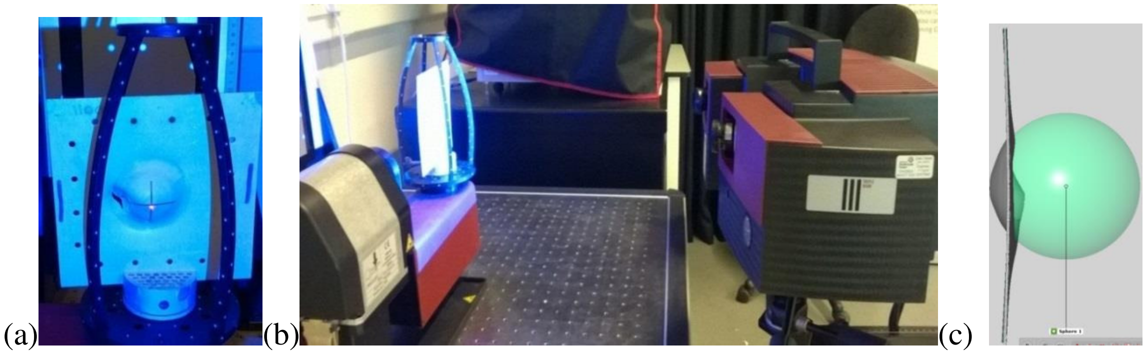


Figure 10: 3D scanning; (a) Formed part in scanning frame, (b) Part being scanned, (c) Scanned geometry centered.

Parts formed with Aluminum sheet through ISF process were observed to have a generally good condition (i.e. shape, surface finish etc) as shown in Figure 11. All three results show uniform distribution of thickness in the area formed by ISF i.e. regions A and B.

Regardless of the fact that a point load is applied on the sheet at distance from center, creating a moment and a torsion, in both sheet and the flexible fixture's structure, and that the test were continued up till their failing point, a significant degree of symmetry and evenness of distribution in thickness was achieved in all the test results. This confirmed the stability and rigidity of the flexible fixture while moving vertically during ISF process. Surfaces on both sides of the sheets were fairly smooth although bends can be seen near the external diameter of the formed shape. A grid of etched marks was worn off the surface where the tool was in contact with the surface, but is visible on other side of the surface. It is observed through thickness profile analysis that all the sheets had localized thin areas [Figure 11]. These thin areas were in contact with the rotating tool and wooden die. Central green circle (X) was in contact with the wooden die and material was thinned over the edges of die up to 1mm (initial thickness of the sheet was 1.3mm) with width of 5mm. The external circular region Y was forced down through localized dynamic application of the force. The external circular region width varies from case to case. Case A, B and C formed part by rotating tool and region Y has width of 6mm, 8mm, 15mm with area equal to 6940mm^2, 9160mm^2 and 1021mm^2 and fracture depth of 14.2mm, 16.3mm and 17.8mm respectively. Case B has non-uniform distribution of thickness reduction due to off-centered die. Region Y is deformed through multiple passes of the tool over the sheet. Thickness is not uniform throughout this region and the minimum thickness was observed in the middle of this region for all the three cases. However magnitude of the sheet thickness varies from case to case. For case C, thickness on sides of this region is 1.25mm and it reduces to 0.95mm in the middle and further to 0.75mm just before the fracture.

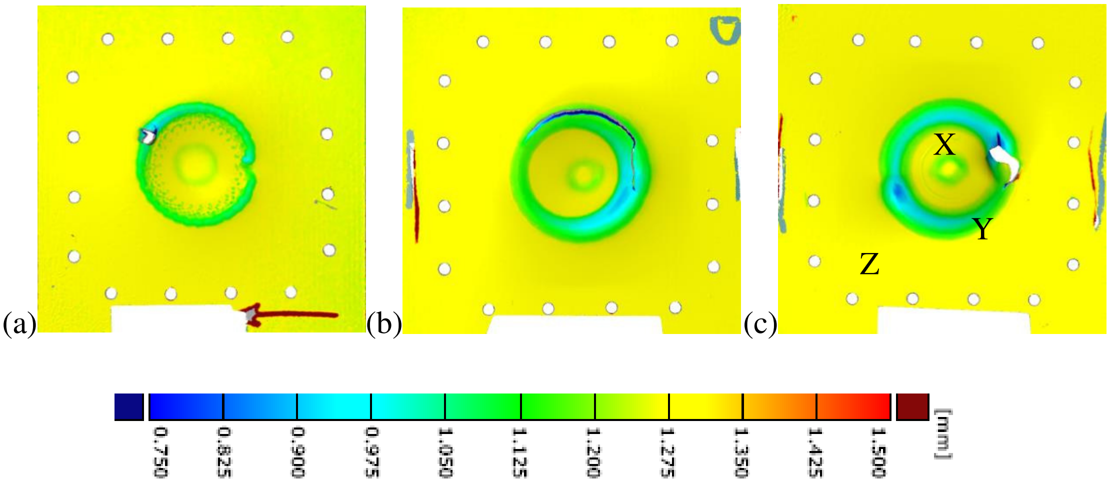


Figure 11: Thickness profiles of the sheet for; (a) CASE A, (b) CASE B, (c) CASE C.

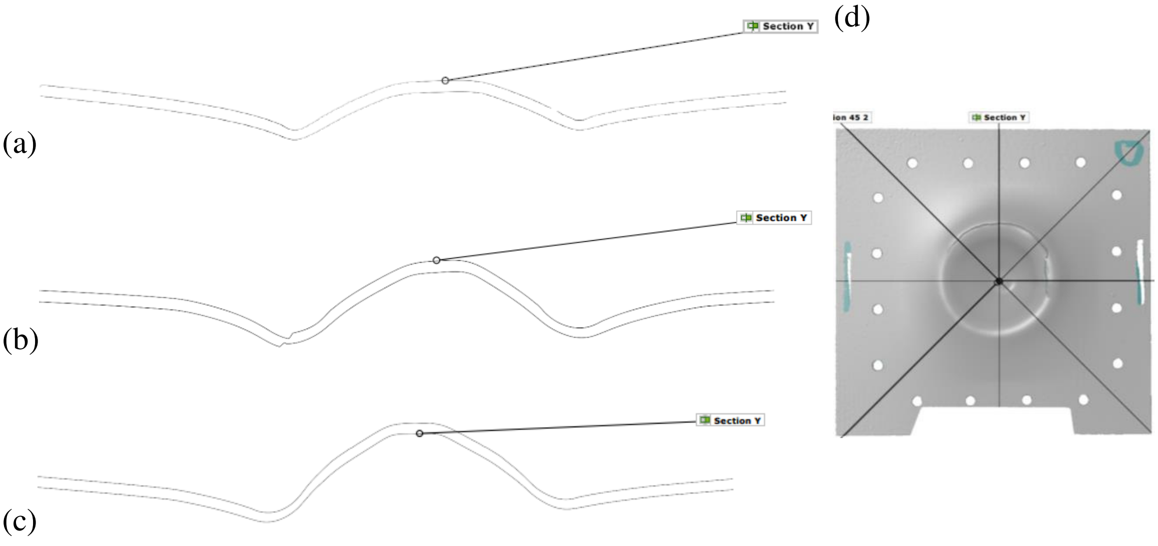


Figure 12: Geometric profiles of the sheet; (a) CASE A, (b) CASE B, (c) CASE C., (d) 3D scan of Case B with section lines.

Region Z i.e. from sides of the sheet until region Y, should have no reduction in thickness. Although region Z has no thickness reduction it does not have a straight profile as shown in Figure 12 and it is evident that sheet makes a small angle (less than 10°) to horizontal plane. This phenomena occurs due to spring back and similar results have been reported previously [57]. The location of the maximum bend and minimum thickness are, surprisingly, not the same. It is observed in all three cases that crack starts along rolling direction.

It is concluded from these three cases that both the tool path and the size of forming tool compared to geometry size influence the formability and quality of the ISF process. However crucial these results confirmed that the fixture's dynamics were not impacting significantly on forming process and that the Nylon bushes had sufficient stiffness to support the process.

Thickness reduction percentage for all the three cases are observed in localized regions and shows that the flexible fixture has sufficient alignment, rigidity and freedom to move. The range of thickness reduction for all the cases is similar but the magnitude of percentage reduction in thickness varies at from case to case with respect to location as shown in Figure 13. For case A, region Y, the thickness reduction is between 8% to 12%. After which rapid thinning is observed at the very last instant due to the tearing effect of the narrow tool (4.5mm). Case B is similar to case A but instead of thinning at a point gradual thinning in quarter of the circular region is observed. Case C shows more uniform distribution of thinning reduction and the sheet is thinned gradually for the whole circumference of the spiral tool path. For case C thickness reduction around corners of the circular region is 8% and increases to 20% in the middle. A thin line with

25% thinning is observed exactly in the middle of the region which increases to 35% while moving towards the fractured area. This change of thickness across cross-section of sheet is due to multiple passes over the sheet. Maximum thickness reduction of 35% is observed just before cracking for all the cases. Arrows show the rolling direction of the sheet. Tool should not repetitively contact sheet at the same location to avoid this thinness effect. Tool path optimization can play main role to avoid this to happen.

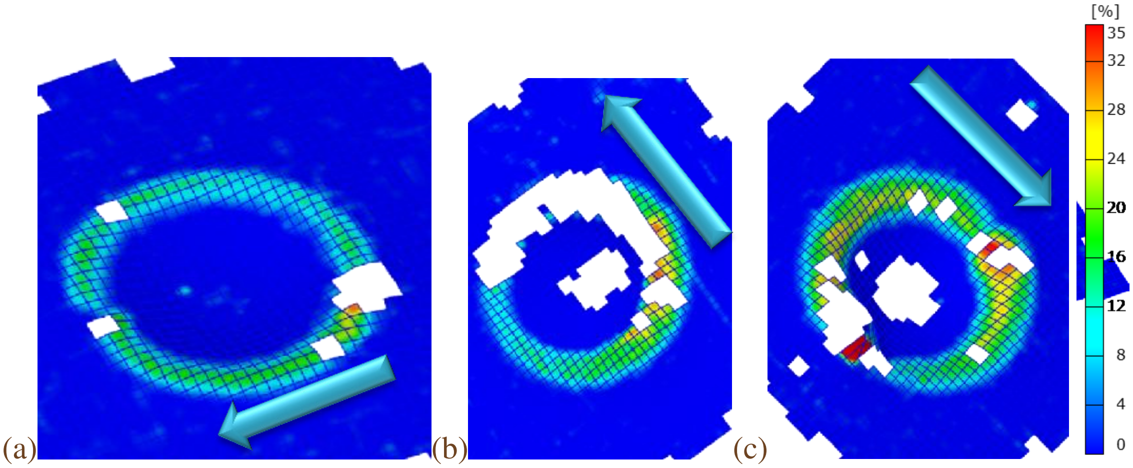


Figure 13: Thickness reduction % of the sheet; (a) CASE A, (b) CASE B, (c) CASE C. (Arrow shows rolling direction)

4.2.2) Strain assessment (major, minor and Von-misses)

To further investigate the dynamic behavior of the ISF fixture aluminum sheet was electrochemically etched, before performing ISF process, with a grid of circles of 1mm diameter and 2mm apart from each other. Photographs with Nikkon D300 camera were taken at various locations to digitize these circles as shown in Figure 14a. Two scales were used to identify the size of the part as shown in Figure 14b. Major and minor strains were acquired using strain point data through Circular Grid Analysis technique which is widely used in sheet metal forming [20, 74-77]. At times some data is lost during acquisition of result which creates discontinuity or patches [55, 76]. This is because circular grid is either erased or becomes very faint due to the forming process and thus could not be recognized by the system.

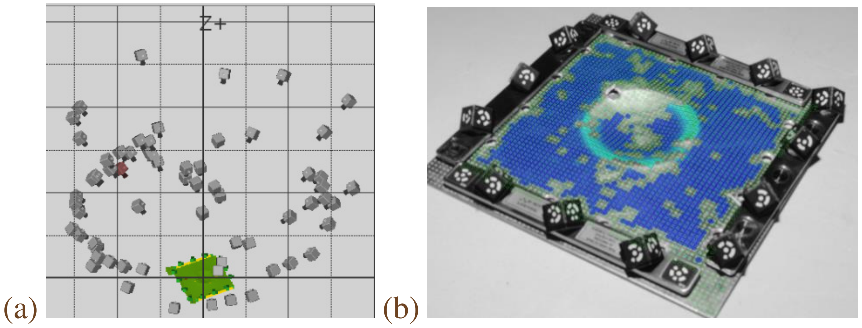


Figure 14: (a) Location of photos, (b) Formed surface through ARGUS.

Major strains are positive in all the three cases as shown in Figure 15 and confined to the localized region X and Y while rest of the area was not deformed. This demonstrates rigidity of the fixture even though it was moving vertically downward while high lateral forces were being applied on the sheet to fracture the part. For case A major strain is zero at region Z and ranges12% for most of the area. But as the tool is following a spiral path it increases to 35% just before it cracks. The maximum value of case B and C is 35%. Case C has the largest area under action due to higher tool size and centered die. For this case last pass of the rotating tool has a higher magnitude of major strain ranging from 25% to 35% distributed along circumference.

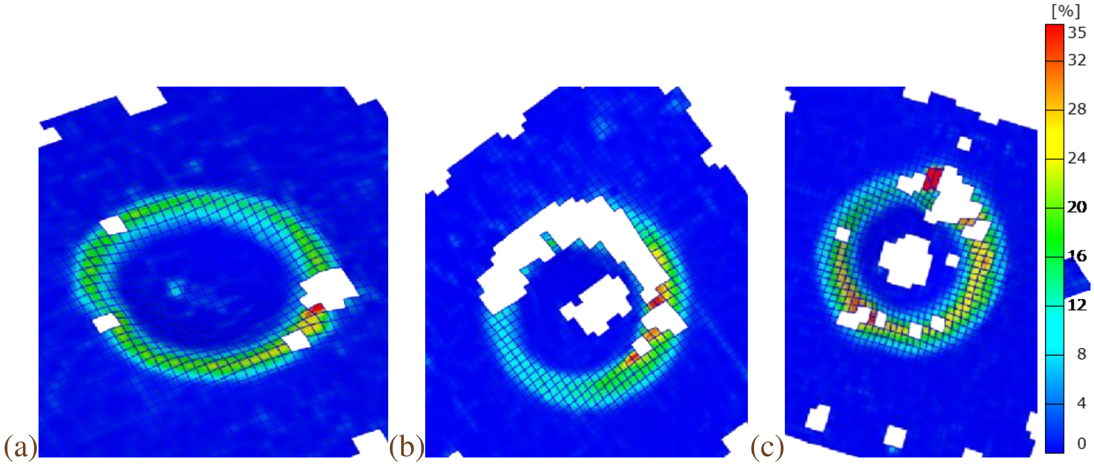


Figure 15: Major strain profile in the sheets; (a) CASE A, (b) CASE B, (c) CASE C.

Minor strain is negative for all three cases as shown in Figure 16. The values lie in a range of 0% to -10%. All the cases show similar behavior but case C has more clear divisions between different areas. In region X and Y strain clearly ranges from -6% to -10% while rest of area is near 0%. So it can be concluded from these three figures that the more the part is formed (higher deformation) the more area will go under compression for positive die. It is evident from Figure 16 that only localized area has minor strains in negative value while it is zero across rest of the sheet, thus it can be concluded that stiffness of the fixture is sufficient to hold the sheet aligned.

Because the minor strain has negative value in all the formed regions thus it is a tension-compression case, which is known to be acting in other sheet forming processes as well. The evenness of the distribution suggest that the fixture is enabling but not distorting the ISF process..

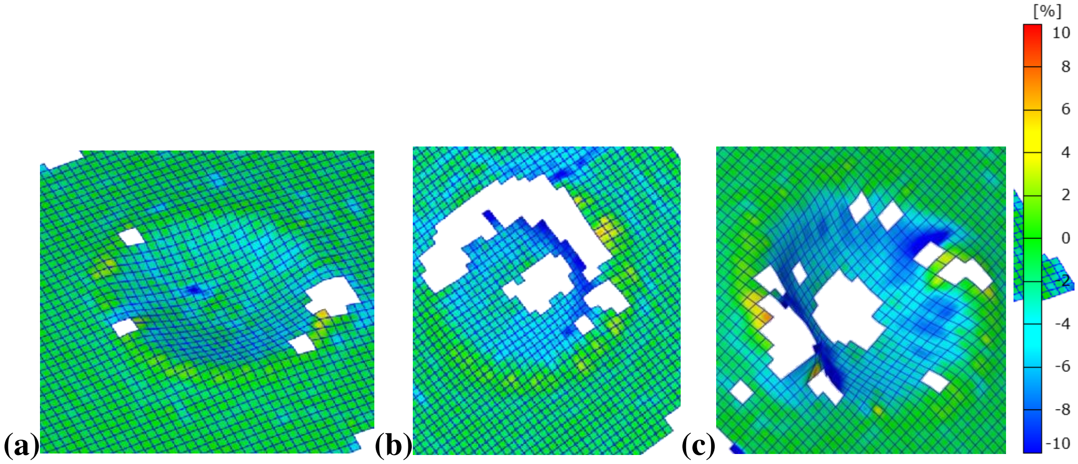


Figure 16: Minor strain profile in the sheets; (a) CASE A, (b) CASE B, (c) CASE C.

As Von Misses strains are the equivalent strains of all six components of strains ($\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \gamma_{xy}, \gamma_{yx}, \gamma_{yz}$) they provide a useful metric for assessing the evenness of the sheets deformation on the fixture. Strain in other regions of sheet would mean that fixture had moved while sheet was being formed. For all three cases A, B and C strain was localized in regions specified by the tool path as shown in Figure 17. Von misses strains in region Y vary in a range of 7% to 50% for all three tests but distribution of strains varies from case to case. For case A, i.e. thinner tool size, most of area remains between 10% to 20%. Strain moves from 20% to 30% across 90° of region and suddenly ruptures the part in a comparatively small distance and goes to 50%. This is due to more localized stress because of smaller tool size which tears sheet apart. For case B, i.e. off center die with larger tool size, strain remain between 10% to 20% for 2/3rd of the region Y. For rest of 1/3rd it varies uniformly and increases gradually to 50%. Case C, i.e. Centre die with bigger tool size, shows most uniformly distributed Von Mises strains range between 35% to 50%. This shows that to acquire greater formability from a part, larger tool size and centered die are the best options. Different dynamics seem to be working in all three different cases due to different input effects. It is hard to establish from current results which criteria of failure is causing rupture and what is the state of the stress in elements just before failure. Although these results point to several interesting avenues for future research they confirm the designed equipment is correctly functioning.

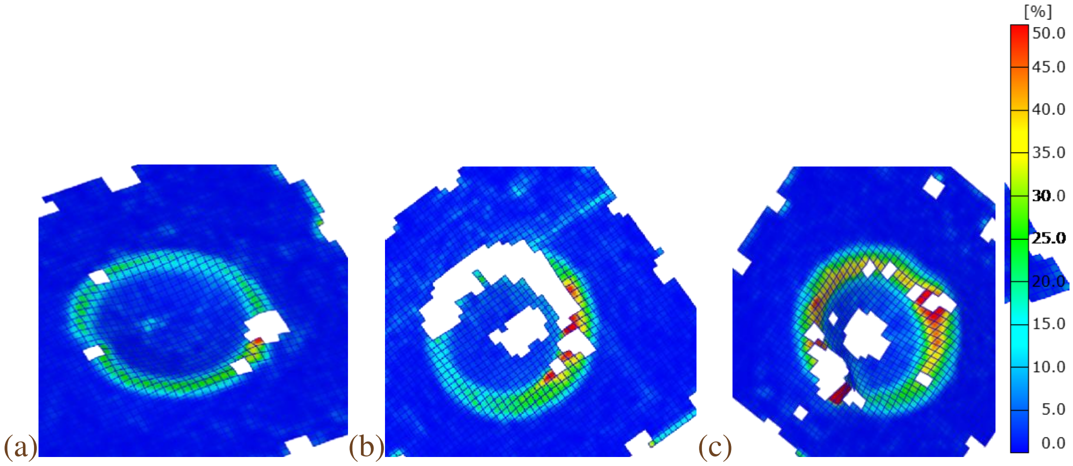


Figure 17: Von misses strain profile in the sheets; (a) CASE A, (b) CASE B, (c) CASE C.

5) Discussion and Conclusion

Incremental sheet forming is one of the most simple, effective and efficient sheet forming process. One of the areas researchers are working on is the fixture and tool design for this process. Flexible fixture design for ISF process is a challenge because of highly localized but moving off centered torsional load applied to form the sheet metal. This loading condition can jam the fixture and jeopardize its freedom of movement and stiffness while part is being formed. Aware of this problem the authors created several concepts and evaluated against the design specifications of Incremental Sheet Forming Process. 3D modeling, visualization and finite element analysis and functional prototypes were assessed before manufacturing the flexible fixture with nylon bushes.

The results suggested that the Scissors design did not have sufficient lateral (i.e. horizontal) stiffness so consequently a 3 pillars concept with nylon bushes was selected as the final design. Polymer sheet with industrial heater was used to check the functionality and the large vertical movement of the fixture during ISF process. Tests were successful and sheets were formed in shape of die. After which fixture was mounted on a CNC machine and further tests were performed on Aluminum sheet to check rigidity and stiffness of the system under high loading conditions. Spiral tool path was generated with CAM software for tool movement to form the geometry. Three cases were studied to check fixture movement for different tool sizes, symmetric and asymmetric geometries. After which results such as thickness reduction, profile changes, major and minor strains and von misses strains were acquired from these sheets using circular grid analysis, 3D scanning and other state of the art methods. All the parts were formed up to their failing point, despite which significant symmetry and evenness of distribution in formed parts was achieved. Results such as strain in other regions of sheet would mean that fixture had moved unevenly while the sheet was being formed. Cheap wooden dies were successfully used to form Aluminum parts. Using polymer or wooden dies would bring down cost and time of forming substantially. Other geometries were formed up to 40mm depth using the same Aluminum sheet metal.

Regardless of the fact that a point load is applied on the sheet at distance from center, creating a mixture of bending, tensile and torsional loading both on sheet and structure the fixture remained stable, showing no signs of unwanted movement with the Nylon bushes providing sufficient stiffness.

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