Enhancement of fracture forming limit by crystallographic texture reformation of AA1050 sheets in Single Point Incremental Forming

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Abstract. Single Point Incremental Forming (SPIF) process that results in the formation of sheet metal components leads to higher forming capabilities in comparison to conventional forming strategies. However, the formability in SPIF is critical and limited by the rapid/sudden failure in the sheet material (without material localization) for the components with high wall inclination angles. The state of stresses and strains plays a huge role in determining the forming limits in SPIF, which is complexly governed by various factors such as sheet thickness, lubrication, incremental step depth, tool rotational speed, part geometry, tool dimensions, and geometry, to name a few. The present work focuses on investigating formability of the sheets from its microstructure and crystallographic texture point of view. Preliminary experimentation led to the conclusion that SPIF of the original commercially supplied AA1050 H14 sheet results in early and premature failure. Microstructural investigation of the undeformed sheet showed that the commercially supplied sheets undergo strain hardening due to cold rolling and therefore, results in dislocated and disorientated microstructure and texture. The present work attempts to reform the microstructure of the sheet by preheating at the optimized temperature. Finite element analysis (FEA) of the process led to the observation that the reformed microstructures result in enhanced fracture forming limit strain and reduced stresses in SPIF. This may be attributed to the decrease in the number of dislocations and dislocated grains, and decrease in the surface area of grain boundary per grain with preheating. Improved fracture forming limits due to preheating were experimentally validated by utilizing digital image correlation technique (DIC) for acquiring true strain values subjected to fractured original and different preheated samples.

1. Introduction
Single Point Incremental Forming (SPIF) process is an advancement of the traditional spinning process, which facilitates the rapid formation of highly complex and customized sheet metal components. The process mechanics involves the shape generation by utilizing simple hemispherical shaped punch that moves in a predetermined path over the sheet, which in turn is clamped along the periphery. The process offers advantages in terms of customization, formability, flexibility, sustainability, and elimination of die in comparison to the conventional forming processes. However, the formability in SPIF is critical and limited by the rapid/sudden failure in the sheet material (without material localization) for the components with high wall inclination angles. In addition, formability
evaluation in SPIF has always been complex due to the combined effect of bending, stretching and shear. The state of stresses and strains plays a huge role in determining the forming limits in SPIF, which is complexly governed by various factors such as sheet thickness, lubrication, incremental step depth, tool rotational speed, part geometry, tool dimensions, and geometry, to name a few [1].

Significant research has been carried out to establish the forming limits in SPIF. Due to highly localized nature of deformation in SPIF, which although grows in subsequent tool passes, the transition from material instability to failure is comparatively slow in comparison to traditional forming, which is also due to predominant bending and through-the-thickness shear mechanisms in SPIF [2]. Forming Limit Curves (FLC), which are used to predict failure in conventional forming fails to define fracture strain in SPIF [3, 4]. Fracture Forming Limit Diagrams (FFLD) are the most common and efficient way to predict failure in SPIF [5]. So far the research has been limited to the investigation of dependency of formability on the process parameters like tool size, feed rate, spindle speed, sheet thickness, tool rotation speed, forming tool geometry, forming temperature, forming angle and tool path trajectory [1]. Few studies are reported that investigate the dependency of forming limits (in SPIF) on the initial microstructure and crystallographic texture of the sheet material.

In one of the previous works, microstructures and textures have been reformed via preheating of the sheet and the effect has been investigated over geometrical accuracy and thickness distribution in SPIF [6]. The present work is an extension of the previous work and is focused on the detailed investigation of the formability (forming limit strains) in SPIF. In this work, microstructure and crystallographic texture of the sheet were reformed by preheating at the optimized temperature and the effect of reformed texture and dislocation densities on fracture forming limit strains were compared to that resulting with the original non-preheated sheets. The resultant forming limit curves (FLCs) from finite element analysis were verified with the experimentally obtained FFLD. FLCs are obtained through simulations merely to compare the formability resulted for preheated samples in comparison to that with the non-preheated condition. For actual and precise evaluation of formability FFLDs were determined experimentally.

2. Materials and methods

This section provides the details of finite element analysis (FEA) and experimental procedure.

2.1. Material

In the present investigation pure (99.9%) Aluminium alloy sheet (AA1050A H14) was used as a raw material for SPIF experimentation due to its good appearance, high ductility, low weight density and resistance to corrosion.

2.2 Reformation of microstructure and crystallographic texture

The sample left at the room temperature (i.e., 28°C) provided the initial and original microstructure and spatial grain orientation. It was established that the preheating temperature of 330 ºC provides the optimized results in SPIF and the temperature higher than that merely resulted in grain growth with insignificant improvements in the results [6]. Therefore, the sheet samples were preheated in the muffle furnace for an hour to a temperature of 330°C (half the melting point of aluminium alloy). To ensure the slowest rate of cooling, the samples were cooled in the furnace unless room temperature was reached. Therefore, the rate of cooling was unrestrained. It was done because fast or controlled cooling induces hardness in the sheet material.

2.3 Microstructural analysis

For microstructural analysis, metallographic specimens were prepared and scanning electron microscope (SEM) was used with an accelerating voltage, hit rate and speed of acquisition as 20 keV, 77.85% and 20.06 Hz respectively. The samples were cut, polished and etched to reveal grain boundaries. The samples were diamond polished (water-based), electropolished by A2 electrolyte (STRUERS R) at 13 volts for 15 s and further etched to reveal the microstructure and grain
boundaries. For etching, Keller’s etchant (constitutes Distilled water, Nitric acid, Hydrochloric acid, and Hydrofluoric acid) was used. The specimens were tilted by 70.00° to obtain Inverse Pole Figures (IPF) by Electron Backscatter Diffraction (EBSD) technique.

2.4 Finite element analysis (FEA)
A numerical investigation had been carried out using Altair HyperWorks CAE software v12.0. In the present work, Johnson Cook (JC) material model was used to predict elastoplastic deformation in SPIF. Mechanical characterization was done to obtain the values of JC material model parameters for preheated and non-preheated sheet samples. The evaluated values of the parameters are presented in Table 1. Equivalent plastic strain was used as a fracture criterion during the simulation of SPIF. Critical plastic strain was experimentally evaluated for both the original and preheated sheet sample. It was considered that if during simulation, the value of the plastic strain for any element exceeds the critical value then that element will be deleted. During simulation, element deletion was considered as fracture in SPIF. The considered criterion is less accurate in comparison to Gurson–Tvergaard–Needleman (GTN) and Lemaitre models. However, these models are difficult to calibrate and demands rigorous experimentation for the parameters evaluation. In addition, it is already established [7] that the considered criterion provides acceptable accuracy and is not experimentally expensive. Simple uniaxial tensile test is sufficient for the model’s parameter determination. The tool path coordinates, evaluated as per the process parameters (Table 2), were provided for truncated pyramid geometry. The values of the major and minor strains associated with the simulated components were plotted to form Fracture Limit Curve (FLC). To eliminate geometrical errors and to seal the gaps between the surfaces of IGES file, ‘Auto clean up’ tool of HyperMesh was utilized. HyperMesh tool was used to mesh the mid surfaces of both the tool and the sheet. Improved under-integrated shell element was used as it resulted in only 15% higher cost than the conventional ‘Flanagan Belytschko’ (FB) shell element but eliminated the hour glass effect, which initially resulted when ‘FB’ shell elements were used. Thus, the shell element resulted in best compromise between cost and quality. The tool was meshed with ‘rigid body mesh’ function. Boundary conditions were provided in such a manner that the nodes present on the outer periphery of sheet were constrained in both translational and rotational motion in ‘X’, ‘Y’ and ‘Z’ direction. The tool was constrained with rotations in X and Y directions with the rotation allowed in Z direction. During simulation, the tool was considered as a master and sheet was considered as a slave. The tool is considered as the rigid body and the tool path is assigned to the master node of the tool. RADIOSS as an explicit solver was utilized for pre-fabrication simulation. Post processing of the results was done by utilizing HyperView and Hypergraph [1, 6].

Table 1 Johnson cook material model parameters’ values

| Properties                              | Original non-preheated sample | Preheated sample |
|-----------------------------------------|-------------------------------|------------------|
| Young’s modulus (E) (MPa)               | 69000                         | 69000            |
| Poisson’s ratio(υ)                      | 0.33                          | 0.33             |
| Initial Yield stress (a) (MPa)          | 81.905                        | 35               |
| Strain hardening coefficient (b) (MPa)  | 204.13                        | 130.21           |
| Strain hardening exponent (n)           | 0.1392                        | 0.32             |
| Ultimate tensile Stress (σₘₐₓ) (MPa)    | 118.36                        | 99.99            |
| Max. Plastic Strain (%εₘₐₓ)            | 5.54                          | 46.6             |
| Plastic Strain at damage (%ε₅₉₉₉₁₆₆₉) | 2.55                          | 44.16            |
| Softening Slope (Eₛ)                   | 0                             | 0                |
2.5 Experimentation

SPIF was carried out with the help of a 3 axis CNC milling machine available in the laboratory. The values of fixed SPIF parameters, as obtained based on the literature and preliminary tests conducted, are given in Table 2. Frustum of pyramid geometry was formed and for forming limits analysis, as the component should fracture, the wall angle of the geometry was gradually increased until the component fractured. Square blanks of sides 100 mm were formed to the square pyramid with a base dimension of 75 mm and wall inclination angle 73°.

To obtain maximum forming limit strain in SPIF, there is a need for the part to fracture after a certain depth of the formation. Thus, the wall angles of the components having the above geometry were gradually increased until the component fractured. The geometries with a wall angle of 73° were formed up to the point of fracture and process was terminated when the fracture occurred.

Table 2 Single Point Incremental Forming parameters

| Tool diameter (mm) | Vertical step size (mm) | Rotational speed (RPM) | Tool feed rate (mm min⁻¹) | Lubricating oil | Tool path | Sheet thickness (mm) |
|--------------------|-------------------------|------------------------|---------------------------|----------------|-----------|---------------------|
| 8                  | 0.2                     | 200                    | 1000                      | Hydraulic oil (grade-68) | Spiral    | 0.91                |

Further, a circular grid of diameter 1 mm (d₀) was chemically etched on sheet samples. Post fracture, the major (d_major) and minor diameters (d_minor) of the ellipses near the crack was measured by ARGUS 3D optical strain measurement system. Major (ε_major = (d_major − d₀)/d₀) and minor strains (ε_minor = (d_minor − d₀)/d₀) were measured. Determination of FFLC includes highly sophisticated apparatus like ARGUS 3D optical strain measurement system which captures high resolution images of the formed components by Digital Single Lens Reflex (DSLR) cameras. Obtained 3D coordinates (after scanning) were further evaluated in ARGUS software. DIC technique is utilized to evaluate the major and minor strain distribution on the surface of the formed component. To minimize the possibilities of experimental error, three runs of each experiment were conducted and an average of these three values was considered.

3. Results and discussion

SPIF parts formed with original commercially supplied AA1050 H14 sheets resulted in early and abrupt failure at the corners of the formed pyramid components due to biaxial strains. Fractured SPIF component and IPF along with misorientation histogram is shown in Fig. 1 (a-c) respectively [2]. It is apparent from the analysis that higher amount of misorientation results under biaxial strains.

![Figure 1](image-url)

(a) Fractured SPIF component, (b) IPF of the extracted sample and (c) Misorientation histogram resulted for fractured component

To investigate the root cause of an early failure, preliminary microstructural investigation of the undeformed, commercially supplied AA1050 H14 sheet was done. The analysis led to the observation
that the commercially supplied sheets undergo strain hardening due to cold rolling and therefore, results in dislocated and disorientated microstructure and texture. IPF showing crystallographic orientation in the original undeformed sheet is shown in Fig. 2 (a) whereas kernel average misorientation (KAM) plot is shown with the help of Fig. 2 (b). EBSD measured KAM plots show dislocation density in the sheet. The abundance of green color in the map confirms high dislocation density and may trigger failure in SPIF due to tangling of the dislocations array. Tangling of the dislocation arrays leads to work hardening in the material on the application of load and therefore, results in failure of the material. In addition, as the commercially supplied sheets possess fine grains, they are more prone to tangling and piling up of the dislocations at the grain boundaries [6].

Figure 2 Orientation color-coded EBSD measured (a) IPF and (b) KAM plots showing crystallographic grain orientation and dislocation density respectively in original AA1050 sheet

To overcome the issue, preheating of the sheet was performed up to 330 ºC to reform and recrystallize the dislocated microstructures. IPF showing recrystallized microstructures and texture of the sheet preheated till 330 ºC is shown in Fig. 3 (a). EBSD measured KAM plot provided in Fig. 3 (b) shows that the amount of dislocation reduces considerably due to preheating. The blue color in KAM plot illustrates the regions with no dislocations, whereas green color depicts the presence of dislocation. The red color in the plot depicts the dislocation presence in abundance.

Figure 3 EBSD measured (a) IPF and (b) KAM plots on preheating the sheets up to 330 ºC

Finite element analysis was performed before actual experimentation to investigate the effect of preheated microstructures on the forming limits in SPIF. Figure 4 confirms that sheets pertaining to preheated microstructures and textures attain higher plastic strain values at fracture in comparison to that of the original non-preheated sheet. Maximum plastic strain value was 0.786 for a non-preheated sample which increased to 0.888 for preheated samples. For simulation, FLC were simulated in accordance to the critical value of plastic strain corresponding to the fracture in the material under
uniaxial tension condition. For original and preheated samples, the forming limit curves (FLC) resulting from the simulation are provided in Fig. 5 (a) and Fig. 5 (b) respectively. As conventional plasticity models are used for the simulation of the process, the obtained major and minor strain values from the simulation resulted in conventional FLC. FLCs were obtained through simulations merely to compare the formability resulted for preheated samples in comparison to that with the non-preheated condition. For actual and precise evaluation of formability FFLDs were determined experimentally. Experimental fracture forming limit diagram obtained on performing digital image correlation on the fractured specimen, for non-preheated and preheated samples are shown in Fig. 6.

Figure 4 Simulated plastic strain distributions for SPIF parts formed with (a) original and (b) preheated sheet samples

FFLD in SPIF indicates that the region under biaxial condition stretches in both the major and minor directions. Biaxial region suffers more deformation (in both major and minor directions) and therefore, forming limits are lower in comparison to that for plane strain conditions. Fig. 5 showcases that with preheat treatment, the formability enhances, which is validated by experimentally obtained FFLD (Fig. 6). Prior to actual experimentation, the simulated FLC merely validate that the microstructure and texture reformation due to preheating enhances the forming limits in SPIF.

Figure 5 Simulated forming limit curves for (a) original and (b) preheated sheet samples

Experimentally obtained FFLD confirms that the plastic strain values were significantly higher for preheated samples in comparison to the original non-preheated samples. Through FFLD it can be verified that preheat treatment leads to limiting strain enhancement by 43%. This may be attributed to a decrease in the number of dislocations and dislocated grains as well as a decrease in the surface area of grain boundary per grain, with preheating. Textured samples due to a larger area of homogeneously orientated grains favor the dislocation movement past grain boundary (due to lesser obstruction offered by neighboring grains having a similar orientation) and as a result, facilitate the dislocation movement as well as delay the piling up of dislocations at grain boundaries. This decreases the amount of pressure required to cross dislocations, as larger areas of similar orientation can pile up more dislocations leading to larger driving power for dislocations to cross the grain boundaries.
4. Conclusions
The present work attempts to reform microstructure and crystallographic texture of AA 1050 sheets to enhance fracture forming limits in SPIF. The important findings can be concluded as follows:

- The commercially supplied sheets undergo strain hardening due to cold rolling and therefore, results in dislocated and disorientated microstructure and texture. On the application of load, tangling and piling up of the dislocations leads to early failure in SPIF.

- Apart from decreasing the surface area of grain boundary per grain, preheating of the sheet results in a decrement in the amount of dislocation density. As a result, maximum permissible plastic and true strain values increase considerably for the SPIF components formed with preheated sheets.

Therefore, in addition, to enhancing geometrical accuracy and thickness distribution, preheating also results in enhanced formability in SPIF.

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