Failure prediction in incremental sheet forming based on Lemaitre damage model

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Abstract. Single Point Incremental Forming (SPIF) is a dieless forming process. In this process sheet is clamped on its periphery and a hemispherical tool clamped on a CNC (Computer Numeric Control) machine applies small incremental pressure to deform the sheet in three dimensional component. During the process, strain increases on successive steps of forming and it is much above the conventional forming limit. These higher strains lead to excessive thinning which eventually results in failure. The aim of this work is to revisit the failure analysis in SPIF and study the effect of tool diameter on the failure. Finite element method (FEM) is used for the analysis of the process and a truncated cone is simulated using different tool diameter. For failure prediction, Lemaitre damage model, based on continuum damage mechanics, has been numerically implemented in FE software Abaqus/Explicit using user subroutine. Further, the results from numerical analysis such as strain evolution in deformation zone and thickness reduction are analysed.

1. Introduction

The Single Point Incremental Forming (SPIF) process is an advanced sheet metal forming technique. A CNC controlled tool follows the profile of final geometry and imposes small incremental pressure on the sheet. This forming process requires no dies and mandrel, hence it is “dieless forming” process. Eliminating the dies from the forming process, makes it faster, flexible and cost effective process for low volume production and rapid prototyping. In addition to generic equipment requirement in SPIF, the higher formability and suppression of necking in SPIF are of great interest. However, excessive thinning of parts, unpredictable fracture, spring-back and bending are the drawbacks of SPIF.

The work of Filice et al. [1] gives a methodology for predicting fracture based on the forming forces trends. However, Szekeres et al. [2] showed that forming force based fracture prediction does not work on pyramidal shape. Silva et al. [3] reported the failure mechanism in SPIF by using conventional forming limit curve (FLC). They reported the effect of tool radius on the failure and concluded that for large tool radius, failure is due to the necking which is similar to stamping process and for small tool radius failure takes place due to fracture with suppression of necking. Many authors have reported that FLCs have drawback in failure prediction in SPIF. It is reported that FLCs are not applicable if bending and through the thickness shear [4] takes place during forming, which is significant in SPIF. Nguyen et
al. [5] had used the Oyane’s fracture criterion with combined kinematic/isotropic hardening and Johnson-Cook model to predict the damage during forming of truncated pyramid using SPIF. Xue [6] model had been implemented by Malhotra et al. [4] to predict the damage and fracture behavior in Incremental Sheet Forming (ISF). They also proposed the noodle theory to explain the increased formability in ISF. A microvoid volume fraction based Gurson-Tvergaard-Needleman (GTN) model coupled with Hill’s 48 criterion was implemented by Li et al. [7] to predict the damage and fracture in ISF. Dwivedi et al. [8] used the constant equivalent plastic strain criterion to predict the fracture in truncated cone using FEA. Their result shows an associated error of approximately 5%. Mirnia and Shamsari [9] implemented the modified Mohr-Coulomb model to investigate the fracture prediction in different geometries with an average error of 10% in comparison to experimental results. Thus, different models have been implemented in finite element analysis to predict the failure in ISF. It is observed that, Lemaitre damage model has been rarely discussed in the literature for failure prediction in ISF. In this work Lemaitre damage model was numerically implemented in finite element analysis (FEA) using user subroutine (VUMAT) within Abaqus/Explicit software. A truncated cone has been simulated using two different tool diameters to predict the failure in ISF, which was further validated by experiments. The strain evolution and thickness distribution in the components are also reported in the results.

2. Material model

The material modelling in finite element analysis consists of plasticity model and damage model. In this analysis Johnson-Cook model has been considered as plasticity model and Lemaitre model is used for damage prediction.

2.1. Johnson-Cook Model

The Johnson-Cook model is a type of von Mises model and its constitutive equation depends on the large plastic strain, strain rate effect and high temperature. The constitutive equation of Johnson-Cook model [10] is given below:

$$\sigma = (A + B \varepsilon_p^n) \left(1 + C \ln \varepsilon^\prime \right) \left(1 - T^m \right)$$  \hspace{1cm} (1)

where,

- $\sigma$ is flow stress,
- $\varepsilon_p$ is plastic strain,
- $A$ is yield stress,
- $B$ is hardening modulus,
- $n$ is hardening exponent,
- $C$ is strain rate coefficient,
- $\varepsilon^\prime$ is strain rate,
- $\varepsilon_0$ is reference strain rate,
- $m$ is temperature exponent and
- $T$ is the (homologous temperature) $t - 298 \over t_{melt} - 298$.

Where, $t$ is material temperature, in kelvin, and $t_{melt}$ is melting temperature (in K), while assumed $t_{room}$ is 298K. The three parentheses in equation 1 represents three different factors i.e. strain hardening, strain rate and temperature effect. In this analysis on strain hardening and strain rate effects have been considered for the ISF analysis.

2.2. Lemaitre Model

To predict failure in ISF, Lemaitre model [11] has been used as damage criterion. In this model a scalar intrinsic damage variable $D$ is introduced as structural weakening factor which results from plastic deformation. The damage model incorporates an effective stress $\bar{\sigma}$, which can be defined as[12]:

$$\bar{\sigma} = \frac{\sigma}{1 - D}$$  \hspace{1cm} (2)

where, $\sigma$ is the stress tensor of undamaged material. The Lemaitre damage evolution law is defined as:

$$\Delta D = \frac{D_c}{\varepsilon_{R} - \varepsilon_{D}} \left[\frac{2}{3} (1 + \nu) + 3 (1 - 2 \nu) \left(\frac{\sigma_m}{\sigma}\right)^2 \varepsilon^p \right] ^{2n} \Delta \varepsilon^p$$  \hspace{1cm} (3)
where, $D_c$, $\varepsilon_R$ and $\varepsilon_D$ are Lemaitre damage constants and $\nu$, $\sigma_m$, $\Delta \varepsilon^p$ and $\bar{\varepsilon}^p$ are Poisson’s ratio, mean stress, plastic strain increment and equivalent plastic strain respectively.

3. Finite Element Model

The above discussed material model has been implemented in Abaqus software using user subroutine. Aluminium alloy AA6061-T6 of 1 mm thickness has been used as blank material. For FEA, the sheet blank was discretised using reduced integration, eight node linear brick elements. Tool has been taken as analytically rigid part. Further, tool feed rate has been artificially increased and a mass scaling of 1000 was used in the analysis to reduce the simulation time. Johnson-Cook and Lemaitre damage model parameters for AA6061-T6 were taken from the work of Lesuer et al. [13] and Turton et al. [14] respectively. Material constants and material model parameters used in this analysis are listed in the table 1.

| Density ($\rho$) g/cm$^3$ | E (MPa) | Poisson’s ratio (\(\nu\)) | A (MPa) | B (MPa) | C | n | m | $D_c$ | $\varepsilon_R$ | $\varepsilon_D$ |
|--------------------------|---------|---------------------------|---------|----------|---|---|---|--------|----------------|-----------------|
| 2.7                      | 68900   | 0.33                      | 324     | 114      | 0.002 | 0.42 | 1.34 | 0.53 | 0.84 | 0.0001        |

4. Experimental Validation

Experiments were performed on the three axis CNC milling machine and truncated cones were formed using different tool diameters. The sheet blank was taken in the size of 160 mm $\times$ 160 mm $\times$ 1 mm and was clamped on its periphery. The forming tool was made of high strength steel and its one end was given hemispherical shape. A spiral tool path was taken to form the components with incremental depth of 0.5 mm. The details of all forming process parameters and cone geometry used in experiments are given in table 2.

| Parameters                        | Value       |
|-----------------------------------|-------------|
| Tool diameter (mm)                | 8           |
| Tool type                         | Hemispherical end |
| Tool rotation (rpm)               | 1000        |
| Feed rate (mm/min)                | 1000        |
| Incremental depth (mm)            | 0.5         |
| Tool path                         | Spiral      |
| Maximum diameter of cone (mm)     | 70          |
| Minimum diameter of cone (mm)     | 24          |
| Wall angle of cone                | 65.3°       |

5. Results and Discussion

Failure in ISF is uncertain as it depends on different forming parameters. Thus, to reduce the number of experiments, material and tooling cost, failure prediction is important. In the current work, the fracture is predicted by the Lemaitre damage model. Two different tools have been used for the forming. Figure 1 (a) and 2 (a) show the fractured truncated cones in experiments using tools with 10 mm and 8 mm diameter respectively. The forming depth and the prediction of fracture location via FE simulation are shown in figure 1 (b) and 2 (b) for both conditions. The experimental and predicted depth of fracture for both simulations are compared in table 3. The simulation results depict that the CDM based damage criterion provides a satisfactory prediction of forming depth and fracture location.
Figure 1. Fracture depth comparison of component formed with 10 mm diameter tool.

Figure 2. Fracture depth comparison of component formed with 8 mm diameter tool.

Table 3. Comparison of fracture depth

| Tool diameter (mm) | Simulation fracture depth (mm) | Experimental fracture depth (mm) |
|-------------------|--------------------------------|---------------------------------|
| 8                 | 11.59                          | 12.5                            |
| 10                | 12.69                          | 12.1                            |

In ISF, the deformation occurs in incremental manner and hence, strain in the sheet increases with the depth of formed component. Figures 3 and 5 show the equivalent plastic strain distribution for 8 mm and 10 mm diameters tools respectively. Further, in sheet metal forming, product quality is mainly affected by the thickness distribution in the formed parts. If the thickness reduction reaches a certain value then the chances of fracture may increase. The thickness distribution along the selected path just before the fracture has been shown in figures 4 and 6 for 8 mm and 10 mm tool diameter conditions respectively. The minimum predicted sheet thickness in the components formed with 8 mm and 10 mm diameter tools are 0.55 mm and 0.61 mm respectively.
6. Conclusions
In this work, the fracture and the thickness distribution are predicted for ISF process. In experiments, the fracture takes place at similar depth for the forming with both, 8 mm and 10 mm diameter tools. The CDM based Lemaitre damage criterion provides a satisfactory prediction of forming depth and fracture location and an average error of 6 % is calculated between experiment and simulation results. The tool diameter shows less effect on the formability. As part of future work, implementation of same model for different geometry and experimental calculation of thickness distribution in the components will be considered.

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