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Circumferential cracking in conventional Metal Spinning Process

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Abstract

Circumferential cracking of conventional metal spinning process is investigated by means of finite element simulation using the Generalized Incremental Stress State dependent damage model (GISSMO). This model provides a damage scalar as an indicator to remove elements on where a crack appears. Result show that simulation predictions are in very good agreement with experiment cracking locations. A region around the cracking area deforms in the opposite direction of a roller's stroke during cracking. This phenomenon is considered as a reason for circumferential cracking at the interaction between a plate and a tailstock. This paper shows a successful damage model to predict circumferential crack and new insights into this defect.

Keywords: metal spinning process; circumferential cracking; GISSMO.

1. Introduction

Metal spinning is a process of forming a circular plate or disc into an axisymmetric part over a rotating mandrel. The elementary components of the process are a circular plate (Figure 1a) required to be formed, a rotating mandrel (Figure 1b), a tailstock for clamping the plate on the mandrel (Figure 1c), a forming tool or roller (Figure 1d). Simultaneous combination of roller path (Figure 1f) and mandrel rotational speed (Figure 1e) causes the initial flat plate to be formed into an axisymmetric shape over the mandrel (Figure 1g).

The most common defects in the spinning process are wrinkling, circumferential crack and radial crack. However, the wrinkling is the only failure which has been conducted so far by some authors such as (Chen et al. 2019; Kong, Yu, Zhao, Wang and Lin 2017) . On the review of spinning process (Music, Allwood and Kawai 2010), the circumferential crack can be observed intuitively by the high tensile radial stress. In this paper, the Finite Element method is used to analysis the circumferential crack observed in the experiment of one - path conventional spinning process. This phenomenon is presented in Figure 3 where the plate suffered to the complete circumferential crack which create two separated part after failure. The experimental configuration is showed in Figure 2. The roller deforms the 2mm thickness aluminum plate at a clearance of 10mm away from the mandrel.

In the literature of predicting material failure, there are three common approaches which are based on the maximum effective plastic strain, Gurson yield criterion and the Generalized Incremental Stress State dependent damage model (GISSMO).

In case of failure prediction based on the maximum effective plastic strain, the material is considered as failure when the effective plastic strain reaches a critical value. The critical value usually is the maximum true plastic strain obtained from the tensile test. The failure sets on if the effective plastic strain reaches the maximum true plastic strain. However, these terms are defined in the Appendix A and Appendix B by an assumption that the material is isochoric meaning the volume is constant during deformation. This assumption is only applied for the plastic deformation. In the other hand, the fracture is pressure - dependent. Therefore, these terms are not properly defined beyond the plastic hence they cannot be used to assess the failure of the material.

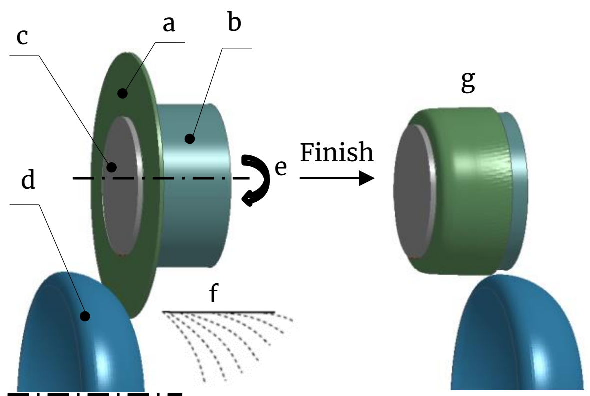


Figure 1. Metal spinning process, (a) a circular plate, (b) a mandrel, (c) a tailstock, (d) a roller, (e) mandrel rotation, (f) roller path, (g) final part

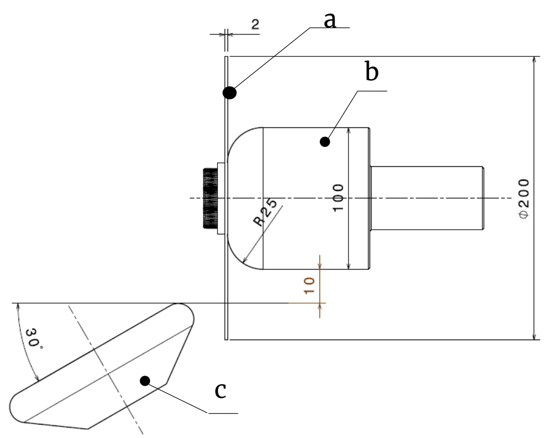


Figure 2. Experiment configuration, (a) a plate; (b) a mandrel; (c) a roller

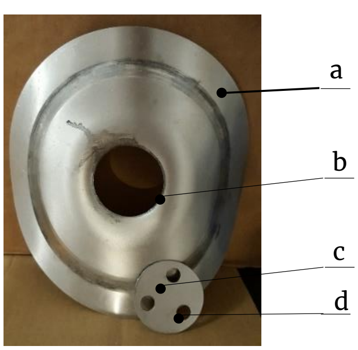


Figure 3. Circumferential crack; (a) the plate; (b) circumferential crack line; (c) failure part; (d) tailstock mounted hole

The Gurson yield criterion is the micromechanical model which is described by nucleation, growth and coalescence of micro voids (Needleman and Tvergaard 1984). This model uses the alternative yield function which applied for both plastic stage and damage stage. Therefore, the plastic model has to be replaced by the Gurson model hence the predefined plastic model cannot be chosen freely for example as anisotropic plasticity, etc. This is a disadvantage of the Gurson yield criterion.

The material model called GISSMO, developed by (NeukammF, Feucht, Haufe and Roll 2008; NeukammFrieder, Feucht and Haufe 2009), introduces the damage parameter in the material which can fully describe the material softening and fracture. In addition, this model resolves the Gurson's disadvantage which is independent to the plasticity formula. This model has been widely used in the crashworthiness and forming process simulation (A. Haufe M. Feucht, P. DuBois and T. Borvall 2010; Effelsberg, Haufe, Feucht, Neukamm and Bois 2012).

Therefore, GISSMO is used to simulate the circumferential cracking in metal spinning process. In the next sections, the GISSMO's formula is presented shortly. This formula illustrates the meaning and the number of parameters needing to be known. A simple strategy, applied only for the spinning process, is proposed to obtain these parameters. Finally, the simulation of spinning process using the GISSMO is conducted and analyzed.

2. GISSMO for predicting failure in spinning process

The evolution of material under deformation contains three states in the orders of elastic, plasticity and fracture. Each state requires some properties for complete definition. Shell element is used to modeling the thin sheet metal with plane stress condition. Therefore, the material model now only focuses to 2D stress and 2D strain.

2.1. Constitutive in elastic region

In the elastic region, the material's properties are assumed to be isotropic. The relationship of stress and strain is linear and presented as below

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} = \frac{E}{1-\nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ 2\epsilon_{12} \end{bmatrix} \quad (1)$$

Two properties need to be determined are the Young modulus E and the Poisson's ratio ν.

2.2. Constitutive in plastic region

A switch of elastic to plastic state is determined by the yield condition as be written as

$$f(\sigma, \epsilon_p) = \sigma_{eff}(\sigma_{11}, \sigma_{22}, \sigma_{12}) - \sigma_Y(\epsilon_p) \leq 0 \quad (2)$$

With σ_{eff}: effective stress; σ_Y: yield stress; ϵ_p: effective plastic strain

If the yield condition is negative, the state of material is on the elastic and vice versa. The yield stress $\sigma_Y(\epsilon_p = 0)$ and the hardening stress curve $\sigma_Y(\epsilon_p)$ are determined experimentally by the tensile test because this test presents the uniform deformation in the gauge region and constant volume change (the Poisson's ratio is 0.5) in plastic state hence the conversion from the measurement (force vs displacement) to the hardening stress curve $\sigma_Y(\epsilon_p)$ is straight forward as be illustrated in appendix A.

The effective stress σ_{eff} is Von Mises stress for assumption that the material is isotropic.

2.3. Constitutive in fracture region

The Generalized Incremental Stress State dependent damage Model (GISSMO) is used for adding a damage to the existing material model (elastic and plasticity). A damage (scalar) $0 \le D \le 1$ is added to the stress tensor

$$\boldsymbol{\sigma}^* = \boldsymbol{\sigma}(1 - D) \tag{3}$$

An assumption is that the material has already very small defect prescribed by $D = 1e^{-20}$ so $\boldsymbol{\sigma}^* \cong \boldsymbol{\sigma}$. During the deformation, the defect expands itself inside the material until $D = 1$ so $\boldsymbol{\sigma}^* = 0$ at which the material is totally fracture.

According to a work (Mackenzie, Hancock and Brown 1977), the failure strain depends on a triaxiality which means that there are many failure strains respecting to various triaxiality. The triaxiality is defined as a ratio of pressure stress on the effective stress.

$$\eta = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3\sigma_{eff}} \tag{4}$$

The evolution of damage scalar is

$$\Delta D = \frac{n}{\epsilon_{failure}(\eta)} D^{1-\frac{1}{n}} \Delta\epsilon_p \tag{5}$$

With ΔD: the incremental damage scalar

D: the current damage

n: the damage exponent

ϵ_p: the effective plastic strain

$\epsilon_{failure}$: the failure strain

η: the triaxiality

In equation (5), two parameters damage exponent n and failure strain $\epsilon_{failure}$ are unknown. The damage exponent n is chosen so that the damage scalar only grows significantly at the final region of plastic strain instead of elastic and plastic region. Usually, $n = 3$ is chosen. The effective plastic strain at which fracture is the failure strain.

In conclusion, the fracture model needs the failure strain as a function of triaxiality.

3. Strategies to determine model parameters

Properties which are needed to obtain, are:

For elastic

E: The Young modulus

ν: The Poisson's ratio

For plasticity

$\sigma_Y(\epsilon_p)$: The hardening curve

For fracture

$\epsilon_{failure}(\eta)$: The failure strain

The properties E, ν, $\sigma_Y(\epsilon_p)$ are obtained by tensile test. The hardening curve $\sigma_Y(\epsilon_p)$ is a function of effective plastic strain versus yield stress. In tensile test, the effective plastic strain is the true plastic strain and the yield stress is the true stress. They are calculated using equations in Appendix A.

The final parameter, needed to determine, is the failure strain curve $\epsilon_{failure}(\eta)$ which is a collection of failure strain respected to various triaxialities. This parameter requires a numerous of experimental tests, including shear 0^0, shear 45^0, small tensile test, notched tensile test and biaxial test (Andrade, Feucht and Haufe 2014) to fully define which are expensive to do. However, the simulation of spinning process showed that the critical region has the triaxiality of 0.5. Fortunately, the fracture region in the tensile test also has the triaxiality of 0.5 showed in Figure 4 which is the same as spinning process circumferential crack area. This means that the state of stress on the failure period is the same of both tensile test and spinning process. Therefore, the only failure strain of tensile test is enough to predict circumferential crack for spinning process.

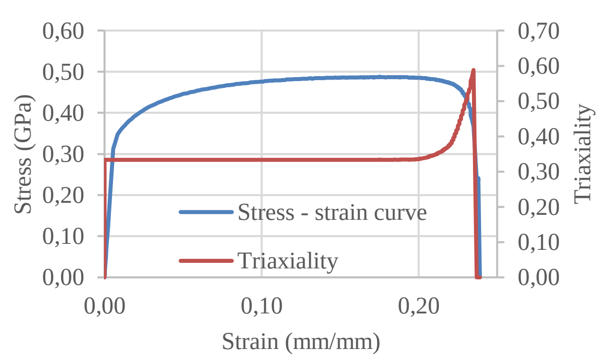


Figure 4. Stress – strain curve and triaxiality

The failure strain is obtained by reverse – engineering approach because the effective plastic strain in damage area cannot be calculated by the data from the tensile test. These formulas in the Appendix is only applicable in the plasticity region. The steps are:

- Calculate the young modulus, effective plastic strain versus yield stress.
- Conduct tensile test simulation. This should give the same stress – strain curve as tensile test experiment.
- In the tensile test simulation, note the maximum effective plastic strain according to the elongation of failure in the experiment tensile test.
- This value is chosen as an initial failure strain. The tensile test simulation is conducted. The expected result will be only different beyond necking point.
- Try to adjust the failure strain to match results between tensile test simulation and tensile test experiment.

4. Analysis of simulation

The circular disc is made from the aluminum 2024 with properties are presented in Table 1.

Table 1. Aluminum 6061-T6 properties.

Young modulus	E = 56.388 GPa
Yield offset	0.002
Yield strength at offset	σ_y = 347.9 MPa
Engineering ultimate tensile strength	EUTS = 487.4 MPa
Mass density	2.7E-6 kg/mm³

The material model is isotropic elastoplastic using a power law hardening rule.

$$\sigma_t = K\epsilon_t^n \quad (6)$$

With

σ_t: True stress

ϵ_t: True strain

K: Strength coefficient

n: Strain hardening coefficient

The values of K and n are 0.1642 and 0.7723 respectively. The failure strain is 0.75. The output of a material model with GISSMO is showed in **Figure 5**.

The kinematic setup uses a special approach developed by (Nguyen, Champliaud and Lê 2018). This setup requires the stationary mandrel and so the rotating tool. The implicit time integration scheme is used to eliminate the trial – error of mass scaling guess-work and provides an unconditional stable.

The Figure 6 showed the first place where crack is initial. The Figure 7 showed the crack grown in the circumferential direction and expected to complete a circle at the intersection of the plate and the mandrel. This position matched exactly with the experiment showed in Figure 3.

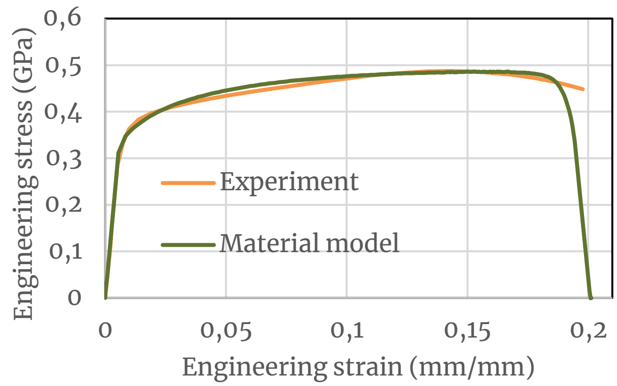


Figure 5. Engineering stress - strain curve of experiment and material model

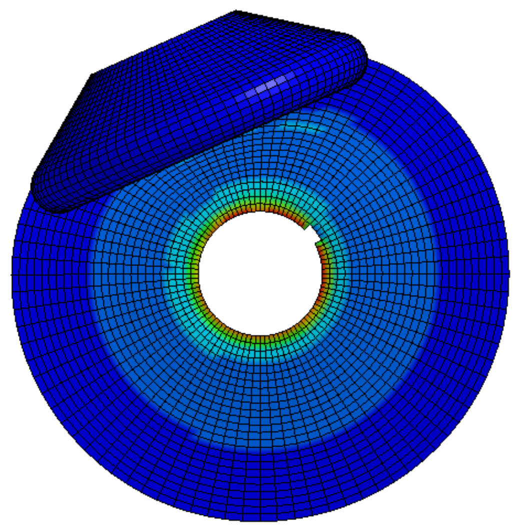


Figure 6. Circumferential crack at beginning

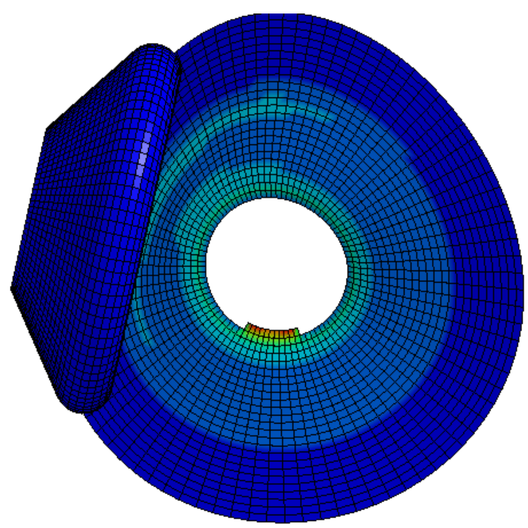


Figure 7. Circumferential crack at ending

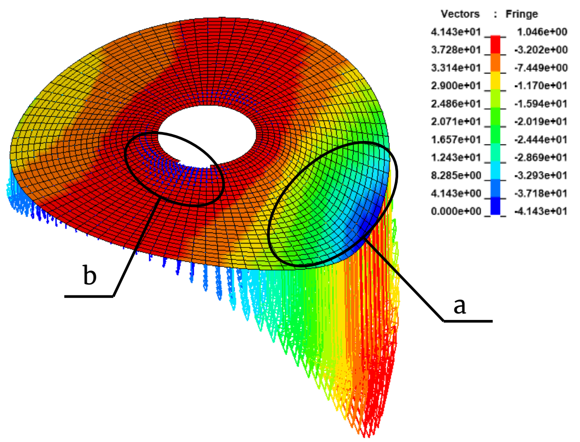
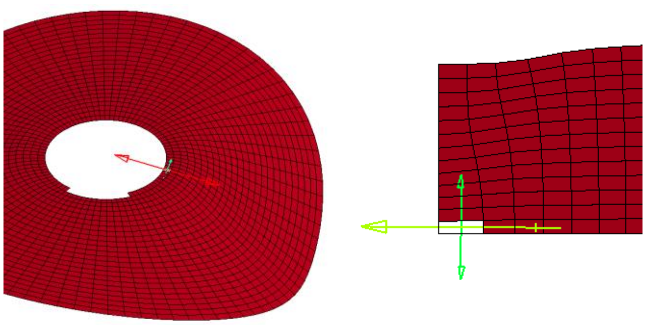


Figure 8. Displacement contribution when cracking; a. Roller contact area; b. Displacement around circumferential cracking

The displacement around cracking is in the opposite direction with the stroke direction of the roller where is showed in Figure 8. Therefore, this area doesn't get support from the mandrel behind it. The stress state in this area, showed in Figure 9, is the same as the middle of tensile test beyond the necking moment. The magnitude of this displacement increases gradually following the roller's stroke increment until damage reach unity then those elements were deleted as cracking happened.



(a) (b)

Figure 9. Stress state at cracking area; (a) metal spinning process; (b) tensile test

5. Conclusion

(1) The GISSMO used in spinning process is fully developed. The failure strain is calculated by reverse engineering method from the tensile test simulation. The stress – strain curve output of the model is seen matched well to experiment.

(2) The spinning process simulation showed the promised results which matched to the experiment.

(3) The circumferential cracking mechanism was presented thoughtfully. This knowledge has a potential to propose a theoretical approach to calculate the process parameters such as rotating speed, feed ratio and paths, roller diameter and radius, etc.

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Appendix A. Engineering stress – strain to true stress - strain conversion

L, L_0 are the current and original gauge length. Engineering strain is defined as

$$\epsilon_{engineering} = \frac{L-L_0}{L_0} = \frac{L}{L_0}-1 \qquad (A.1)$$

True strain is calculated from engineering strain as

$$\begin{aligned} \epsilon_{\text{true}} &= \ln\left(\frac{L}{L_0}\right) \\ \rightarrow \epsilon_{\text{true}} &= \ln\left(\epsilon_{\text{engineering}}\text{-}1\right) \end{aligned} \quad (A.2)$$

The conversion of engineering stress to true stress:

Definition of A, A_0 are the current and original cross section area. Engineering stress refers to origin area, $\sigma_{\text{engineering}} = \frac{P}{A_0}$ while true stress refers to current area $\sigma_{\text{true}} = \frac{P}{A}$, thus the relation between engineering stress and true stress is

$$\frac{\sigma_{\text{true}}}{\sigma_{\text{engineering}}} = \frac{A_0}{A} \quad (A.3)$$

Because the change of volume is constant in the plastic region which yields

$$AL = A_0 L_0 \quad (A.4)$$

The formula is valid before necking onset. Substitute equation () and (A.4) into equation (A.), the true stress is

$$\sigma_{\text{true}} = \sigma_{\text{engineering}}\left(\epsilon_{\text{engineering}} + 1\right) \quad (A.5)$$

Appendix B. The definition of the effective plastic strain

The effective plastic strain is defined intuitively by a similar formula as the effective stress (Von Mises). The incremental form of effective plastic strain is defined as

$$d\epsilon_p = C\sqrt{\left(d\epsilon_{p1}\text{-}d\epsilon_{p2}\right)^2 + \left(d\epsilon_{p2}\text{-}d\epsilon_{p3}\right)^2 + \left(d\epsilon_{p3}\text{-}d\epsilon_{p1}\right)^2} \quad (B.1)$$

With C is an unknown parameter. C is chosen such as $d\epsilon_p$ reduces to $d\epsilon_{p1}$ in case of tensile test. The material does not change its volume during plastic so the Poisson's ratio is 0.5. Therefore, $d\epsilon_{p2} = d\epsilon_{p3} = \text{-}\frac{1}{2}d\epsilon_{p1}$ which $d\epsilon_{p2}$, $d\epsilon_{p3}$ is the incremental transverse plastic strain and $d\epsilon_{p1}$ is the incremental axial plastic strain in tensile test. Based on this information, the equation () becomes

$$d\epsilon_p = Cd\epsilon_{p1}\sqrt{\frac{9}{4} + 0 + \frac{9}{4}} = C\frac{3}{\sqrt{2}}d\epsilon_{p1} \quad (B.2)$$

Applies $d\epsilon_p = d\epsilon_{p1}$, so $C = \frac{\sqrt{2}}{3}$. Finally, the incremental plastic strain is

$$d\epsilon_p = \frac{\sqrt{2}}{3}\sqrt{\left(d\epsilon_{p1}\text{-}d\epsilon_{p2}\right)^2 + \left(d\epsilon_{p2}\text{-}d\epsilon_{p3}\right)^2 + \left(d\epsilon_{p3}\text{-}d\epsilon_{p1}\right)^2} \quad (B.3)$$