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Effects of triaxiality and lode parameter on deep drawing process

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Abstract. The aim of this study is to explore the effects of stress triaxiality and Lode angle parameter as a function of the cup height in the deep drawing process. For this purpose, deep drawing of square cups made of AISI304 steel are analyzed numerically by using von Mises and Hill'48 yield criteria with isotropic hardening. The fracture of the sheet is predicted by applying the Johnson-Cook and the Hosford-Coulomb ductile criteria. The results obtained by using the finite element method are presented in terms of effective plastic strain, triaxiality and Lode angle parameter distributions for the deformed blank. The tensile, compressive and shear nature of the deformation is evaluated by referring the corresponding triaxiality and Lode angle parameter values.

Introduction

Stress state is one of the important factors that affect the deformation and failure of the metals. Recent researches have shown that stress triaxiality and Lode angle are two critical parameters of the stress state. The effects of triaxiality and Lode parameter on deformation behavior of the materials have been studied extensively. Xue and Wierzbicki [1] have developed a fracture criterion with the effect of Lode angle and stress triaxiality and Mirone et. al. [2] has developed a yield criterion with the effect of Lode angle and stress triaxiality. Bao and Wierzbicki [3], carried out a series of experiments on the aluminum alloy Al2024-T351 and it was shown that stress triaxiality, in addition to strain intensity, is the most critical factor affecting the start of ductile fracture. The mechanism of fracture for negative stress triaxialities is determined by shear. For large triaxialities, void growth is the major failure mode. However, for low stress triaxialities between the two regimes described above, a mix of shear and void growth modes may arise. Early investigations by McClintock [4] and Rice and Tracey [5] demonstrated that the stress triaxiality controls the formation of voids by using a porous plasticity model with the void volume as an internal variable that was proposed by Gurson [6]. In Bai and Wierzbicki's [7] study, it was shown that the third invariant and hydrostatic pressure have an effect on material behavior. Moreover, the proposed 3D asymmetric fracture locus was validated by the test results of Bao [8] on aluminum 2024-T351 and A710 steel. Hancock and MacKenzie [9], examined the relationship between the ductility and stress triaxiality of three different steels. In the Bai and Wierzbicki's work [10], the modified Mohr-Coulomb model used by relating to the Lode angle and stress triaxiality.
The aim of this study is to find out the effects of stress triaxiality and Lode parameter on deep drawing processes by using Von Mises and Hill'48 yield criteria combined with Johnson-Cook and Hosford-Coulomb ductile failure criteria. For this purpose, square blanks made of AISI 304 steel were used. Analyzes were performed by a commercial finite element software.

Theory

The yield and ductile fracture criteria that are used in this study and the equations related with triaxality and Lode angle are presented in this section.

Yield Criteria: In this study, von-Mises and Hill'48 yield criteria are used with isotropic hardening assumption. The von Mises yield criterion is given below

$$\left(\frac{3}{2}\sigma'_{ij}\sigma'_{ij}\right)^{1/2} = \sigma_Y \tag{1}$$

where σ'_{ij} are the deviatoric stresses and σ_Y is the yield strength. The Hill'48 yield criterion is

$$2f = F\left(\sigma_{yy} - \sigma_{zz}\right)^2 + G(\sigma_{zz} - \sigma_{xx})^2 + H\left(\sigma_{xx} - \sigma_{yy}\right)^2 + 2L{\sigma_{yz}}^2 + 2M{\sigma_{xz}}^2 + 2N{\sigma_{xy}}^2 - 1 \tag{2}$$

and the constants *F, G, H, L, M* and *N* are calculated experimentally.

Ductile Fracture Criteria: Two ductile fracture criteria are used in the analyses; Johnson-Cook and Hosford-Coulomb. The Johnson-Cook criterion is

$$\bar{\varepsilon}_D^p = [d_1 + d_2 exp(-d_3\eta)]\left[1 + d_4\, ln\left(\dot{\bar{\varepsilon}}^{pl}/\dot{\varepsilon}_0\right)\right](1 + d_5\hat{\theta}) \tag{3}$$

where, $\bar{\varepsilon}_D^p$ is the equivalent plastic strain at fracture, η is the stress triaxiality and $\hat{\theta}$ is the nondimensional temperature defined as,

$$\hat{\theta} \equiv \begin{cases} 0 & \text{for} \quad \theta < \theta_{transition} \\ (\theta - \theta_{transition})/(\theta_{melt} - \theta_{transition}) & \text{for} \quad \theta_{transition} < \theta < \theta_{\text{melt}} \\ 1 & \text{for} \quad \theta > \theta_{\text{melt}} \end{cases}$$

here *d₁, d₂, d₃, d₄, d₅* are the failure parameters, θ_{melt} is the melting temperature, $\theta_{transition}$ is the transition temperature and $\dot{\varepsilon}_0$ is the reference strain rate. According to the Hosford-Coulomb criterion the equivalent plastic strain at the onset of damage $\bar{\varepsilon}_D^p$ is

$$\bar{\varepsilon}_D^p = b\left[1 + d\, ln\left(\dot{\bar{\varepsilon}}^p/\dot{\varepsilon}_0\right)\right](1 + c)^{1/n}\left\{\left\{\frac{1}{2}[(f_1 - f_2)^a + (f_2 - f_3)^a + (f_1 - f_3)^a]\right\}^{1/a} + c(2\eta + f_1 + f_3)\right\}^{-1/n} \tag{4}$$

In the above equation *a, b, c, d* and *n* are material parameters, $\dot{\varepsilon}_0$ is the reference strain rate and f_1, f_2, f_3 are functions of the Lode angle parameter.

Triaxiality and Lode Parameter: Stress triaxiality is given as

$$\eta = \frac{\sigma_m}{\bar{\sigma}_{VM}}$$

where $\sigma_m = \sigma_{ii}/3$ is the mean stress, $\bar{\sigma}_{VM}$, is equivalent von Mises stress. The Lode parameter *L* is given in terms of the principal stresses σ_i as,

$$L = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}$$

Using the normalized third deviatoric stress invariant *ξ*, the Lode angle *θ* can be presented as

$$\theta = \frac{1}{3}\cos^{-1}\ \xi = \frac{1}{3}\arccos\left(\frac{3\sqrt{3}}{2}\frac{J_3}{\sqrt{J_2^3}}\right)$$

where J_2 and J_3 are second and third invariants of the deviatoric stresses. Since the range of the Lode angle is $0 \leq \theta \leq \pi/3$, the range of ξ is $-1 \leq \xi \leq 1$. Further, the Lode angle parameter is $\bar{\theta}$ ($-1 \leq \bar{\theta} \leq 1$) can be formulated as shown below

$$\bar{\theta}\ = 1 - \frac{2}{\pi}arccos\left(\frac{3\sqrt{3}}{2}\frac{J_3}{\sqrt{J_2^3}}\right) = 1 - \frac{6\theta}{\pi}$$

Finite Element Analysis

In the finite element analysis of the square cup drawing a commercial program is used. Due to symmetry conditions, quarter of the square blanks are modelled by using 6400 eight-node brick elements with reduced integration. The punch, die and blank holder are assumed as rigid parts. The dimensions of the blank, punch and die are given in Table 1.

Table 1. The dimensions of the blank, punch and die

Blank size [mm]	80 x 80
Sheet thickness [mm]	1
Punch dimensions [mm]	40 x 40
Punch shoulder radius [mm]	4.5
Punch corner radius [mm]	10
Die dimensions [mm]	42.5 x 42.5
Die shoulder radius [mm]	4.5
Die corner radius [mm]	11.25

The AISI304 stainless steel alloy is used in the analysis with elastic modulus $\boldsymbol{E = 207.8\ \mathrm{MPa}}$, Poisson's ratio $\boldsymbol{\nu = 0.3}$ and yield strength $\boldsymbol{\sigma_Y = 280\ \mathrm{MPa}}$. The true strain-true stress curve is digitized and entered the program. The anisotropy coefficients for the material are; $\boldsymbol{r_0 = 0.923}$, $\boldsymbol{r_{45} = 1.011}$, $\boldsymbol{r_{90} = 0.840}$. Coefficients of Johnson-Cook damage initiation criterion and the Hosford-Coulomb damage initiation criterion given in Table 2 and Table 3, respectively.

Table 2. Johnson-Cook damage initiation coefficients for AISI-304

$\dot{\varepsilon}_0$	θ_{melt}[K]	$\theta_{transition}$[K]	d_1	d_2, d_3 d_5	d_4
1	1673	1000	0.69	0	0.0546

Table 3. Hosford-Coulomb coefficients for AISI-304

a	b	c	n	d	$\dot{\varepsilon}_0$
0.623	1.671	0.096	0.1	0.193	1

Results and Discussion

The results are given for two different cases.

Case 1: For this case, Hill'48 yield criterion is applied with the Johnson-Cook ductile fracture criterion. It is observed that the fracture has started at 20 mm punch travel as shown Fig. 1. The variations of equivalent plastic strain and thickness strain, stress triaxiality, and Lode angle parameter values for the diagonal direction of the cup are presented as a function of the distance from the center of the blank up to the fracture in Fig. 2, Fig. 3 and Fig. 4, respectively. Further, the variation of stress triaxiality and Lode angle parameter values with respect to equivalent plastic strain are given by considering both von Mises and Hill'48 criteria as the metal deforms until failure for the element that fractured first in Fig. 5(a) and Fig 5(b), respectively.

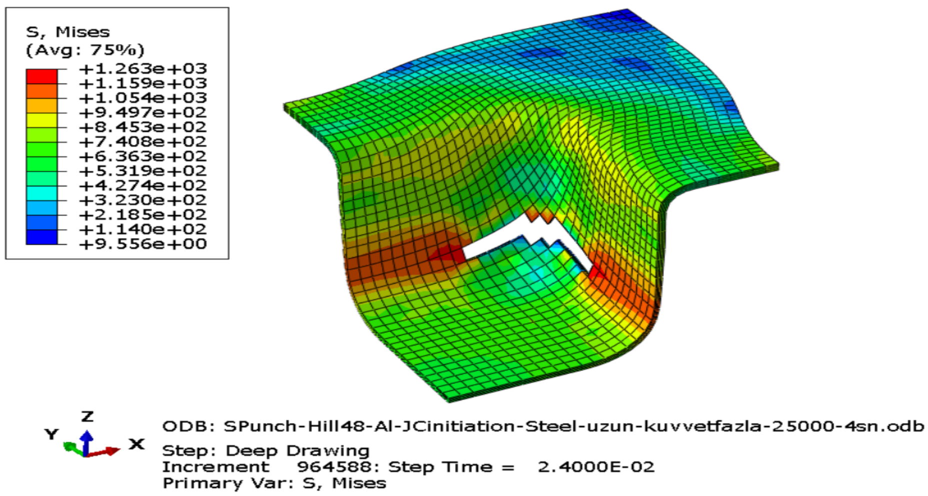

Fig. 1. The deformed cup just after the fracture (Johnson-Cook)

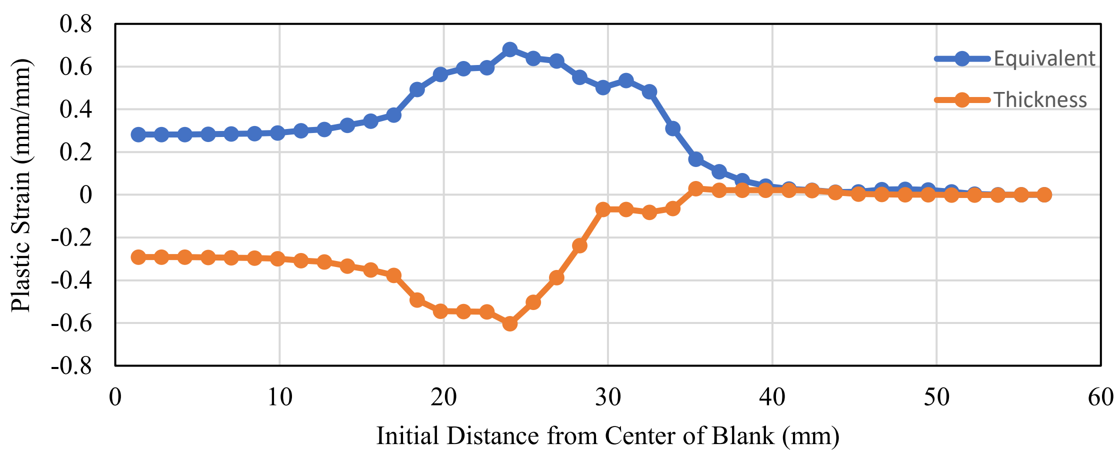

Fig. 2. The variations of equivalent and thickness plastic strain values along the diagonal of the cup at 20 mm cup height (Johnson-Cook)

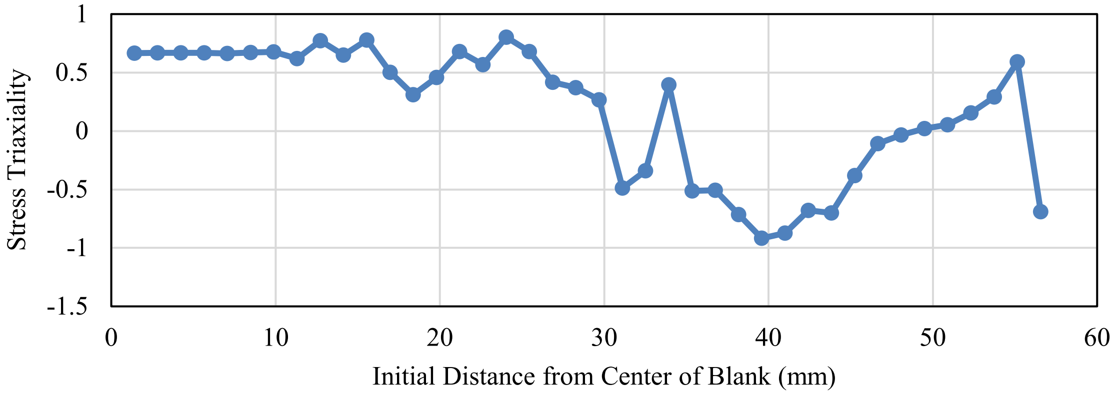

Fig. 3. The variation stress triaxiality values along the diagonal of the cup at 20 mm cup height (Johnson-Cook)

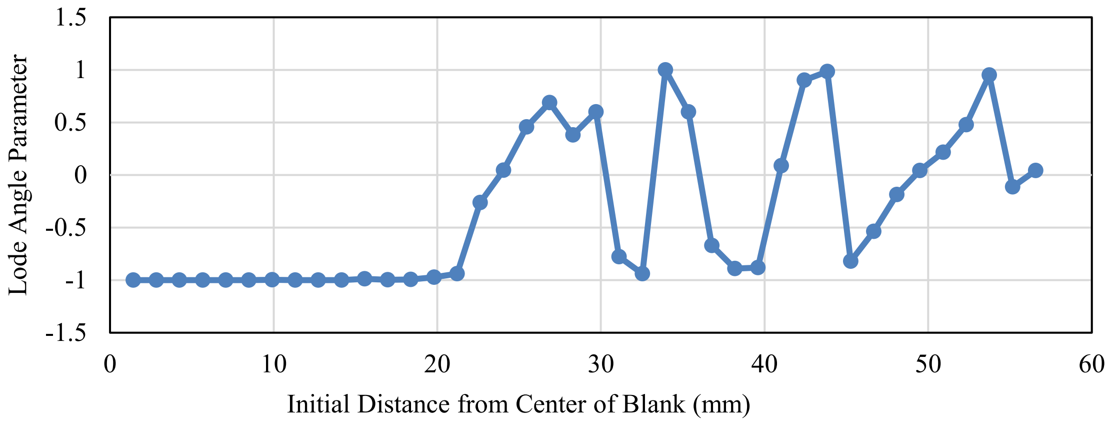

Fig. 4. The variation of Lode Angle Parameter along the diagonal of the blank at 20 mm cup height (Johnson-Cook)

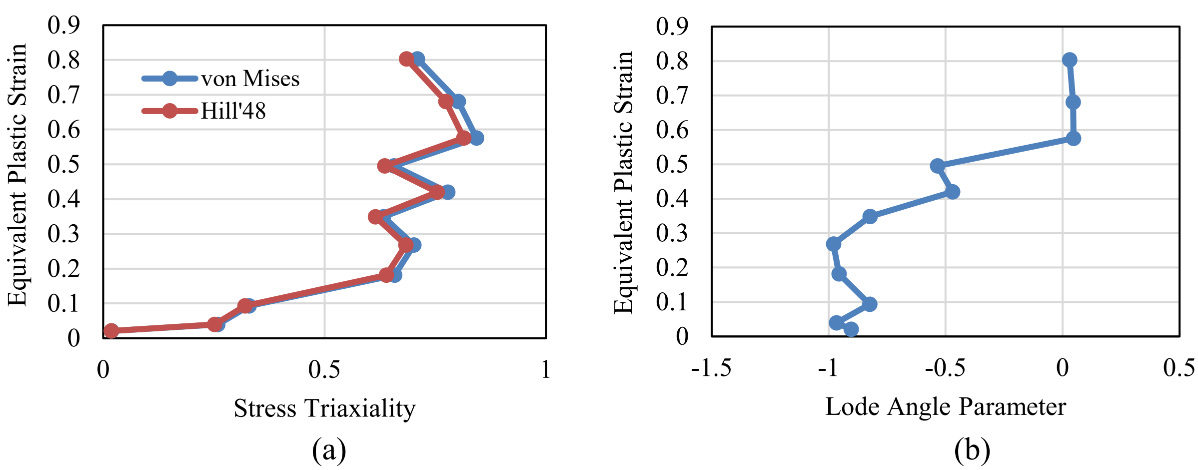

Fig. 5. Variation of the (a) stress triaxiality and (b) Lode angle parameter with respect to equivalent plastic strain for the first fractured element (Johnson-Cook)

In the diagonal direction, when the pre-rupture state of the sheet is examined, it is observed that equi-biaxial tension state dominates up to a distance of 20 mm from the center of initial blank. It is noted that the stress situation of the region changes from tension to shear from punch corner to die corner. After 35 mm from the center of the initial blank, there is a change of stress state from compression to equi-biaxial compression. Following this, the values of the Lode angle parameter and the triaxiality both increasing and became positive. Finally, fracture occurs in the punch shoulder in tension state.

Case 2: In this case, Hill'48 yield criterion is applied with the Hosford-Coulomb ductile fracture criterion. It is seen that the fracture has started at 16 mm punch travel as shown in Fig. 6. The variations of equivalent plastic strain and thickness plastic strain, stress triaxiality, and Lode angle parameter values are presented as a function of the distance from the center of the initial blank up to the fracture for the diagonal direction of the cup in Fig. 7, Fig. 8 and Fig. 9, respectively. Further, the variations of stress triaxiality and Lode angle parameter values with respect to equivalent plastic strain are given by considering both von Mises and Hill'48 criteria as a function of the deformation of the element that fractured first in Fig. 10(a) and Fig 10(b), respectively.

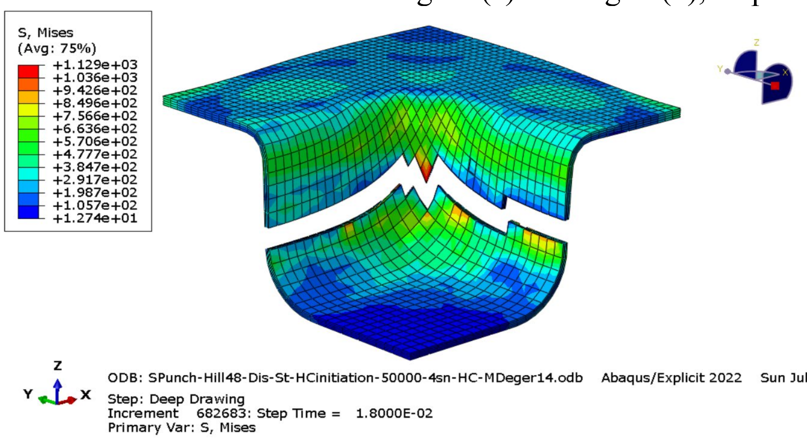

Fig. 6. The deformed cup just after the fracture (Hosford-Coulomb)

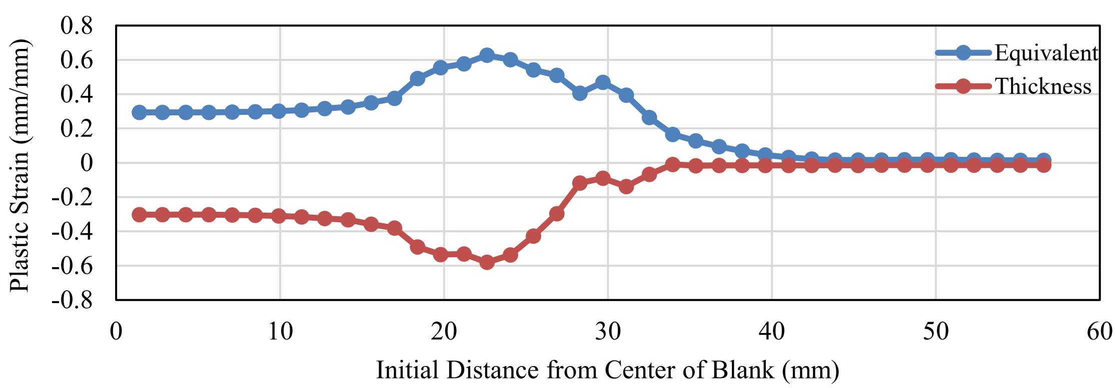

Fig. 7. The variations of equivalent and thickness plastic strain values along the diagonal of the cup at 16 mm cup height (Hosford-Coulomb)

In the diagonal direction, as in the transverse and rolling directions, equi-biaxial stress condition is observed under the punch. When the pre-rupture state of sheet is examined, it is seen that equi-biaxial stress conditions dominates up to 16 mm from the center of the blank. At the punch shoulder, stress state changes from tension to shear while triaxiality values are decreasing. After this region, Lode angle parameter values are decreasing, and triaxiality values are increasing followed by a limited drop towards the blank corner. Fracture occurs at the punch shoulder in tension situation.

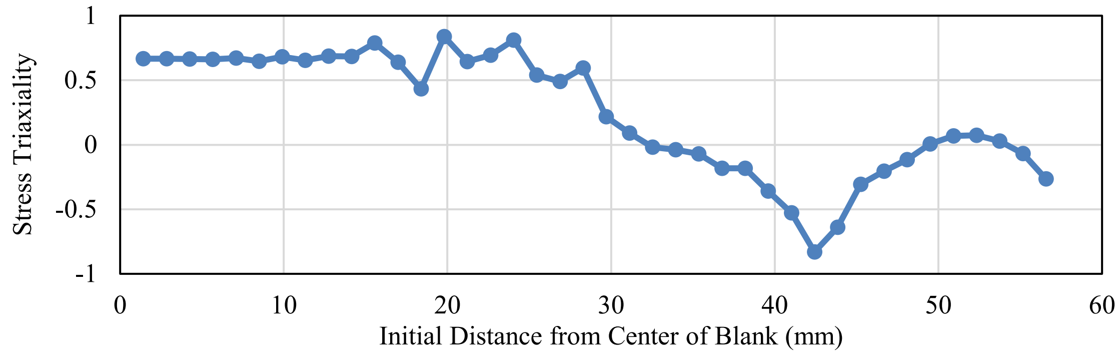

Fig. 8. The variation stress triaxiality values along the diagonal of the cup at 16 mm cup height (Hosford-Coulomb)

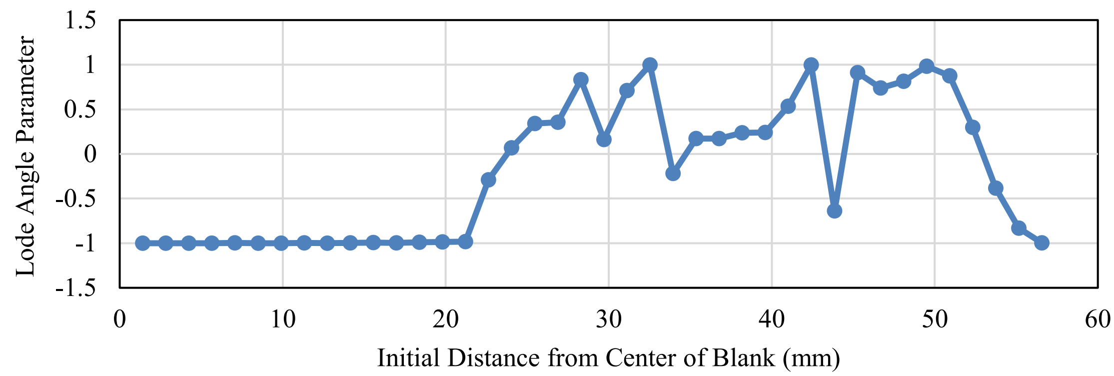

Figure 9. The variation of Lode Angle Parameter along the diagonal of the blank at 16 mm cup height (Hosford-Coulomb)

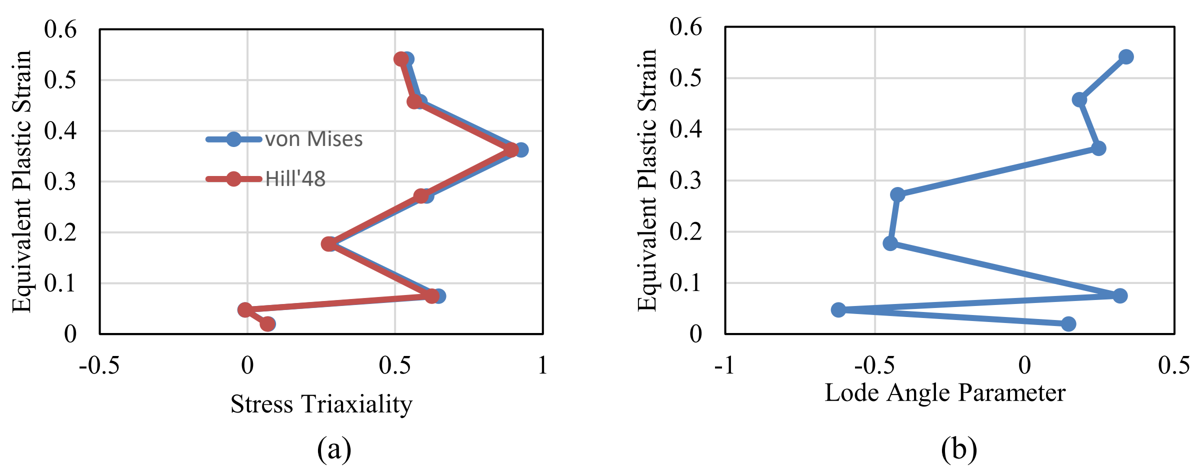

Fig. 10. Variation of the (a) stress triaxiality and (b) Lode angle parameter with respect to equivalent plastic strain for the first fractured element (Hosford-Coulomb)

Conclusions

In this study, von Mises and Hill'48 yield criteria, and Johnson-Cook and Hosford-Coulomb ductile fracture criteria are considered to simulate the square cup drawing process for AISI304 sheet materials. The following conclusions are acquired referring to the diagonal direction since all square cups fractured along the diagonal direction:

1. The part of the sheet under the punch is in equi-biaxial tension condition.
2. On the punch shoulder the sheet is in tension and the dominant deformation type changes from equi-biaxial tension to uniaxial tension as the distance from the center of the blank increases.
3. At the clearance between the die and the punch, the sheet is in tension and the uniaxial tension condition is the dominant deformation type.
4. On the die shoulder the deformation type changes from tension to compression.
5. Under the blank holder the sheet is in compression condition; however, the thickness decreases towards the rim.
6. High variations are observed for the lode angle parameter and stress triaxiality values in the region between die and punch.
7. Significant differences are observed in determining the fracture point depending on the ductile fracture criterion and yield criterion used.
8. It is observed that triaxiality and Lode angle parameter values can be efficiently used to determine the deformation nature of the cup drawing and determine the fracture.

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