ANALYSIS OF WARM DEEP DRAWING FOR Ti-6Al-4V ALLOY

Nitin Kotkunde¹, Sachin Rane¹, Amit Kumar Gupta¹, Swadesh Kumar Singh²

¹Department of Mechanical Engineering, BITS-Pilani, Hyderabad Campus, Hyderabad, 500078, Email: nitink@hyderabad.bits-pilani.ac.in
²Department of Mechanical Engineering, GRIET, Hyderabad, 500072, Email: swadeshsingh@griet.ac.in

Abstract

An accuracy of finite element simulation for sheet metal forming is significantly dependent on the trustworthiness of input properties and appropriate selection of material models. In this work, Hill 1948 and CazacuBarlat anisotropic yield criteria have been implemented for Ti-6Al-4V alloy at 400°C. Material constants required for the yield criteria have been determined using uniaxial tensile test. These yield criteria have been implemented in commercial available DYNAFORM finite element software with LSDYNA solver. In order to validate the finite element results, circular deep drawing experiment has been performed at 400°C. Further, comparison of yield criteria based on thickness distribution and earing profile has shown CazacuBarlat yield criterion is well suited for deep drawing of Ti-6Al-4V alloy.

Keywords: Ti-6Al-4V alloy, Yield Criteria, FEM, Thickness distribution, Earing Phenomena

1. Introduction

In recent years, Ti-6Al-4V alloy is increasingly being used because of their lightweight characteristic and an excellent combination of strength, corrosion resistance and fabricability (Poondla et al., 2009). The importance of this alloy is indicated from the fact that currently it is mostly used alloy accounting for more than 50% of all titanium tonnage in the world (Kotkunde et al., 2014). Sheet metal forming is one of the major manufacturing processes to fabricate titanium alloy components which cannot only reduce the cost due to machining but also enhance the performance of the products (Chen and Chiu, 2005). But the formability of Ti-6Al-4V alloy is very poor compared with other traditional metallic materials at room temperature. The main reasons for poor formability are low ductility at room temperature due to its hexagonal close-packed structure and high degree of springback (Li et al., 2014). Hence, to overcome the difficulty in forming of HCP crystal structure alloys, the best choice would be warm forming (Naka et al., 2008).

Nowadays, finite element simulations are extensively used to reduce inaccurate and expensive tryouts in sheet metal industries (Kotkunde et al., 2014). However, the trustworthiness of the numerical simulations largely depends on the input material models used and correctness of the input material data (Singh et al., 2010). Particularly, in warm-forming simulation, selection of an appropriate yield criterion is essential because it provides an accurate prediction of the observed initial and subsequent yield behaviors of a material (Naka et al., 2008).

Since selection of a yield model is essential in finite element simulations, considerable effort has been made for experimental observations of yield loci on various types of metals (Barlat et al., 2003). In the last few years, several efforts have been made for the development of anisotropic yield criteria which consider plastic anisotropy (Cazacu et al., 2006). For example, Hill 1948 proposed an extension of the von-Mises isotropic criterion to cover plastic anisotropy. This model considered orthotropic symmetry and four anisotropy coefficients in the plane stress condition. Hill 1948 yield model is the most popular for finite element simulations because of limited number of parameters which are easy to determine using uniaxial tensile test. Barlat and Lian (1989) proposed an anisotropic yield criterion which also required four parameters to describe a yield locus. Further, Barlat et al. (2003) developed yield criteria for metals with an increase in eight parameters. For determination of these parameters both uniaxial and biaxial stress state are required. These yield criteria considered symmetry in yielding between tension and...
compression. However for better prediction of yielding in the case of HCP crystal structure, Hosford (1973) stated that the stress asymmetry is also considerable. Considering the effect of asymmetry in yielding further development in the yield criterion is done by Cazacu et al. (2006). But limited study has been reported for the implementation of anisotropic yield criteria for HCP alloys in forming applications at elevated temperatures. Therefore, applicability of these yield models in finite element simulations need to be validate for Ti-6Al-4V alloy.

The objective of the present work is to study the applicability of Hill 1948 and CazacuBarlatanisotropic yield criteria in finite element simulation of deep drawing of Ti-6Al-4V alloy at 400°C and validation of results based on thickness distribution and earing phenomenon in deep drawn cup.

2. Experimental Details

In this work, Ti–6Al–4V alloy sheet of 0.9 mm thickness is used. The composition of the employed material is given in Table 1. The experiments were carried out on the test rig which is shown in Figure 1. Nickel based super alloy is used for manufacturing the die, blank holder and punch because of its excellent dimensional stability even at elevated temperatures.

<table>
<thead>
<tr>
<th>Element</th>
<th>Al</th>
<th>V</th>
<th>Fe</th>
<th>C</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp (wt. %)</td>
<td>5.56</td>
<td>4.07</td>
<td>0.185</td>
<td>0.022</td>
<td>89.99</td>
</tr>
</tbody>
</table>

The setup temperature was controlled and prevented from overheating by means of water circulation from cooling tower. A noncontact type pyrometer was used to measure the operating temperature. Circular blank specimens were machined by using wire-cut electro-discharge machining process for high accuracy and finish. Temperature higher than 400°C increases the oxygen contamination in Ti-6Al-4V alloy and with oxygen the material becomes more brittle due to formation of α-scale. Therefore, it is preferred to perform warm forming of Ti–6Al–4V alloy in an inert and protective environment (Kotkunde et.al. 2014). Considering the limitations of the experimental facility at higher temperatures with an inert environment, the experiments have been performed at 400°C. Molykote was used as lubricant for forming process at elevated temperatures (Singh et al., 2010). Blanks were kept at particular temperature for certain duration (approximately 3-5 minutes) for uniform heating of sheet. Deep drawing operation was performed when the blank reached the required temperature.

The material properties required for determination of yield criteria parameters were obtained from uniaxial tensile test at 0°, 45° and 90° orientations to rolling direction. For uniaxial tensile test, the specimen dimensions are used as per sub-size ASTM: E8/ERM-11 standard. The samples are prepared by using wire cut electro-dischargemachining for better surface finish and dimensional accuracy. The experimental test rig is as shown in Figure 2.

The load-displacement data obtained from computer controlled universal testing machine have been used to calculate the engineering stress (S) and engineering strain. Further, the data is converted to true stress and true strain data. The description of the stress strain curves and strain-hardening of metals by mathematical expressions is a frequently used approach (Kleemola and Nileminen, 1973). This is because it allows the plastic part of the curve to be treated by certain parameters which can be applied to the study of...
formability and deformation mechanisms. In literature, Holloman equation is the most popular and widely used to predict stress strain in plastic region (Choudhary and RaoPalaparti, 2012). Therefore, for present study, Hollman equation (1) is used to calculate strain hardening exponent (n).

\[ \sigma = K\varepsilon^N \]  

(1)

Also, the anisotropic coefficient required for yield criteria development and finite element simulation was calculated using ASTM: standard E517. Biaxial yield stress and compression yield stress value were taken from previous work (Odenberger et.al. 2013). The calculated material properties for Ti-6Al-4V alloy at 400°C are mentioned in Table 2.

<table>
<thead>
<tr>
<th>Table 2 Material Properties for Ti-6Al-4V alloy at 400°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_0 ) (MPa)</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>681.0</td>
</tr>
<tr>
<td>( r_0 )</td>
</tr>
<tr>
<td>0.6</td>
</tr>
</tbody>
</table>

3. Anisotropic Yield Models

Anisotropic yield criteria Hill 1948 and CazacuBarlat were selected for warm deep drawing analysis of Ti-6Al-4V alloy. The material parameters of yield function have been determined and yield loci are compared.

3.1 Hill 1948 Yield Criterion

Hill (1948) is one of the most popular yield criterion for finite element simulation of sheet metal forming processes (Hill R., 1950). The plane stress yield function is given by equation (2).

\[ F(\sigma) = \sigma_{11}^2 + \sigma_{22}^2 - 2\frac{2R+1}{R+1}\sigma_{11}\sigma_{22} + \frac{2^{2R+1}}{2R+1}\sigma_{12} \]  

(2)

where, R is normal anisotropy coefficient, \( \sigma_{11}, \sigma_{22} \) are the principal stresses. The material response after yielding is governed by elastic-plastic constitutive relation with plastic hardening modulus and yield stress of the material as an input. The yield loci for Hill 1948 yield criterion is as shown in Figure 3.

![Figure 3 Hill 1948 yield loci for Ti-6Al-4V alloy at 400°C](image-url)

3.2 CazacuBarlat Yield Criterion

Cazacuet. al. (2006) proposed an anisotropic yield criterion which consists of both tension and compression asymmetry. For extending this criterion, stress deviator s is linearly transformed and the principle values of Cauchy stress deviator in the yield function are replaced by transformed tensor. The proposed anisotropic yield function is given as equation (3).

\[ \left[ |\Sigma_1| - k\Sigma_1 \right]^a + \left[ |\Sigma_2| - k\Sigma_2 \right]^a + \left[ |\Sigma_3| - k\Sigma_3 \right]^a = F \]

\[ \Sigma = C[s] \]

(3)

where, C is a fourth order transformation tensor with reference to orthotropic (x,y,z) axes and F is the size of yield locus, k is based on yield stress in tension/compression and material parameter a in the yield function.

Material parameter a is considered as 8 for Ti-6Al-4V. The material constants in tensor C are determined by performing uniaxial yield stress in tension and compression along with balanced biaxial test and anisotropy coefficients (Cazacu et al., 2006).

\[
C = \begin{bmatrix}
C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\
C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\
C_{13} & C_{23} & C_{33} & C_{34} & C_{35} & C_{36} \\
C_{44} & C_{55} & C_{66} & & & \\
\end{bmatrix}
\]
The material constants have been calculated by solving a set of non-linear equations using MATLAB. The material constants are presented in Table 3. The yield locus plotted by CazacuBarlat function is as shown in Figure 4.

**Table 3** CazacuBarlat yield model material parameters for Ti-6Al-4V alloy

<table>
<thead>
<tr>
<th>( C_{11} )</th>
<th>( C_{22} )</th>
<th>( C_{33} )</th>
<th>( C_{12} )</th>
<th>( C_{13} )</th>
<th>( C_{23} )</th>
<th>( C_{44} )</th>
<th>( a )</th>
<th>( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>1.8</td>
<td>1.9</td>
<td>0.68</td>
<td>0.48</td>
<td>0.45</td>
<td>1.88</td>
<td>8</td>
<td>-0.08</td>
</tr>
</tbody>
</table>

![Figure 4 CazacuBarlat yield loci for Ti-6Al-4V alloy at 400°C](image)

**Figure 4** CazacuBarlat yield loci for Ti-6Al-4V alloy at 400°C

4. Finite Element Analysis

The finite element analysis in the present work is done by using DYANAFORM version 5.6.1 with LSDYNA version 971 as solver. The deep drawing setup model used for the simulations is as shown in Figure 5. Setup consists of die, punch, blank and blank holder.

The model is discretized by using Belytschko-Tsay shell elements to avoid higher computation time required for continuum elements (Singh et al., 2010). In order to simplify finite element model, only quarter geometry is modeled since the material properties, geometry and loading are considered to be symmetric along in-plane mutually perpendicular axes.

![Figure 5 Axisymmetric model of deep drawing setup](image)

**Figure 5** Axisymmetric model of deep drawing setup

The die, punch and blank holder are considered as rigid materials. Different material models are assigned to the blank for comparison. Selective mass scaling is done to reduce computational time, adaptive remeshing is used since it captures the deformation in blank in critical regions like punch corner and wall accurately. Further, the difficulty in determining the friction coefficient is overcome by inverse approach (Singh et al., 2010). In this work, a blank is drawn to form a cup at 400°C and punch load vs. displacement is recorded. Following this, simulations are run by selecting a range of friction values. The punch load vs displacement data obtained by finite element simulations is compared with that of experimental. Thereby, the friction coefficient for which the graph matches with a satisfactory level of accuracy is selected for simulations. The coefficient of friction value was chosen as 0.09 for finite element (FE) simulations.

5. Results and Discussion

Figures 3 and 4 show locus of Hill 1948 and CazacuBarlat yield functions. Material constants evaluation for Hill 1948 yield criteria is comparatively simpler than CazacuBarlat yield criteria. But, Hill 1948 is unable to show yielding behavior in uniaxial compression and biaxial tensile stress state as shown in Figure 3. Inspite of this drawback, these criteria are frequently used in finite element simulations due to ease in identification of material parameters (Banabic, 2010).

On the other hand, loci obtained by CazacuBarlat yield function very well cover all the experimental data point as shown in Figure 4. In Ti-6Al-4V alloy Bauschingher effect is considerable, Since CazacuBarlat yield function considers stress asymmetry therefore, it is very well suited for Ti-6Al-4V alloy. Similar results were observed by (Cazacu et al., 2006), for Mg–0.5%Th alloy which is also a HCP crystal structure.
Further, the applicability of yield criteria needs to validate with finite element analysis. In order to validate the yield criteria, the experiments have been performed at 400°C. The maximum blank diameter of 54 mm was successfully drawn at 400°C; hence the limiting draw ratio (LDR) of 1.8 was achieved. It is seen that LDR of Ti-6Al-4V alloy is significantly lower than other structural alloys. Finite element analysis has been carried out at 54 mm blank diameter and 400°C with Hill 1948 and CazacuBarlat yield criteria. The experimental deep drawn cup at 400°C and simulated cups are as shown in Figure 6 and Figure 7 (a and b) respectively.

Thickness distribution and earing profile are taken as quantifiable measures to validate the simulation results with experimental results. Experiments were performed three times and the average thickness and cup height values were taken. Experimental and Finite element thickness distribution is as shown in Figure 8.

![Figure 8 Thickness distribution 54 mm blank at 400°C](image1)

Average percentage error of thickness distribution and its standard deviation are chosen as statistical measures for comparing experimental results with finite element simulation using Hill 1948 and CazacuBarlat yield criteria. The calculation of relative error of thickness along deep drawn cup is presented in Table 4. It is clear from Table 4 that CazacuBarlat yield has the least error in prediction compared with Hill 1948 Yield criterion.

![Figure 9 Earing profile of experimental and simulated cup](image2)
Table 4 Comparison of percentage error in thickness distribution

<table>
<thead>
<tr>
<th>Material Model</th>
<th>Average Error (%)</th>
<th>Std. Dev. of error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hill</td>
<td>3.1</td>
<td>0.0236</td>
</tr>
<tr>
<td>Cazacu Barlat</td>
<td>1.6</td>
<td>0.0112</td>
</tr>
</tbody>
</table>

Earing is a pronounced phenomenon in deep drawing for anisotropic metals which is also evident from experimental drawn cup in Figure 6. Therefore, this necessitates comparison of yield models based on earing prediction in deep drawing. Figure 9 shows earing profile of experimental and simulated cups. Earing is poorly predicted by Hill 1948 however, earing phenomena is accurately predicted by Cazacu Barlat yield model. Therefore, considering these qualitative parameters of deep drawn cups, Cazacu Barlat yield model is well suited for deep drawing of Ti-6Al-4V alloy.

Conclusion

This work involves finite element simulations of deep drawing using Hill 1948 and Cazacu Barlat yield criteria implemented for Ti-6Al-4V alloy and their validation with experimental results. Based on results, the important finding is:

Cazacu Barlat criterion is well suited for Ti-6Al-4V alloy compared to Hill 1948 yield criteria since anisotropy in yielding and stress asymmetry resulted in excellent validation of yield function with experimental thickness distribution and earing profile.

Future work involves implementation of Cazacu Barlat yielded criterion with advanced constitutive models.

References

Hill R. (1950), The mathematical theory of plasticity, Oxford Publisher.