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# Prediction of earing defect and deep drawing behavior of commercially pure titanium sheets using CPB06 anisotropy yield theory

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ABSTRACT

Recently, sheet metal forming industries have shown interest in characterization of anisotropy properties, tension-compression strength differential and deep drawing behavior of commercially pure titanium (CP Ti) material for successful fabrication of lightweight components. In present work, the formability of 1.0 mm thick CP Ti sheet metal was studied using a laboratory scale deep drawing test set-up, and the limiting drawing ratio (LDR) was found to be 2.143. Four ears were observed in the LDR cup with maximum cup height along diagonal direction (DD) and troughs along both rolling direction (RD) and transverse direction (TD), and the earing height was approximately 13.7% of the total cup height. Tensile and stack compression tests were carried out along different orientations to evaluate the anisotropy properties and tension-compression strength differential, and these data were used to develop the CPB06 constitutive yield model. Also, the developed CPB06 anisotropy plasticity theory was implemented in an FE model to predict the non-uniform material flow, earing defect and thickness distribution successfully. In order to reduce earing defect, a two-stage blank modification technique was proposed incorporating directionalities of both yield strength and plastic strain ratio. A significant 83% reduction in earing height was achieved through use of modified blank with simultaneous benefit of improvement in thickness distribution and reduction in peak load.

## 1. Introduction

Deep drawing process is extensively used to manufacture various lightweight sheet metal components for automotive, aerospace, nuclear, ship building and chemical industries. In this process, a blank is clamped between upper and lower dies with the application of blank holding force as shown in Fig. 1a, and a rigid punch is moved down to deform the blank into the die cavity [1,2]. The stress state acting at the different portions of the cup i.e. bottom, wall and flange are shown in Fig. 1b, neglecting the normal stress component. The material at the cup bottom portion is subjected to a biaxial tensile stress state. On the other hand, the cup flange is under tension-compression deformation mode with tensile stress along the radial direction and compressive stress along the circumferential direction. During the flow of material from flange into the die cavity, the sheet metal bends across die corner which induces tensile and compressive bending stresses in the outermost and innermost layers respectively as depicted in the inset of Fig. 1b. The cup wall experiences a plane strain deformation mode under bi-axial tensile stress state as it is tightly wrapped over the rigid punch. Several defects such as wrinkling in the flange and localized necking in the cup wall may appear due to development of different stress states, and these hinder the productivity of the deep drawing process. In order to minimize these defects, laboratory scale simulative tests were suggested by researchers and in this context, the deep drawability was evaluated in terms of limiting drawing ratio (LDR). The LDR is defined as the ratio of the diameter of the largest circular blank that can be drawn successfully into a cup, to the punch diameter [3,4]. Many researchers extensively studied the dependence of LDR on anisotropy properties (*r*-value), strain hardening exponent (*n*-value) [5,6], die and punch radius, blank holding force, deformation speed, temperature, friction, lubrication etc. [7–11]. A major defect which affects the quality of the deep drawn cups is the occurrence of a wavy edge at the top, commonly referred to as the earing defect. Earing is a result of non-uniform flow of material into the die cavity from different anisotropy directions of the sheet. In practice, a significant amount of material is lost as this wavy edge of the cup needs to be trimmed.

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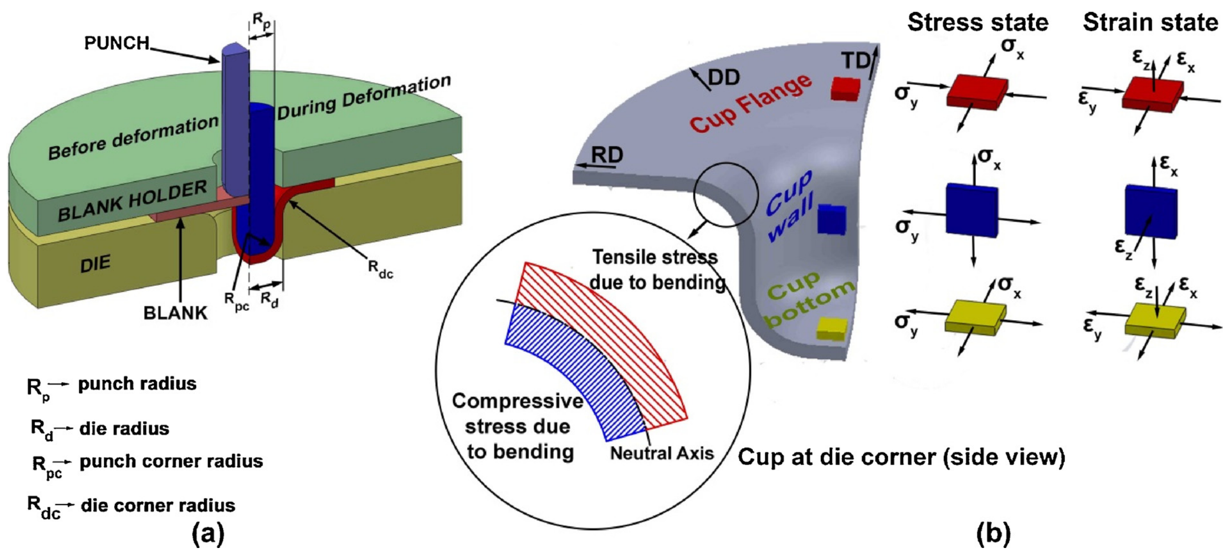


**Fig. 1.** Schematic diagram of deep drawing process: (a) two different punch positions and (b) sectional view showing stress and strain states at various regions.

Sheet metal manufacturing industries are very much interested to stamp commercial pure titanium (CP Ti) as it has high cold formability, specific strength and corrosion resistance. For this reason, this material is extensively used in the fabrication of airframe components like the nacelle, pylon etc. in aircraft industry [12,13], exhaust system in the automotive industry, large tanks in chemical industries [14] and containers for storage and disposal of hazardous waste in nuclear industries [15]. Pure titanium exhibits an HCP structure below a temperature of 882 °C [16]. The axial ratio (or lattice parameter ratio, c/a) of pure Ti HCP crystal is 1.587, and the densely packed lattice leads to easy activation of the prismatic slip over basal slip [14,16]. In rolled HCP structured sheets, the dominant twin and slip systems produce negligible deformation perpendicular to the plane of the sheet [17]. Consequently, titanium sheet material has high plastic strain ratios ($r$ -values) indicating a strong resistance to thinning during deformation [18,19]. Additionally, it was reported that there is a difference in tensile and compressive yield strength of this material due to the orientations of various twin systems [20]. There were very few open literature available on the deformation behavior of CP Ti sheets under complex stress state during the deep drawing process [21–23]. The deep drawability of CP Ti sheet material was investigated by Chen and Chiu [22] and it was concluded that CP Ti has appreciable formability at room temperature. Inagaki and Kohara [23] performed cylindrical deep drawing tests and consequently showed that the differences in twinning frequencies were responsible for the observed non-uniform deformation in the flange. In the above mentioned deep drawing studies, very prominent earing defect was observed in the deep drawn cup. Considering the high cost of Ti, a reduction in earing defect could bring the manufacturing costs significantly down. Therefore, it is very important to predict the earing defect and deep drawing behavior using the appropriate constitutive model in finite element simulation.

The earing phenomenon and its dependence on material properties was investigated by many researchers on sheet metals. It was observed that earing peaks occurred along rolling direction (RD) and transverse direction (TD) in sheet material having positive planar anisotropy value ($\Delta r > 0$) [3]. On the other hand, for a material having negative planar anisotropy value ($\Delta r < 0$), the earing peaks were observed along 45° to the RD or diagonal direction (DD). Yoon et al. [24] developed an analytical relation for predicting the cup heights along different directions during deep drawing of three different aluminum alloys. The model considered the effects of yield strength as well as $r$ -value directionalities. Apart from earing prediction, few attempts were made for modifying the initial blank shape to achieve a reduction in earing. A shape error metric was proposed by Pegada et al. [25] to quantify the earing of a simulated deep drawn cup. Subsequently, the error metric was used to modify the initial blank shape iteratively and reduce the earing. Kishor and Kumar [26] proposed a trial and error approach through FE model to determine the optimum blank shape by removing the material iteratively from the initial blank. The Barlat Yld-89 anisotropy material model was used for the EDD steel sheet material to predict the earing defect. Recently, Cazacu et al. [18] proposed an advanced yield theory to capture the asymmetric yield locus (i.e. tension and compression yield strength differential) and anisotropy properties of HCP materials. This orthotropic yield model, commonly known as CPB06 model, has been successfully used for predicting the formability of Ti alloys like Ti-6Al-4V and Ti-3Al-2.5V [27,28] as well as other HCP materials like Magnesium [29] and Zirconium [30].

After a rigorous literature review, it was observed that there was no open literature available on the prediction of deep drawing behavior of CP Ti sheet metal in the context of material flow, earing defect and thickness distribution using the CPB06 orthotropic yield model. Moreover, for reducing the earing defect of a deep drawn cup, none of the previously proposed blank optimization techniques had considered both the strength and plastic strain ratio directionalities simultaneously. In the present work, the deep drawing behavior of CP Ti sheet was experimentally investigated in terms of LDR, thickness distribution, and earing profile. The CPB06 constitutive model was developed using the yield strength and $r$-value data obtained from tensile and compressive tests. This developed constitutive model was implemented in the FE model to predict the earing defect successfully. Incorporating the yield stress and $r$-value directionalities, a two-stage blank modification technique was proposed to reduce earing defect.

## 2. Experiments

### 2.1. Mechanical characterization

#### 2.1.1. Uniaxial tensile tests

Subsize tensile test specimens were cut along rolling direction (RD), diagonal direction (DD) and transverse direction (TD) from CP Ti sheets of thickness 1 mm as per ASTM E8/E8M-11 [31] standard. These specimens along three different orientations are shown with dimensions in Fig. 2a. The tests were carried out along the above three orientations using a 50 kN universal testing machine (UTM) at a quasi-static constant crosshead speed of 2 mm/min to estimate the plastic flow properties under tensile loading. As shown in Eq. (1), the Lankford