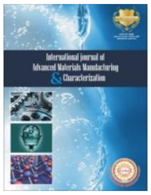

Advanced Materials
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Modification of Initial Blank Shape to Minimize Earing in Deep Drawing Process

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ARTICLE INFO

Article history:
Received 21 Nov 2012
Accepted 26 Dec 2012

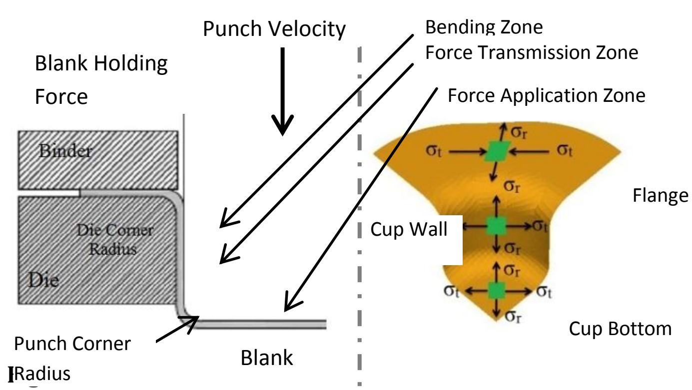
Keywords:
deepdrwaing;
limiting drawing ratio;
anisotropy;
earing;
finite element modeling.

ABSTRACT

Earing is a common defect that occurs in deep drawing process due to non-uniform material properties within the plane of the sheet that is planar anisotropy. In this study, efforts were made to study the earing problem in deep drawing of cylindrical cups by finite element modeling using HYPERWORKS-6.10. Interstitial Free (IF) steel sheet of 1.0 mm thickness has been considered as it has wide application in fabricating critical automobile components. Mechanical properties of IF steel along with tool design parameters were incorporated in the finite element modeling of deep drawing process.Significant earing was observed at rolling and transverse direction in the deformed cup from a circular blank. The cup heights were measured at several points with respect to the rolling direction of the sheet. To minimize earing, flow of material was observed at various steps during the simulation and accordingly initial blank shape had been modified. Modified blanks showed significant reduction in earing and improvement in thickness distribution in simulation.

Introduction

Sheet metal forming is one of the most widely used manufacturing processes for making wide range of products in many industries. It is due to the ease with which metal may be formed into useful shapes through plastic deformation processes in which the volume and mass of the metal are conserved. Deep drawing is a well-established sheet metal forming process where a deformable blank is hold between rigid die and binder, and punch is given motion to deform the blank into a hollow cup as shown in Fig.1.The sheet metal undergoes different stress state, mainly biaxial stresses at different section of the cup during this deformation. The stress states are mainly tensile in all the section except on the cup flange where the tangential stress is compressive in nature [1] as shown in Fig 1, where σ_r and σ_t are radial and tangential stresses respectively. The tangential compressive stress leads to buckling of thin sheet called wrinkling. It is avoided by providing appropriate blank holding force.The formability in deep drawing is measured in terms of limiting drawing ratio (LDR) which is defined as maximum blank diameter that can be drawn using a particular punch and die without wrinkling and failure. The drawability of sheet metal depends mainly ondesign variables: die diameter, punch diameter, punch corner radius, die corner radius [2]; process variables: blank holding force [3], friction-lubrication [4] and material variables: anisotropy parameters (R-values) [5], grain size, grain structure, sheet thickness, strain hardening exponent (n-value) [6] and strain rate sensitivity index (m-value).



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- Doi: http://dx.doi.org/10.11127/ijammc.2013.02.018

Matic of deep drawing process showing stress state at differentregions

Four ears are formed usually at the top of the wall of the cup when a cylindrical cup is drawn from a circular blank. Earing occurs in the drawn cup due to anisotropy in sheetmetal which comes due to preffered crystallographic texture developed during rolling process. Anisotropy is measured in terms of Lankford anisotropy parameters (R) which is defined as:

$$R = \frac{\varepsilon_w}{\varepsilon_t} = -\frac{\varepsilon_w}{\varepsilon_w + \varepsilon_l} = \frac{\ln(\frac{w_f}{w_0})}{\ln(\frac{l_0 w_0}{l_f w_f})} \qquad (1)$$

Where w_0, l_0: Initial width and length and w_f, l_f: Final width and length of the specimen.

The LDR is directly related to normal anisotropy ($\bar{R}$) which is defined as

$$\bar{R} = \frac{1}{4}(R_0 + 2R_{45} + R_{90}) \qquad (2)$$

Higher $\bar{R}$ means higher resistance to thinning, i.e. deeper cup can be drawn [5]. Hence, a high value of R denotes that the material has a very good drawability, i.e. high LDR. Ears are formed due to uneven metal flow in different directions and is directly related with planar anisotropy (ΔR) which is defined as

$$\Delta R = \frac{1}{2}(R_0 - 2R_{45} + R_{90}) \qquad (3)$$

Where R_0, R_{45} and R_{90} are Lankford anisotropic coefficients along rolling direction (0^0), diagonal direction (45^0) and transverse direction (90^0).

Earing is undesirable since it requires an additional processing step where excess metal must be trimmed causing wastage of material. Also, the metal representing the ear will be deformed into the cylindrical cup, and this will demand extra load and power. Several researchers had carried out investigation to modify the initial blank to minimize the earing and adopted different approaches. Kishore and Ravi Kumar [8] modified initial blank by reducing material from 0^0 and 90^0 for EDD steel and found significant reduction in earing. Shim [9] modified the blank using sensitivity analysis and initial nodal velocity. Pegada [10] used error metric to re-design the initial blank shape and repeated the cycle until the error metric satisfied a preset convergence criterion. Sangado [11] assumed ideal cup shape with uniform wall height and the metal flow was traced backwards to modify the initial blank. Yang [12] used reverse forming method is to optimize blank shape for aluminum. The present study aims to determine the modified shape of blank using reduction of material by looking at flow of material at different stages of deformation process in deep drawing using FE Modelling to obtain a cylindrical cup without ears.

Methodology

Finite Element Modeling

Deep Drawing Set-Up and Discretization of Model:

Cylindrical cup drawing process was modeled using a die of Ø64.0 mm with corner radius of 8.0 mm and a cylindrical punch of Ø60.0 mm with a corner radius of 6.0 mm as schematically shown in Fig.2.

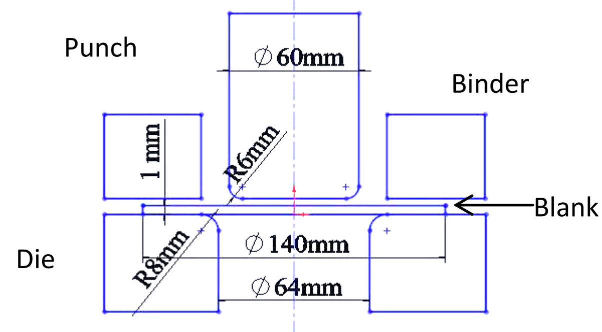


Figure 2. Schematic view of toolings used in deep drawing process.

Finite element modeling was done using HYPERFORM where the complete set-up of deep drawing was first created. All tooling surfaces were modeled using four-node shellelements. The blanks were modeled using four noded quadrilateral Belytschko-Tsay shells (Fig.3). Punch, die and binder were assigned as rigid entity (Master Surfaces) and Blank was assigned as deformable entity (Slave Surface). Die was fixed, however both punch and binder were allowed to move only in the z direction which was coinciding with the punch-axis. Adequate blank holding force (binder force) was applied to avoid flange wrinkling. Numerical calculations of the deep drawing process were performed using RADIOSS non-linear solver.

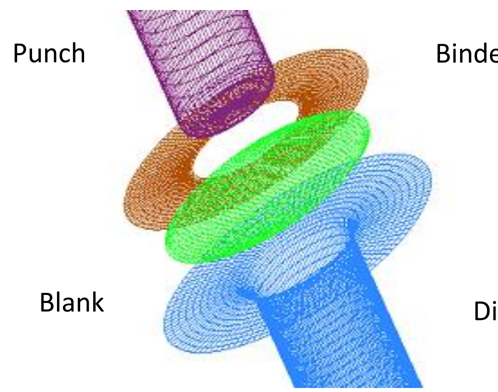


Figure 3. Exploded view of FE model of cylindrical deep drawing

Boundary Conditions:

The different boundary conditions which have been applied into finite element modeling are as follows:

Force Boundary Condition

Blank Holding Force 12kN

Velocity Boundary Condition

Punch Velocity 5000mm/min

Displacement Boundary Condition

Punch Displacement 100mm

Contact Boundary Conditions (Friction*)*

Between Punch and Blank 0.125

Between Die and Blank 0.1

Between Binder and Blank 0.1

Modeling of Deformable Blank:
Selection of Material

IF steel is aluminum-killed steel with extra-low carbon content (nominally 0.005%), in which the residual carbon got combined with niobium, titanium, or some similar element causing a strong affinity of carbon. As most of interstitial spaces were not occupied, hence is called interstitial-free (IF) steel.IF steel primarily has fine ferrites in grain structure which make it highly formable. As mentioned in Table 1 normal anisotropy ($\bar{R}$) of IF steel is higher than EDD [8] and IFHS [13]. So analytically the LDR will be higher for IF steel and it has potential to draw large aspect ratio products in deep drawing. It has higher planar anisotropy (ΔR), which may leads to higher earing. In this aspect IF steel was chosen to be suitable to carry out the deep drawing analysis in the present work.

TABLE I. Mechaniclal properties of if steel [13]

Yield Stress (MPa)	UTS (MPa)	n-Value	K (MPa)	Lankford Anisotropy Parameters				
				R₀	***R₄₅***	***R₉₀***	$\bar{R}$	***ΔR***
131	278	0.29	550	2.12	1.73	2.47	2.01	0.565

Yield Criteria

The deformable blank was modeled using Von-Mises, Hill's quadratic and Barlat'89 yield criteria. In sheet metal, the thickness of sheet is much smaller than length and width. So, stresses along the thickness direction (z-direction) are neglected and is considered to be plane stress condition. The Von-Mises yield criterion is one of the most widely accepted yield functions for isotropic materials. It is expressed as:

$$\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2 = \sigma_{eq}^2 \quad (4)$$

Where σ_1 and σ_2 are the principal stresses along rolling and transverse directions respectively. The Hill's 48 yield criterion is most commonly used for anisotropic sheet materials. In plane stress condition it is expressed as:

$$\sigma_1^2 - \frac{2R_0}{1+R_0}\sigma_1\sigma_2 + \frac{R_0(1+R_{90})}{R_{90}(1+R_0)}\sigma_2^2 = \sigma_{eq}^2 \quad (5)$$

Where, R_0, R_{45} and R_{90} are Lankford anisotropy parameters along the three tensile axes. Barlat and Lian proposed a non-quadratic yield function in 1989 which would accurately predict the anisotropic behavior of materials. Under conditions of plane stress it has the non-quadratic form.

$$a\left|K_1 + K_2\right|^M + a\left|K_1 - K_2\right|^M + c\left|2K_2\right|^M = 2\bar{\sigma}^M \quad (6)$$

Where the parameters, K_1 and K_2 are defined as

$$K_1 = \frac{\sigma_{11} + h\sigma_{22}}{2}, \quad K_2 = \sqrt{\left(\frac{\sigma_{11} - h\sigma_{22}}{2}\right)^2 + p^2\sigma_{12}^2} \quad (7)$$

$$a = 2 - c = 2 - 2\sqrt{\left(\frac{R_0}{1+R_0}\right) \times \left(\frac{R_{90}}{1+R_{90}}\right)} \quad (8)$$

$$h = \sqrt{\left(\frac{R_0}{1+R_0}\right) \times \left(\frac{R_{90}}{1+R_{90}}\right)} \quad (9)$$

The coefficient p has to be calculated by a numerical procedure. The material hardening behavior was described using Hollomon's power hardening law:

$$\sigma_{eq} = K\varepsilon_{eq}^{\,n} \quad (10)$$

Where σ_{eq} is the equivalent stress and ε_{eq} is the equ strain.

Limiting Drawing Ratio
Finite Element Modeling Prediction:

Limiting drawing ratio represents the largest blank that can be drawn through a die without tearing and wrinkling. LDR was predicted by FE modelling using the blanks of different diameter while keeping the tooling and other input parameters constant. It has been found that when the blank size exceeds a critical diameter, buckling at the flange and higher stretching at punch corner does not allow sufficient material flows into the die cavity which leads to necking and failure. The strain based forming limit diagrams (FLDs) were used to identify the first appearance of localized necking on the drawn cup, which limits the formability of the sheet metal. When the strain state crosses a pre-specified value it shows failure. The values were calculated using Keeler Brazier equation.

$$FLD_0True = ln\,[1 + (0.233 + 0.413t)\; n / t]$$

$$\epsilon_1 = FLD_0True - \epsilon_2, \quad \text{while } \epsilon_2 < 0 \quad (11)$$

$$\epsilon_1 = ln\,[0.6\; exp\;\epsilon_2 - 1 + \exp FLC_0True]$$

Analytical Prediction:

LDR was also analytically calculated using Whiteley's [5] equation as follows:

$$\text{LDR} = e^{f\sqrt{(1+\bar{R})/2}} \quad (14)$$

Where, f is the factor which is generally considered to be 0.9 accounts for influence of process conditions on drawing efficiency. It can be observed from this equation that LDR increases with increasing $\bar{R}$ but it ignores the effect of strain hardening exponent (n). Later Leu [7] proposed the following method to calculate the LDR by incorporating the effect of both n and $\bar{R}$.

$$\text{LDR}= \sqrt{[\{e^{2\,fe^{-n}\sqrt{(1+\bar{R})/2}}\} + \{e^{2n\sqrt{(1+\bar{R})/2}}\}] - 1} \qquad (15)$$

Earing Measurements

Earing height was predicted for several blanks of different diameter using FE modeling by following procedure:

1. Circular blank was divided into 24 equal parts by drawing lines at 15^0 intervals from center to the circumference of the blank with respect to rolling direction.
2. The node numbers at the circumference of the blank were found corresponding to the points where the above lines intersect the circumference.
3. The differences were measured between the displacements (z-coordinate) at those particular nodes with the center node (at bottom) of the cup. These differences (Fig.4) showed the heights of the cup at those particular nodes mentioned earlier.

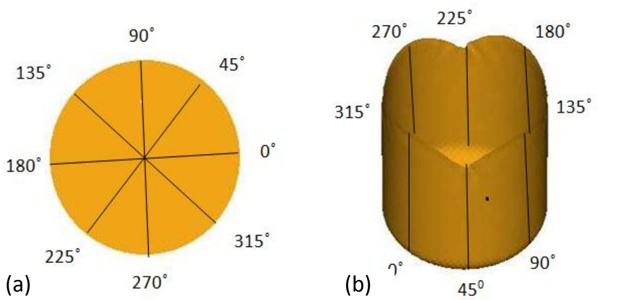


Figure 4.Cup height measurements at different places on (a) initial blank and (b) deformed cup

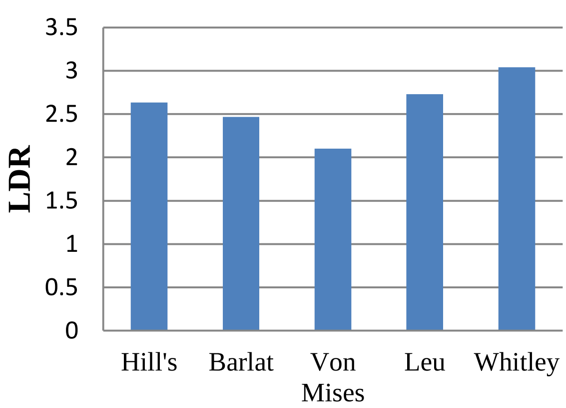


Figure 5.Comparison of LDR predicted in FE Modelingand

Earing Profile

The IF steel used in the present study has higher planar anisotropy (ΔR=0.565) and hence significant earing has been observed in the cups drawn with this material. From Fig.6 it can be seen that four ears have formed in case of cylindrical cup, at 0° and 90° to the rolling direction because the ΔR value of this material is positive. In FE modelling using Von-Mises yield criteria no ears were observed in the deformed cup. Hence, it is concluded that in cylindrical cup drawing, anisotropy plays crucial role in formation of earing.

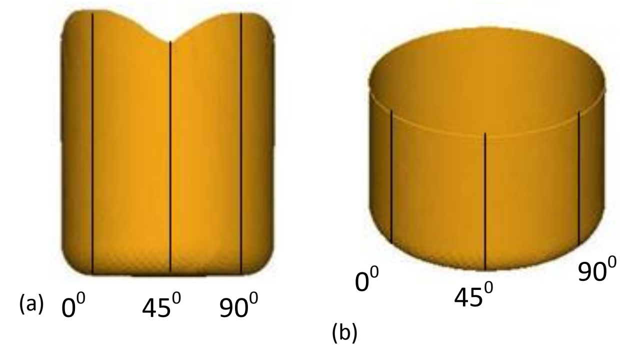


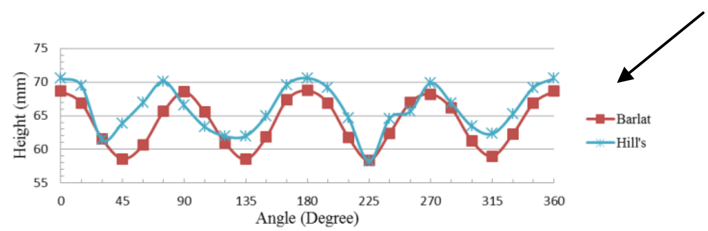
Figure 6. Earing profile predicted incorporating (a) Hill's and (b) Von Mises yield criteria

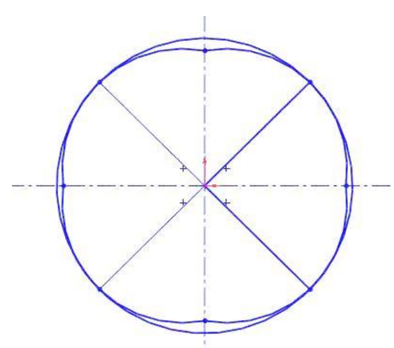
However it is very difficult to point out the yield criterion that is predicting the ear profile in a better manner. Hill's criterion shows higher ear height compare to Barlat's yield criterion as Hill's yield criterion takes care of large variation of strength with angle. The comparison of cup heights has been shown in Fig.7.

Modification of Initial Blank to Monomize Earing

To minimize earing following procedure was adopted to modify the initial blank shape:

1. Blank shape was modified by removing material from 0° and 90° with rolling direction using Solidworks 2009





1, 2, 3, 4, 5, 6, 7, 8: Points on circular blank
1', 2', 3', 4', 5', 6', 7', 8': Points on modified blank

Figure 8. Method of sketching the modified blanks

2. The Δr_1 and Δr_2 values were found out as:

$$\Delta r_1 = R_0 - R_{45} \qquad (16)$$

$$\Delta r_2 = R_{90} - R_{45}$$

3. To remove material, four new points was determined (two each on X-axis and Y-axis). These points were numbered as 1', 3', 5' and 7' (Fig. 8).

The X- and Y- coordinates of these four points were determined as follows:

$$\text{Modified X-coordinate} = R - \beta\, \Delta r_1 \qquad (18)$$
$$\text{Modified Y-coordinate} = R - \beta\, \Delta r_2$$

Where, R is the radius of circular blank.

4. Taking three different values of β modified blanks were prepared. They are
   (a) Modified blank 1 for β=4
   (b) Modified blank 2 for β=6
   (c) Modified blank 3 for β=8

5. Arcs were created connecting 3 points. Two end points were newly identified points on X (0^0) and Y (90^0) axis. Mid-point was intersection point of circular blank and lines drawn at 45^0 to rolling direction. Four arcs have been created which were 1'2'3'; 3'4'5'; 5'6'7' and 7'8'1' (Fig.8) with centers at C_1, C_2, C_3 and C_4 respectively.

Among all three modifications, the cup height was more uniform using the 2nd modification with β=6 where the variation of cup height was less than 3mm. The deformed cup obtained from this modified blank shown in fig.9. for reference. The cup heights were measured at different points with respect to rolling direction and plotted as shown in Fig.10 for different initial blank shape.

Variation of the cup height is better observed through % ear height as shown in Fig.11, where % ear height is defined as:

$$\%\ \text{ear height} = \frac{\text{max. cup height} - \text{min. cup height}}{\text{min. cup height}} \times 100 \qquad (20)$$

Among all three modifications, the % ear height variation was less than 5% with the 2nd modification where β=6.

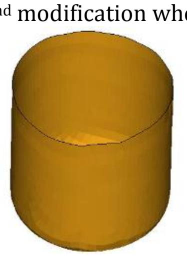
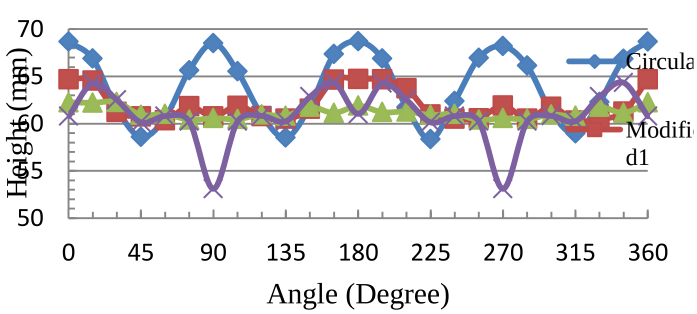


Figure 9. Cup drawn with modified blank-2



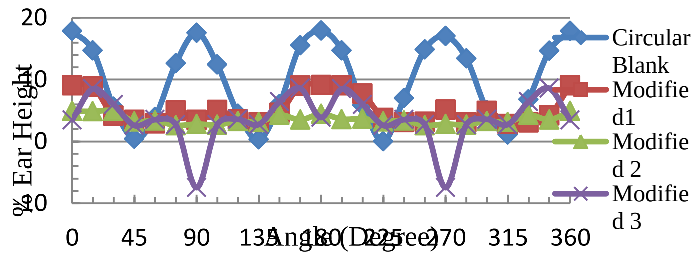


Figure 11. Comparison of earing profile of different modified initial blanks in cylindrical deep drawing in terms of % ear height

Thickness Distribution

The drawn cups were cut along the rolling direction to measure the thickness distribution along the rolling direction. It was found the fall in thickness everywhere in the punch corner region of the cups. Necking usually initiates from this areas due to severe thinning of material. Deep drawing of modified blank shows improvement in thickness distribution (Fig.12) which may leads to higher drawability.

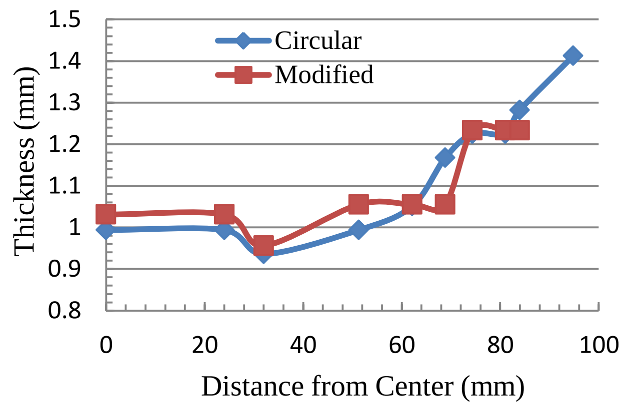


Figure 12. Comparison of thickness distribution

Results and discussion

Limiting Drawing Ratio

The comparison between LDR values predicted using different methods are shown in Fig.5. Hill's yield criterion predicted higher LDR than Barlat's yield Criteria. Whiteley's and Leu's formula over predicted the LDR in cylindrical drawing as these analytical relations do not consider design parameters and thickness into account. The Von-Mises's yield criterion, which is an isotropic yield criterion, doesn't consider $\bar{R}$ and underpredicted LDR.

Conclusion

FE simulation predicts the LDR more accurately compared to analytical results. Incorporation of Barlat's yield criterion predicts LDR lesser than Hills yield criterion in FE simulations. Planar anisotropy plays the major role in formation of earing in cylindrical drawing. Hill's yield criterion incorporates the changes in strength in different directions of material and predicts higher ear profilethanBarlat's yield criterion in cylindrical drawing. Reduction of the earing t is possible using noncircular blanks and for that a new approach was employed for anisotropic sheet material. The variation of ear heights got reduced to lesser than 5% of cup height using modified blank. Deep drawing of modified blank shows improvement in thickness distribution. It may leads to higher drawability.

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