Estimating surface hardening profile of blank for obtaining high drawing ratio in deep drawing process using FE analysis

C. J. Tan$^{1,2,4}$, A. Aslian$^{1,2}$, B. Honarvar$^3$, J. Puborlaksono$^{1,2}$, Y. H. Yau$^1$ and W. T. Chong$^1$

$^1$Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Lembah Pantai, Kuala Lumpur, Malaysia
$^2$Centre of Advanced Manufacturing and Material Processing (AMMP Centre), University of Malaya, 50603 Lembah Pantai, Kuala Lumpur, Malaysia
$^3$Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Lembah Pantai, Kuala Lumpur, Malaysia

E-mail: tancj1@yahoo.com/ tancj@um.edu.my

Abstract. We constructed an FE axisymmetric model to simulate the effect of partially hardened blanks on increasing the limiting drawing ratio (LDR) of cylindrical cups. We partitioned an arc-shaped hard layer into the cross section of a DP590 blank. We assumed the mechanical property of the layer is equivalent to either DP980 or DP780. We verified the accuracy of the model by comparing the calculated LDR for DP590 with the one reported in the literature. The LDR for the partially hardened blank increased from 2.11 to 2.50 with a 1 mm depth of DP980 ring-shaped hard layer on the top surface of the blank. The position of the layer changed with drawing ratios. We proposed equations for estimating the inner and outer diameters of the layer, and tested its accuracy in the simulation. Although the outer diameters fitted well with the estimated line, the inner diameters are slightly less than the estimated ones.

1. Introduction

Industries have been forming high strength steel and aluminium alloy sheets into lightweight auto parts. However, the formability of the sheets is low at room temperature. Vollertsen and Lange developed the Tailored Heat Treated Blanks technology to improve the formability of the sheets.[1] They applied laser-induced heating to locally soften the blank holding portion of the high strength aluminium alloy blank. They then drew the partially softened blank into a cylindrical cup, and the LDR of the cup increased from 2.0 to 2.6. The soft portion of the cup aged back to its original hardness after seven days. However, this method is only applicable for precipitation hardenable alloys, and the laser heat treated area is large, resulting in low processing speed. Laser transformation hardening has improved wear characteristics, hardness, life performance of tools and dies in the industries with minimum part distortion.[2] It locally heats the surface of a thick specimen, transforming the surface layer to an austenite structure, leaving bulk material unchanged. Due to self-quenching, rapid cooling of the austenite forms the hard and brittle martensite. Kovalenko and Golovko obtained uniform hardened depth by high power diode laser due to its top-hat beam profile.[3] Since heat dissipation from bulk materials hardens the specimen surface, surface hardening of thin specimens is difficult. So and Ki reported that they couldn’t obtain surface hardening for AISI 1020 sheets having 1.3 mm thickness and less.[4] However, Ki et al. developed a heat-sink assisted laser transformation hardening method. [5] They increased the hardened width and depth of a 2 mm thick DP590 dual-phase steel sheet to 5 mm and 1.6 mm, respectively. The hardness of the target section increased from about 190 HV to 350 HV. For large

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$^4$Address for correspondence: C. J. Tan, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Lembah Pantai, Kuala Lumpur, Malaysia. E-mail: tancj1@yahoo.com/ tancj@um.edu.my
stamped parts, the surface hardening speed can be increased by increasing the track width of the laser beam. Seifert et al. reported a track width of more than 50 mm at once is possible with the multi-kilowatt range high power diode laser.[6] Since hardened depths decrease with high laser travel speed and low laser power, it is important to study the minimum dimensions of the hard layer at different hardness levels for high production rate and low equipment cost.[7] Nguyen and Merklein evaluated various heat-treatment layouts in deep drawing process of fast-hardenable aluminium alloy sheets into cross-shape drawn cups using finite element analysis.[8] However, they didn't report the detailed dimensions of the hardened layer and its effects on increasing the LDR.

In this study, we calculated the deep drawing process of cylindrical cups from partially hardened blanks using ABAQUS Standard Ver. 6.10. In the axisymmetric model, we partitioned an arc-shaped hard section into a flat blank following the shape reported by Ki et al.[5] We obtained the values for the inner diameter, outer diameter and the minimum depth of the hard layer at 2 different hardness levels for successful drawings of cups at different drawing ratios. When the drawing ratios exceeded the limit, we observed localised necking around the bottom corner of the cup in the simulation. We determined the LDR of the cup based on the successful drawing right before necking.

2. Increase in LDR with partially hardened blank

Figure 1 shows the comparison between the cylindrical cup formed from the partially hardened blank and the one formed from the normal blank for the same drawing ratio. We observed high stress concentrations in the hard layer with increasing punch stroke. Due to the high tensile strength and the uniform distribution of stresses in the hard layer, we observed no necking in the cup. However, necking occurred around the bottom corner of the cup formed from the normal blank for the same drawing ratio due to stress concentrations.

![Figure 1. Comparison between cylindrical cup formed from partially hardened blank and one formed from normal blank for same drawing ratio.](image)

3. Conditions for FE simulation

Figure 2 shows the simulation conditions and the FE model for the deep drawing process of a cylindrical cup. We modeled the blank as solid deformable and all the tools as analytical rigid. We treated the model as axisymmetry in the simulation. We fixed the initial blank thickness and the diameter of the blank at 2 mm and 80 mm, respectively. \( R_p \), \( R_d \) and \( C \) remained constant. We determined the drawing ratio (DR) from the ratio of the diameter of the blank to the diameter of the punch. We reduced the diameters of the punch and the die by 1 mm for each increment in DR. The clearance between the punch and die remained constant at 3 mm in each increment. We started the test at \( DR=2.11 \) using \( D_p=38 \) mm as the LDR for the DP590 blank is equal to 2.11. We obtained successfully drawn cups for each increment in DR using different hard layers and hardened
depths until we observed localized necking. We applied a constant blank holding force of 11 kN for all DRs. The cross section of the hard layer consists of a horizontal line at the top and an arc at the bottom. We constructed the arc from 3 points i.e. \( D_1, D_2 \) and \( t_h \). The position of \( t_h \) is in between \( D_1 \) and \( D_2 \).

- Target inner diameter of hard layer, \( D_1 = D_p - 2(R_p) - t_0 \)
- Target outer diameter of hard layer, \( D_2 = D_p + C + \frac{t_o}{2} \)
- Width of hard layer, \( w_h(mm) = \frac{D_2 - D_1}{2} \)
- Thickness of hard layer, \( t_h(\%) = \text{percentage of } t_0 \)

Where,
- \( t_0 \) = initial blank thickness (mm)
- \( D_p \) = diameter of punch (mm)
- \( D_d \) = diameter of die (mm)
- \( R_p \) = punch corner radius (mm)
- \( R_d \) = die corner radius (mm)
- \( C \) = Clearance between punch and die

**Figure 2.** Simulation conditions and FE model for deep drawing process of cylindrical cup.

We modeled all contact surfaces following Coulomb’s friction law, and assumed a penalty value of 0.1 for the coefficient of friction. Penalty friction limits motion between the surfaces to an elastic slip. We divided the blank into 4-node quadrilateral elements with reduced integration and hourly glass control. We defined an average global seed size of 0.5 mm for the parent material and 0.2 mm for the hard layer. We assumed the blank including the hard layer to be homogeneous and isotropic in the model. During the simulation, we first applied the blank holding force at the flange portion. A punch moving downward then pushed the blank completely into the die cavity.

We assumed the parent material as DP590 and the hard layer as DP780 or DP980 in the simulation. We adopted the flow stress curves reported by Sung et al. to define the plastic deformation behaviors for DP590, DP780 and DP980.[9] We estimated the hardness for these materials from the Ultimate Tensile Strength (UTS) using the following correlation reported by Martin and Gejza.[10]

\[
\text{UTS} = 2.77 \times \text{Hardness (HV)} + 92.754
\]

The estimated Vickers hardness for DP590, DP780 and DP980 are equal to 186 HV, 255 HV and 328 HV, respectively. The hardness values set for the hard layers i.e. DP780 and DP980 are less than the maximum hardness obtained by Ki et al. i.e. 350 HV in the laser transformation hardening process of DP590 sheets having the same blank thickness.\(^5\) Hence, hardness values set for the hard layers in this study are within the process limit, and it is feasible in reality.

### 4. Results obtained from simulation

#### 4.1. Relationships between drawing ratios and dimensions of hard layers

We obtained the dimensions for the two different types of hard layers from successfully drawn cups using different DRs. Figure 3 shows the relationship between the thickness of the hard layer and the drawing ratio. The LDRs for DP980 and DP780 are equal to 2.50 and 2.42, respectively by taking into consideration of the process limit as reported by Ki et al. i.e. the maximum hardened depth is equal to 1.6 mm or 80% of the initial
blank thickness.[5] $t_h$ increased with DR for both types of hard layers to enhance resistance to failure around the punch corner. The amount of increase in hardened depth for DP780 is more than the one for DP980 due to its lower tensile strength.

Figure 4 shows the comparison between the calculated and the target inner and outer diameters of the hard layer for successful drawing at each DR. $D_2$ for both layers fitted well with the upper target line. However, $D_1$ for both layers are less than the lower target line when the drawing ratio is greater than 2.3. The stress concentration moved from the punch corner toward the punch bottom for high DR. Reduction in $D_1$ increased the resistance to failure of the blank.

![Figure 3. Minimum thicknesses of hard layer for successful drawing at each drawing ratio.](image)

![Figure 4. Comparison between calculated and target inner and outer diameters of hard layer for successful drawing at each drawing ratio.](image)

**4.2. Increase in LDR using hard layer equivalent to DP980 or DP780**

Figure 5 shows the successfully and failed drawn cups obtained from the simulation for different partially hardened blanks indicating the increase in LDR. Without the hard layer, the LDR for DP590 blank is 2.11, in agreement with the one reported by Wang et al. i.e. 2.19 for the same steel grade.[11] We observed a maximum stress value of 623 MPa around the upper portion of the cup due to the circumferential compression in the flange portion during the drawing process. The LDR for DP590 blank having a hard layer of DP980 is 2.50. We observed a maximum stress value of 849 MPa in the hard layer for increase in DR due to stretching caused by the punch during the drawing process. Since the highest stress value is lower than the ultimate tensile strength of the hard layer, we prevented necking in the hard layer, and successfully obtained a fully drawn cup. Further increase in hardened depth for DR=2.58 shifted the stress concentration point from the punch corner to the shoulder of the cup leading to necking in this zone. The LDR for DP590 blank having a hard layer DP780 is equal to 2.42. We observed a maximum stress value of 816 MPa in the hard layer. The
stresses for most of the elements in the hard layer are less than the ultimate tensile strength. We prevented necking owing to the high resistance to failure of the hard layer. We set the limit for the hardened depth at 80%, taking into the consideration of the process limit. Further increase in DR shifted the stress concentration point toward the upper punch corner. Due to the arc-shape of the hard layer, the hardened depth in this point is insufficient, resulting in localized necking.

Figure 6 shows the relationship between the average change in wall thickness around the cup corner and the percentage of hardened depth for different drawing ratios. For successful drawing, the amount of increase in hardened depth for DP780 is larger than the one for DP980 for increasing DR. The resistance to the failure of the cup increases with the tensile strength of the hard layer resulting in high LDR. We measured the average change in wall thickness from 5 points around the corner of the cups. The amount of thinning around the corner for DP780 is higher than the ones for DP980 except for drawing ratio 2.35 due to the 2.5 times increase in hardened depth. The partially hardened blank has potential application in multi-stage stamping process of wheel disks as the inner corner of the wheel disk tends to fail in the fatigue tests. [12-13]

Figure 5. Successfully and failed drawn cups obtained from simulation for different partially hardened blanks indicating increase in LDR.

Figure 6. Relationship between average change in wall thickness around cup corner and % of hardened depth for different drawing ratios.

5. Conclusions
We estimated the hardening profiles of the partially hardened blank for increasing LDR of cylindrical cups using FE analysis. In the simulation, we successfully increased the LDR for DP590 blank from 2.11 to 2.50 by increasing the target surface hardness from 186 HV to 328 HV using \( w_h = 11 \) mm and \( t_h = 50 \% \). However, the LDR reduced to 2.42 when the increase in hardness becomes small i.e. to 255 HV using \( w_h = 13 \) mm and
When the hardness level of the target surface decreased, we increased the hardened width, $w_h$ and the hardened depth, $t_h$ to obtain similar LDR. The proposed equations for estimating the inner and outer diameters of the hardening width for successful drawing fitted well with the simulation results although the inner diameter requires additional width at high DRs.

Acknowledgement
The authors would like to thank University of Malaya for providing the research grant support under the project no. RP021A-13AET.

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