Development of oil canning index model for sheet metal forming products with large curvature

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Abstract. Oil canning is predominantly caused by unequal stretches and heterogeneous stress distributions in steel sheets, which affects the appearance of components and develop noise and vibration problems. This paper proposes the formulation of an Oil canning index (OCI) model that can predict the occurrence of oil canning in the sheet metal. To investigate the influence of material properties, we used electro-galvanized (EGI) and galvanized (GI) steel sheets with different thicknesses and processing conditions. Furthermore, this paper presents an appropriate experimental and numerical procedure for determining the sheet stiffness and indentation properties to evaluate the oil canning results. Experiments were carried out by varying the tensile force over different materials, thicknesses, and bead force. Comparison of the discrete results obtained from these experiments confirmed that the product shape characteristics, such as curvature, have a significant influence on the oil canning occurrence. Based on the results, we propose the new OCI model, which can effectively predict the oil canning occurrence owing to the shape curvature. Verification of the accuracy and usability of our model has been carried out by simulating the experiments that were done with the sheet metal. The authors observed a good agreement between the experimental and numerical results from the model. This research work can be considered as a very effective method for eliminating appearance defects from the automobile products.

1. Introduction
Various automobile parts such as the vehicle outer plate, the roof panel and common sheet metals parts like the outer plate of the household appliances are produced using the Stamping process. The Oil canning (OC) phenomenon is a waviness defect in a flat part of a metal panel occurring on parts produced using the stamping process. Due to the inherent nature of the thin sheet metals, this phenomenon causes defects in the shape and appearance of the stamped products. These defects are difficult to get rid of, through additional processes, so it is important to predict and prevent it in advance. Various studies and attempts have been made to solve this problem because the OC that occurs on the stamped panel affects not only the shape of products but also causes defects such as buckling.

Previous research work done on this topic have been commendable. Gunnar et al. [1] proposed a mechanical testing device to make a reasonable standard for quantitatively measuring the
stiffness and dent resistance of an auto body panel. They found that as the curvature of a plate increases, the stiffness becomes smaller. Likewise, the indentation resistance increases when the material yield strength and the plate thickness are higher. Stefan Holmber et al. [2] found that the stiff dent resistance and stiffness of a double-curved panel are influenced by the raw material thickness (initial plate), the material properties, the shape and curvature of product, thickness reduction, strain hardening, residual stress and spring back. So they developed the static method for measuring the indentation resistance of a double-curved panel. He also et al. [3] developed the thinner automotive exterior panels via the dent resistance and the stiffness experiments of the panels. From numerical verification, they found that the error of the numerical analysis results becomes large when the material strain is large. Shen et al. [4, 5] investigated their work by considering the Bausinger effect to predict the indentation resistance of stamped panels under complex deformation and loading conditions. They stated that the accuracy of numerical simulation could be effectively improved by considering the Bausinger effect in the stamping process of high strength steel subjected to a blank holder force. Kailun Zheng et al. [6] conducted a series of deep drawing experiments to investigate the influence of tool texture, draw ratio, and the blank-holding force. They also proposed a one-dimensional and two-dimensional analytical buckling model considering the micro-textures of the blank holders for the aluminum alloy sheets and then the results were compared with the experiment data. Park et al. [7] proposed a numerical method using a curvature variation algorithm to predict the surface deflection of very small size about 30µm to 300µm and also quantitatively visualized it. They concluded that the good agreement between the experiment and numerical simulation was obtained. This research is committed to develop a new OCI model for predicting the presence of OC and also to prevent its effects in the automobile components and in household appliances.

In this paper, to quantitatively predict the OC effect on the product during stamping process, the dent resistance test of the panel is conducted and the OC damage value is estimated lately. In order to predict the OC effectively, numerous finite element (FE) simulations are modeled and based on the results; a new OCI model is developed. To verify the accuracy of the model, FE simulations and the experiments are conducted on the double-curved panel. Later, the developed OCI model effectiveness is discussed by comparing the FE simulation and experimental results.

2. Proposed Oil Canning Index Model

The oil canning effect is a surface deflection that occurs in the flat part of the panel. It can be quantitatively analyzed by deriving the load-stroke curve through an indentation test. The principal residual stress and the geometric parameters of the panel can be defined as shown in Fig.1. At this time, the panel stiffness and the panel buckling load can be defined for the slope and the inflection point, where the slope starts to change as illustrated in Fig.2. In the load-stroke curve obtained by performing the indentation test, the buckling load and the oil canning damage value (OCDV) are approximated by the third order polynomial model fitting. The OCDV is affected by the geometry and the residual stress of the panel.

Based on the aforementioned discussions, the following mathematical models are proposed for the prediction of oil canning occurrence. For oil canning damage value estimation, the empirical model can be expressed as follows:

\[ f(t^*, \sigma^*) = A_{00} + A_{10}t^* + A_{01}\sigma^* + A_{20}(t^*)^2 + A_{11}t^*\sigma^* + A_{02}(\sigma^*)^2 \]  

(1)

where \(A_{00}, A_{01}\) are the material constants and \(t^*, \sigma^*\) represents the geometric parameters and the residual stresses, respectively. The parameters of the oil canning damage value model are derived by indentation test simulation according to the geometry and principal residual stress conditions and are derived from the results using the reverse engineering techniques. The parameters used in the analysis are as follows: longitudinal curvature radius \((r_1)\), lateral curvature radius \((r_2)\),
longitudinal residual stress ($s_1$), lateral residual stress ($s_2$), thickness ($t$), longitudinal length ($b_1$), and lateral length ($b_2$).

The parameters of the OCDV model are obtained by only integrating the geometric parameters and residual stress to improve the usability of the model. In addition, if the residual stress is not taken into consideration, the possibility of the oil canning effect of the stamped panel can be predicted only by the geometric shape. The oil canning effect is extremely large when the panel thickness is very small and the panel width is too large. In addition, the risk of oil canning effect is increased when the sheet metal has large curvature and the low panel stiffness and vice versa. Based on these geometric factors, we propose a mathematical model for the risk of oil canning effect as follows:

$$OC = \frac{\text{Estimated Stress}}{\text{Critical Buckling Stress}}$$

$$OC = \frac{12\ln\left(\frac{R\theta}{W}\right) \left(1 - \nu^2\right) \left(\frac{w}{t}\right)^2}{k\pi^2E}$$ (2)

![Figure 1. Geometric Parameters.](image1)

![Figure 2. Load-stroke curve from indentation test.](image2)

3. Experimental Procedure

The flat specimens, for EGI and GI steel, were fabricated and tested at room temperature at a tensile speed of 2 mm/min using a tensile test machine and the true stress strain curves are obtained for two different materials as depicted in Fig. 3. In addition, we also conducted an anisotropy test in order to identify the material behavior with respect to the directionality. During the tensile test, the strain variation occurs in the length, width and thickness of the specimen, and these strain values have different magnitude. So we measured the specimens thickness and width after the 10% to 20% of tensile elongation. After the measurements, the planar anisotropy, where the $R$ values vary at different directions to the rolling direction, and the normal anisotropy values are estimated. Here the $R$ value is calculated as the ratio of strain at the width direction to the strain at the thickness direction.

A measure of planar anisotropy is $\Delta R$

$$\Delta R = \frac{R_0 - 2R_{45} + R_{90}}{2}$$ (3)
A measure of normal anisotropy is a mean $R$ denoted as $\bar{R}$

$$\bar{R} = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

In Eqs. 3 and 4, $R_0$, $R_{45}$ and $R_{90}$ represents the anisotropy values at directions, $0^\circ$, $45^\circ$ and $90^\circ$, respectively. The measured anisotropic values for the EGI steel and GI steel materials are summarized in Table 1.

| Material  | $R_0$   | $R_{45}$ | $R_{90}$ |
|-----------|---------|----------|----------|
| EGI Steel | 3.0414  | 1.8586   | 3.3977   |
| GI Steel  | 2.3767  | 2.7833   | 3.4373   |

For the stamping process as shown in Fig.4, we considered an initial plate of size 280 mm $\times$ 375 mm, which is drawn to form a stamped product. For the drawing process, 0.6 mm and 0.8 mm thickness EGI steel and 0.7 mm thickness GI steel sheets are employed. During the
experiment, a blank holding force of 250 N is applied and the friction coefficient is used as 0.1. Also, the punch velocity and the embossing depth are taken as 13 m s\(^{-1}\) and 4 mm, respectively. The beads are studied in three levels as follows: (a) Bead length: 0 mm. (b) Bead length: 7.854 mm and (c) Bead length: 9.3858 mm. The levels are chosen based on how the beads in draw dies vary greatly and their influence on whether or not a draw die is safe or failing during the stamping process [8]. After the stamping process, the indentation test, Fig. 5, is carried out using the stamped product, and the load-stroke curves are estimated from the three points in order to examine how the thickness variation and the residual stress distribution causes the oil canning on the product as depicted in Figs. 6 and 7. From these figures, we can visually see how the oil canning happens on the formed sheet metal due the uneven thickness distribution.

![Figure 6. Load-stroke curve for 0.7mm GI steel material.](image6)

![Figure 7. Load-stroke curve for 0.6mm EGI steel material.](image7)

![Figure 8. Stamping process FE model.](image8)

![Figure 9. Indentation test FE model.](image9)

Subsequently, the stamping process FE model is built into LS-Dyna commercial tool as shown in Fig.8. In order to address the oil canning problem, we utilized a computer simulation for empirical model construction. The FE model is developed precisely based on the specimens that are used in the experiment and their corresponding processing conditions. The meshed FE model is depicted in Fig.9 in order to understand the process. The processing tools such as punch, holder and die are modeled as a rigid part to resemble the experimental conditions. Afterwards, the spring back effect is examined with the help of residual stress distribution on
the stamped part. Then, the stamped product is utilized to conduct the numerical indentation test using the same experimental conditions.

4. Results and Discussion
During the stamping process, the anisotropy induced by work hardening should be considered. Because the hardening occurs in one direction stress space, it may lead to the softening in other directions stress space. If we assume that the material is isotropic, then the compressive yield stress will always increase after the material is tensioned in the stamping process. This will lead to overestimation of the specimen’s compressive yield stress. This could result in the magnified sheet metals dent resistance and is not desired in the practical situations. So the isotropic hardening model is inadequate and it is important to introduce the anisotropic hardening model into the stamping process in order to predict the accurate material behavior effectively.

Based on this knowledge, the anisotropic experiments were conducted for the selected materials at room temperature as we discussed in section 3. Likewise, in order to effectively model the anisotropic behavior into the numerical simulation, we have added Hill’s 48 anisotropic-hardening model in order to include both yield function and kinematic hardening behavior in the LS-Dyna commercial code. Also the kinematic hardening model is included in LS-Dyna commercial code for the spring back estimation in the formed products.

![Figure 10. 0.7t GI steel sheet stamped Product (vertical bead force: low).](image)

![Figure 11. 0.7t GI steel sheet spring back effect (residual stress).](image)

![Figure 12. 0.8t EGI steel stamped Product (vertical bead force: low).](image)

![Figure 13. 0.8t EGI steel spring back effect (residual stress).](image)

Using the same experimental conditions, the numerical model is solved for the GI steel material with 0.7 mm thickness and the formed final product is shown in Fig. 10; on the other
hand, the spring back is examined for the same material after the forming process as shown in Fig. 11. Similarly, the aforementioned procedure is followed for the EGI steel material with 0.8 mm sheet thickness. From the stress distribution results as shown in Fig. 12, we can note that the stress concentrations are less in the EGI steel material product than the GI steel counterpart. It is mainly because the EGI steel thickness is quite higher than that of GI steel material. But from the spring back results, Fig. 13, we can see that the edge has considerably high wrinkling on the faces, which might be due to the sheet stiffening property. After the successful evaluation of numerical simulations, we have modeled numerous FE simulations for different thickness and the curvature radius. The acquired numerical results are utilized to construct a new OCI model as follows:

\[
t^* = \frac{\text{thickness}}{\text{radius}} \times \frac{\text{length}}{\text{width}}
\]

where the sheet dimensions, such as, thickness, width, length and curvature, are considered a one variable, \(t^*\). Similarly,

\[
\sigma^* = \sigma_1 + \sigma_2 + \sigma_1\sigma_2
\]

where the maximum, \(\sigma_1\) and the minimum, \(\sigma_2\), principal stress are treated as a one variable, \(\sigma^*\). From the FE simulation, many data points are collected to fit a new OCI model, Eq. 1, for predicting the material behavior effectively. The proposed model for the oil canning prediction is:

\[
f(t^*, \sigma^*) = 19.6 - 73.4t^* + 2.19\sigma^* + 188(t^*)^2 - 2.94t^*\sigma^* + 0.929(\sigma^*)^2.
\]

**Figure 14.** Tendency between radius and buckling load (0.7t GI steel).

**Figure 15.** Tendency between radius and buckling load (0.8t EGI steel).

In order to verify the developed model, the correlation between the buckling load and the curvature has been established using the experimental results, named as regression in the legend, as illustrated in Figs. 14 and 15. In order to validate the developed model, we always have to conduct some experiments or numerical simulation to prove the accuracy of the empirical model. So the experiments and simulations are randomly modeled for the model validation and from Figs. 14 and 15, we can accurately visualize that the observed experiment and simulation results fall very close to the fitted regression line.

As shown in Figs. 14 and 15, in case of low bending load and low radius some deviations, from the fitting curve, are observed. The main reason for this deviation is given by the fact that the samples in the low radius region are not enough to allow a reliable prediction. However, in order to reduce the the experiential efforts, sample size should be reasonably optimized. Therefore,
the deviation of the developed model is acceptable considering the sample size which has been utilized. This is also confirmed by the good agreement between experimental data and fitting curve, where more experimental samples are available from the material testing, as shown in Fig. 14. From overall results, we conclude that the developed OCI model can be used for the future predictions with reasonable number of samples considering the intrinsic limitations given by the choice of optimizing the size of the sample in the material testing.

5. Conclusions
In this research, the OCI phenomenon, which plays crucial role in the appearance and the product quality of the automotive exterior panels was investigated. This study examined how the thickness, the curvature, and the material properties alter the oil canning phenomenon. Experiment results indicate that the OC phenomenon occurred when the plate thickness is reduced after the stamping process. To overcome these problems, numerous finite element data sets that were obtained through the numerical simulation have been employed for the construction of an empirical model to estimate the material constants. This developed empirical method is based on the curve obtained by the least square fitting, which minimizes the error between the actual and predicted data. In order to verify the effectiveness of the proposed model, a real time experiment was performed. The results obtained from the proposed OCI model had a good agreement with the experimental results. Overall, the proposed model is favorable for predicting the oil canning phenomenon in the flat metal panels after the forming process. We believe that with the help of a new OCI model presented in this research, good quality products, without the OC problem, can be produced in the metal forming industry.

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