Prediction of Forming Strain for Optimum Dent Resistance

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***Abstract*—Dent resistance is one of the main requirements of the automotive exterior panel. Researchers use different methods like experimentation, analytical predictions and numerical methods to evaluate the sheet's dent performance. This work focused primarily on assessing the dent performance of high strength Interstitial free steel of 0.7mm thickness. Laboratory specimens are tested at the different pre-strain levels by forming the sheet to different depths. A semi-empirical relation is developed in the present work to estimate the optimum strain levels to be achieved in the forming for better dent performance. This relation can be used primarily for the performance comparison of the different steel grades as numerical analysis and experimentation needs more resources and time**

***Index Terms*—dent resistance, sheet metal forming, forming strain**

I. Introduction

The majority of automotive outer panels are manufactured from metal sheets (predominantly steels) using stamping presses. One of the performance requirements of these panels is dent resistance. Few denting sources are hail storm, the impact of flying stone chips from roads, the mechanical impact of luggage, doors of another car in the parking [1]. Though various measures are available to mitigate the dent, avoiding it is not possible (SAE-J2575). "Dent" could be defined as an unintended permanent plastic deformation localized at the loading point. As per the standard "SAE J2575-2004", the force required for 0.1mm permanent deformation is considered the static dent resistance. (typical indenter velocities of maximum - 2 mm per second). As per [2], areas such as welds defined in [3] are not considered for the dent. Dents caused by significant accidents such as rollovers [4] are not covered by the J2575 standard.

Increasing the yield strength, thickness, and curvature could improve dent resistance [5]. Stiffness also helps in enhancing the static dent resistance [6, 7]. An increase (independently or combinedly) in blank holding force and stiffening boundaries will improve the static dent resistance [8]. Another approach for improving dent resistance is to use higher strength or bake hardenable steel. Its yield strength increases during paint baking (150-2000C) due to accelerated strain ageing [9]. It has a limited shelf life due to natural ageing.

It is a general practice to evaluate dent performance during the design stage through experimental evaluation [10]. Several researchers used FE analysis with different material models and yield criterion [11, 12, 13] to predict dent resistance. An accurate prediction helps in avoiding experimentation on the final product. There is significant work on analytical models and empirical models to predict sheet metal's dent resistance [14]. Analytical models have limitations due to inherent assumptions made in shell theory, such as constant radius of curvature.

There are two important empirical models in the literature. First, Dicello [15] model is based on yield strength, thickness and stiffness, and it is defined as the energy absorbed before the dent formation of 0.1mm. As per the energy principle, dent resistance is proportional to the second power of yield strength and the fourth power of the thickness. Second, Yutori [16] developed an empirical relation in terms of yield strength and thickness only. Veldhuizen [17] modified the model presented by Yutori by normalizing the variables. Ref. [18] customized the Yutori model specifically for the bake hardened and interstitial free steels. Empirical relations have a limitation of accuracy, and the constants used in the model need to be calculated for the steel grade. These relations are helpful for quick comparison of different steel grades dent resistance.

Both analytical and empirical models predict the dent resistance for the given material and geometric parameters. These models help a quick comparison of two steel grades, provided their material properties (hardening behaviour) are available. Such calculated values are not useful to assess the dent resistance of final components such as door panel. At the design stage, engineers perform numerical analysis to determine the dent resistance of the part [19]. A relation could not be found in the literature to find the forming strain limit for optimum dent performance.

The present study primarily focused on the dent evaluation of interstitial free high strength (IFHS) steel of 0.7mmm thickness. The shelf life of the interstitial free sheets is better than the bake hardenable steels. Sheets are drawn to different draw depths to study the effect of pre-strain on dent resistance. A relation is developed

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between the forming strain and material parameters to calculate the forming strain for optimum dent performance.

II. Experimental Work

High strength interstitial free steel (IFHS) of 0.7mm thickness is chosen for the study. It primarily consists of the ferrite phase (Fig. 1). The yield strength of the material is 210 MPa, and tensile strength is 360MPa. True stress - true strain curve is shown in Fig. 2. Swift law is used to relate the true stress and true plastic strain, as represented in equation **(1)**. Its strain hardening exponent is 0.224.

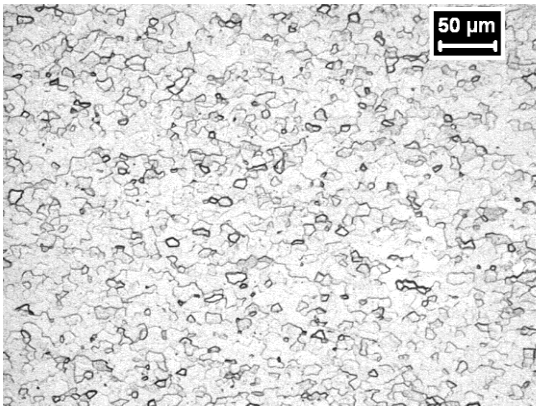

Figure 1. Microstructure image of the high strength interstitial free steel.

$$\sigma = 639(0.00005 + \bar{\epsilon})^{0.224} \tag{1}$$

Schedule-A type specimens are chosen as per the SAE-J2575, and a customized die system is fabricated for forming the panel. The Final formed specimen is shown in Fig. 4. Stringer beads are provided to avoid material flow so that deformation at the centre of the component is pure stretching without any drawing.

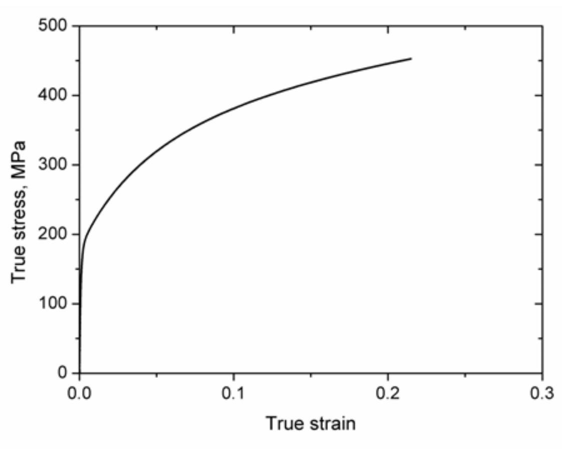

Figure 2. True stress-strain plot of the IFHS steel of 0.7mm thickness.

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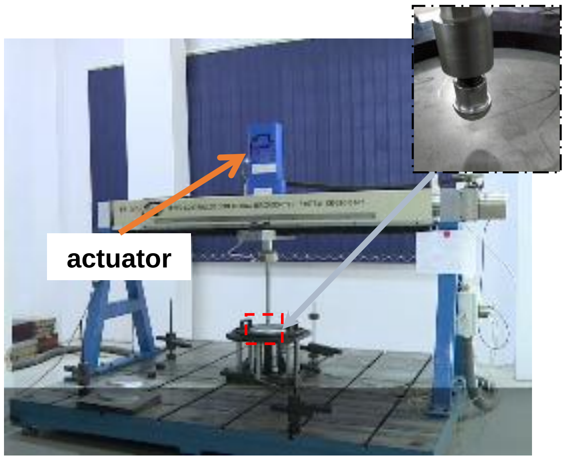

Figure 3. Experimental set-up for dent measurement

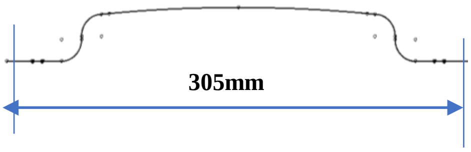

Figure 4. formed specimen for dent testing.

Sheets are formed to the specimen with five formed depths, and they are 12mm, 16mm, 20mm, 24mm and 28mm. Such formed specimens are used for dent testing. The Dent test measurement system at Tata Steel is shown in Fig. 3. Dent testing is done as per the standard mentioned in SAE-J2575 using the schedule-A type component. The indenter is placed perpendicular to the sheet at the selected area (specimen centre), followed by an incremental load. Specimens are tested for the dent resistance at 50, 100, 150 and 200N load cycles. Three specimens are tested for each formed depth. Indenter displacement and load on it are measured.

The load versus displacement curve in the dent testing process is subdivided into three regions: Initial, secondary and final stiffness regions (Fig. 5). Initially, the applied load is resisted by bending and compressive membrane stresses. As the applied load increases, local curvature at dent location changes from a convex to a concave shape. The applied load is resisted by a combination of bending and tensile membrane stresses. Once, local curvature transforms to a concave shape in the final stage; panel stiffness increases again as more of the load is carried by membrane tension.

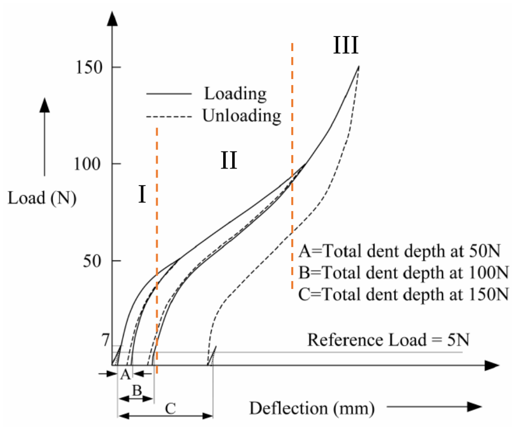

Figure 5. Graphical representation of dent load-defection curve (SAE-J2575)

III. Results and Discussion

Measured indentor load and displacement are plotted as shown in Figs. 6, 7, 8, 9 and 10. Load application is incremental, and they are 50N, 100N, 150N and 200N. Two parameters are of importance to study in these plots, and they are peak deflection and residual dent. Deflection at the peak load of 50N is defined as peak deflection for the 50N load cycle. Subsequently, the specimen is unloaded to measure the residual dent (permanent deformation). The process was repeated for the remaining three load cycles 100,150 and 200N. Such measured residual dent values are plotted in Fig. 6 & 7 and tabulated in Table I.

A. *Effect of Pre-strain on Stiffness*

As the forming depth increases, plastic strain on the sheet increases. With the increase in the forming depth and plastic strain, there is an increase in peak deflection values and a decrease in residual dent values. Fig. 10 compares the dent performance of the specimens at five pre-strains 0.020, 0.035, 0.066, 0.108, 0.132 corresponding to forming depths of 12mm, 16mm, 20mm, 24mm and 28mm forming depths. Strains are measured with the help of a strain grid analyzer. It could be observed that with the increase in the pre-strain, peak deflection is increasing while residual dent values are decreasing (Figs. 6, 7, 8 and Table I).

Schedule-A specimen is a hemispherical specimen (Fig. 4). From the studies of Mahmood et al. 1981, it could be observed that the stiffness of the shallow spherical shells represents the total deflection of panels, and it is proportional to the second power of the thickness as shown in equation (**2**).

$$S = \frac{9.237Et^2h\pi^2}{kL_1L_2\sqrt{1-\nu^2}} \quad (2)$$

Where 'h' is panel crown height, k is the constant, L1 and L2 are the unsupported panel lengths, E is the young's modulus, S is the stiff of the panel, and t is the thickness.

This relation is further improvised by Asnafi et al., 1995 in equation (**3**) by introducing curvature.

$$P = C2\pi E\frac{t^3(\delta/t)^m}{\sqrt{R_1R_2}} \quad (3)$$

For low carbon steels C=0.4 and m=0.8.

From the two relations shown in equations (**2**) & (**3**), it could be concluded that stiffness depends on geometric parameters and the elastic modulus. As discussed earlier, the sheet is under stretching during the forming process to make a specimen. Stringer beads hold the material flow. Hence, as the forming depth is increasing, sheet thickness decreases due to stretching. Reduction in panel thickness results in stiffness reduction (equations (**2**) & (**3**), stiffness is directly proportional to the second power of thickness). Hence, peak deflection is increasing with the formed depth for IFHS steel.

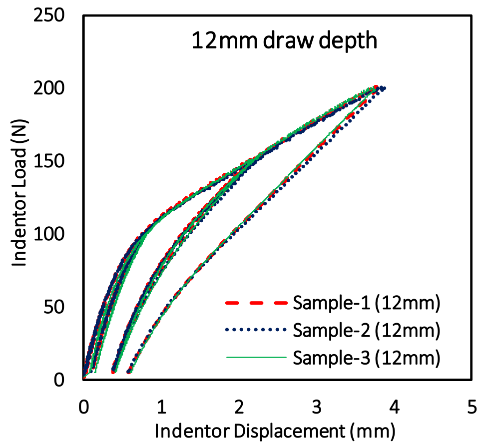

Figure 6. Dent resistance behaviour of IFHS 0.7mm steel for 12mm drawn samples

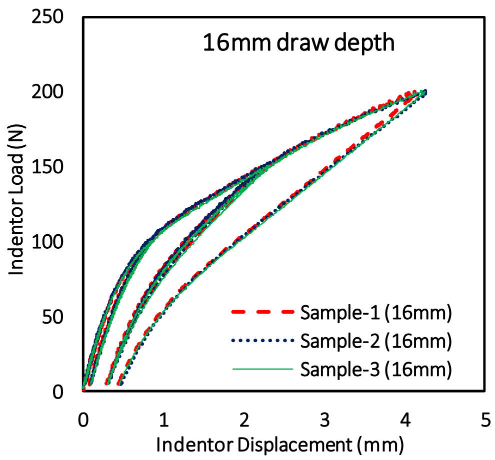

Figure 7. Dent resistance behaviour of IFHS 0.7mm steel for 12mm drawn samples

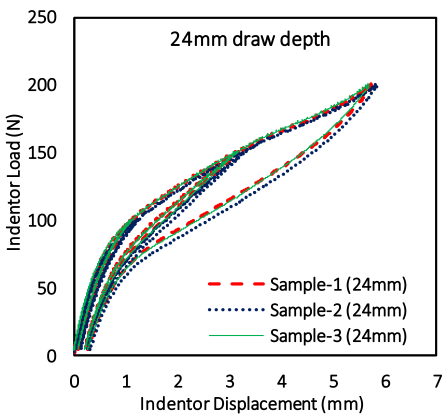

Figure 8. Dent resistance behaviour of IFHS 0.7mm steel for 24mm drawn samples

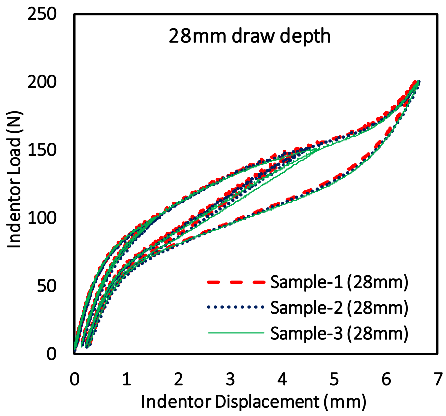

Figure 9. Dent resistance behaviour of IFHS 0.7mm steel for 28mm drawn samples

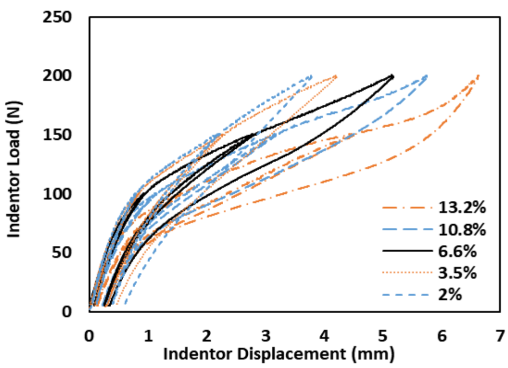

Figure 10. Dent load-deflection behaviour of IFHS 0.7mm steel at five plastic strain values corresponding to the five forming depths considered in the study

B. *Effect of Pre-strain on the Residual Dent*

In the present study, residual dent values decrease with pre-strain (Fig. 11 & 12). Residual dent value for 50N load cycle is decreasing from 0.03mm to 0.017 mm while pre-strain increased from 2% to 10.8%. Further increase in pre-strain to 13.2% increased the residual dent to 0.03mm. This decreasing and increasing trend is observed for the 100N and 150N load cycles as well. For these three load cycles, namely 50N, 100N and 150N, a pre-strain value of 10.8% is the optimum pre-strain value for the dent performance due to lower residual dents. For the 200N load cycle, residual dent value decreases with pre-strain values but saturating at 10.8% strain. There is less than a 3% change in residual dent value while pre-strain increasing from 10.8% to 13.2%.

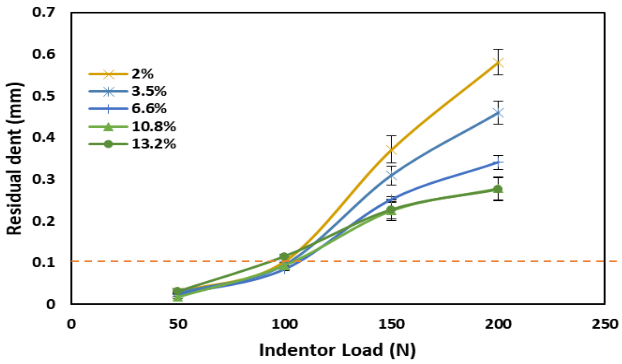

Figure 11. Residual dent values of the IFHS steel of 0.7mm thickness at different indentor loads

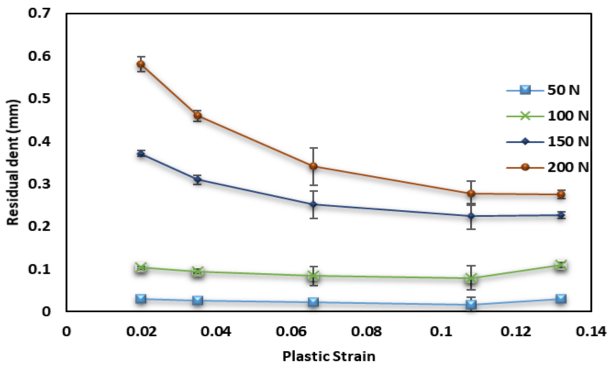

Figure 12. Residual dent values of the IFHS steel of 0.7mm thickness at different plastic strain values

TABLE I. RESIDUAL DENT VALUES OF THE IFHS STEEL OF 0.7MM THICKNESS

Specimen draw depth	Pre-strain	Indentor Load			
		50 N	100 N	150 N	200 N
12mm	0.020	0.030	0.103	0.371	0.581
16mm	0.035	0.027	0.095	0.310	0.460
20mm	0.066	0.023	0.084	0.252	0.341
24mm	0.108	0.017	0.079	0.224	0.278
28mm	0.132	0.0307	0.115	0.227	0.277

C. *3.3. Optimum Forming Strain for Better Dent Resistance at 0.1mm Residual Dent*

As per the SAE-J2575 standard, force required to cause of residual dent of 0.1mm is considered as the dent resistance. IFHS steel’s uniaxial tensile behaviour is shown in Fig. 2. Material work hardening rate decreases with the plastic strain. The rate of flow strength change is varying with plastic-strain. From Yutori et al., 1980 study (equation **(4)**, dent resistance is proportional to the yield strength and 'm' power of the thickness.

$$P_d = Ct^m\sigma_y \tag{4}$$

Where 'C' is a constant, 't' is panel thickness, 'σ_y' is the Actual yield strength, 'Pd' is the minimum load (in N) required to initiate a dent, m is experimentally determined to lie between 2.3 ~ 2.4 for the steel panels tested by Yutori et al., 1980. In the present study, the residual dent is limited to 0.1mm as per SAE J2575 standard. For the IFHS steel, C and m values are fine-tuned by calculating the dent resistance at 0.1mm residual dent, and values are 1.29 and 3.36.

Assuming 1, 2, 3 are the directions in length, width and thickness direction, we have (as per vonMises yield criterion and volume consistency).

$$\epsilon_{11} + \epsilon_{22} + \epsilon_{33} = 0 \tag{5}$$

Where $\epsilon_{11}, \epsilon_{22}, \epsilon_{33}$ are the plastic strains in 1, 2 and 3 directions.

$$\epsilon_{22} = \epsilon_{11} \text{ (equi-biaxial tension condition)} \tag{6}$$

$$\epsilon_{11} = -\frac{\epsilon_{33}}{2} = -\frac{1}{2}\ln\left(\frac{t}{t_0}\right) \tag{7}$$

$$\frac{d\epsilon_{11}}{dt} = -\frac{1}{2t} \tag{8}$$

For equibiaxial loading under plain stress condition, equivalent plastic strain as per the vonMises yield criterion and isotropic hardening

$$\bar{\epsilon} = 2\epsilon_{11}\ (since\ \epsilon_{11} = \epsilon_{22}) \tag{9}$$

C is a constant in equation **(4)** and replacing actual yield strength σ_y with flow strength relation (swift law) in,

$$P = C\sigma_y t^m \tag{10}$$

$$P = CK(\epsilon_0 + \bar{\epsilon})^n t^m \tag{11}$$

$$\frac{dP}{dt} = CK(\epsilon_0 + \bar{\epsilon})^n t^{m-1}\{m - \frac{n}{(\epsilon_0 + \bar{\epsilon})}\} \tag{12}$$

$dp/dt = 0$, for the optimum value of P with respect to 't'. It gives

$$\bar{\epsilon} = \frac{n}{m} - \epsilon_0 \tag{13}$$

Equation **(13)** provides optimum equivalent plastic strain value for better dent resistance. 'm' is evaluated through regression fitting the equation **(4)**, and it is 3.36. by incorporating the n and ϵ_0 into equation **(13)**, it gives the value of 0.067. It could be concluded that the dent resistance (for 0.1mm residual dent) of the material increases till the optimum strain of 6.7% (corresponding to 20mm forming depth), and further straining the material will reduce the dent resistance. Such optimum strain, once evaluated for material, will be helpful to engineers to fix forming limit strain in terms of dent performance. Whereas, experimental observation in section-3.2 shows the optimum strain value as 10.8% because it is irrespective of residual dent limit. If the residual dent is not restricted to 0.1mm (not following the standard SAE J2575), then the optimum strain value is 10.8%, and if the residual dent value limited to 0.1mm, then the optimum strain is 6.7% (following the standard SAE J2575).

IV. Conclusions

Dent resistance of interstitial free steel of 0.7mm thickness is evaluated as per the SAE-J2575 standard. The sheet is formed to five different pre-strain, and dent resistance is assessed for the same with three specimens at each forming depth. It was observed that peak deflection is increasing with the forming depth. It is due to the decrease in thickness of the panel at the indenting location, and stiffness primarily depends on geometry parameters such as thickness and curvature. It was also observed that dent resistance is increasing with the pre-strain. After reaching an optimum strain, dent resistance decreases. A relation is developed for optimum strain by combining the Yutori 1980 model and swift stress-strain relation. Such relation gives a quick solution to support engineers to find out the forming limit strain for the material in terms of dent performance. It avoids full-scale numerical simulations at the design stage, and it is simple to implement in the numerical models

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Corresponding author conducted the research. He was helped by Mr Abhishek Raj during the dent experimentation. Dr Manikandan helped in material characterization. Dr Rahul and Prof N V Reddy supervised the work. They also helped in writing the paper. All authors had approved the final version.

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