Effect of yield strength, pre-strain and curvature on stiffness and static dent resistance of formed Panel

G Manikandan[1*], Rahul K. Verma[2], Abhishek raj[3]

Research and Development, Tata Steel Limited, Jamshedpur 831001, India

***Corresponding author: Email: manikandan.g@tatasteel.com, Tel.: +91-657-2148964**

Abstract

Increased importance on weight reduction is driving automotive industries to reduce thickness of the steel panels without compromising the vehicle safety and performance. High strength steels are looked at as a candidate for automotive applications. To overcome the limitation of less formability in high strength steel, steel makers introduced the bake hardening steel (BH) grades. This study compares the formability of high strength automotive steel grades which are mainly used for body panels with that of bake hardening steel. The influence of material properties, pre-strain (ε_o) and curvature(R) of product on its stiffness and static dent resistance are studied experimentally. It was found that high material strength provides higher dent resistance whereas high panel thickness and smaller curvature resulted in higher stiffness. Higher dent resistance observed in bake hardened steel compared to high strength interstitial free steel is due to the increase in strength by bake hardening process. The use of bake hardened steel in automotive applications instead of high strength interstitial free steel represents a good opportunity for weight reduction, increased stiffness and dent resistance.

Keywords: High strength steel, Bake Hardening, Formability, Dent resistance, Stiffness

1. INTRODUCTION

The practice of using thin sheets and new steel grades in the automotive industries is increasing in the last few years in order to improve safety and fuel efficiency. In the present competitive market, cost reduction with superior performance is the main objective in engineering design. Lightening the structures without decreasing its performance like stiffness, Noise Vibration Harshness (NVH), durability and dent resistance is done by incorporation of high strength steels in design, if affordable[Cole & Sherman , 1995].

In last few decades, steel makers continuously introduced new grades with high strength and good formability to meet the target of stiff and light automotive body. The poor formability of high strength steels is a major concern while considering its candidature for automotive panels [Hisashi Hayashi & Takeo Nakagawa, 1994]**.** Material for outer body panels like fenders, doors, hood and deck lid requires good formability to make the design attractive. As the above components are external parts, chances of getting dented from stone impact and careless opening of an adjacently parked vehicle door is high. Hence they require high static dent resistance (SDR) property, which in turn demands high strength. SDR is a measure of resistance to permanent deformation caused by static forces.

The bake hardening steel (BH) provides a good formability before stamping and enhanced its strength after baking. Hence BH steel is widely used in vehicles, thus leading to a reduction in vehicle weight and improved safety [Alihosseini & Dehghani, 2012]. Bake hardening steels derive their increase in strength from a strain ageing process that takes place on paint baking at 180°C.

Previous studies regarding the dent resistance and stiffness of automotive panels reported some contradictory results. Dicello and George [1974] came to the conclusion that the lower stiffness of the panel, the better the dent resistance. Yutori et al. [1980] found that the higher the stiffness, the higher the dent resistance.

This study focuses on the formability, static dent resistance [SDR] and stiffness property of the Bake hardening steel and understanding the relation between them. The influence of material strength, pre-strain and the effect of varying product curvature on the stiffness and static dent behavior of formed panels is also discussed in detail. SDR tests were conducted for three different pre-strain levels (1%, 2% and 4%) and two different curvatures (2000mm and 4000mm) and the results are discussed. Effect of change in mechanical properties due to bake hardening process was also experimentally studied.

2. EXPERIMENTAL WORK

2.1 Mechanical Properties characterization

Tensile tests were carried out using specimens machined as per ASTM standard specification. Three specimens were tested along three different directions with respect to the rolling direction, with the tensile axis being parallel, diagonal and transverse. The mechanical properties of the material are given in Table 1.

Table 1: Mechanical Properties

Grade	Thick (mm)	Yield strength (MPa)	Tensile strength (MPa)	Total Elongation (50mm G.L.)	Strain hardening exponent (n)	Uniform elongation (%)	R-Bar
HIF	0.70	175	362	40	0.24	25	1.75
BH180	0.70	200	342	38	0.22	22	1.64
BH220	0.70	217	372	36.3	0.209	22.2	1.67

2.2 Forming limit diagram

Press forming is one of the most important processes used in automotive companies. To design a robust press forming process, it is important to have the formability data like forming limit diagram (FLD) and tensile data along different directions. Moreover, most auto companies ask for such data during die design, so that they can use the data in finite element simulations.

The limit or failure strains in sheet-metal forming are represented best by a forming limit curve (FLC) which indicates the onset of localized necking over all possible combinations of strain in the plane of the sheet. To evaluate the strain ratios at necking, rectangular strips of different widths are stretched over a rigid hemispherical punch with the ends of the strip being held down by blank holder.

Test was conducted as per the International standard ISO 12004-2: Determination of forming-limit curves in the laboratory [ISO 12004-2, 2008]. For evaluating the FLD experimentally, hemispherical punch with a diameter of 101.6 mm was used. The speed of the punch was 1.0 mm/sec. Forming limit diagram was generated for High strength IF and bake hardening grade.

2.3 Static Dent Resistance Test

Dent resistance and stiffness are important property requirements for the vehicle body panel and hence these requirements need to be considered in designing or material selection stage itself. Before choosing a particular grade knowledge on its dent resistance is necessary.

Despite these needs, the test methods for determining panel stiffness and dent resistance are not standardized. Automotive industries are using indigenous testing methodology [Blake Hodgins., 2001]. Whichever system is used, the principle of force application and measuring the plastic deformation remains the same. Force and displacement measurements are generally incorporated into a data acquisition system.

SDR test setup shown in figure 1 and experimental procedures used in this study are applicable to Tata Steel.

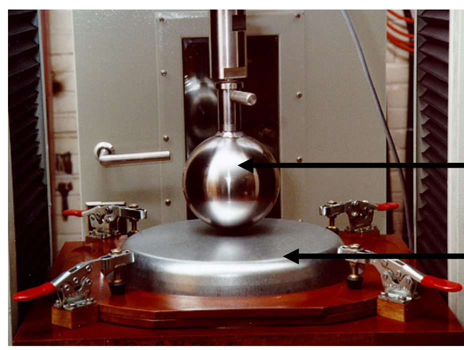

Figure 1: Static Dent Resistance Test Setup

The test product was representative of automotive exterior parts and the product geometry should preferably be pressed on stamps with a specified bottom radius. The thickness after forming the product was measured by ultrasonic thickness measurement technique.

The centre of the product is loaded using a steel sphere to a predetermined force at a speed of 10mm/min and then relieved with the same velocity. After a waiting time, height difference between the unloaded and loaded product is measured by means of three vertical displacement sensors. This process is repeated until a permanent deformation of 0.2 mm is obtained. Maximum dent power of the first load cycle is 10 N. Increase of indentation force per cycle was 10 N as shown in figure 2. Static dent resistance is calculated at the position where the indentation depth is 0.1 mm. The pre-strain levels were 1, 2, 4% and curvatures were 2000 mm and 4000 mm. For each test, three samples were chosen to check repeatability.

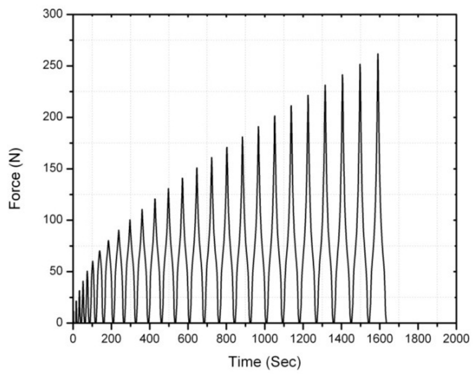

Figure 2: Load Vs Number of cycle

In this study the static dent resistance of BH220 has been determined. Before the initiation of test, the material was stored in freezer to prevent the occurrence of aging process. Then all the specimens have undergone a Bake Hardening treatment at 180°C for 20 minutes before the SDR was determined.

Tensile samples (30 x 230 mm) were cut from the center of the product, which is parallel to the direction of rolling direction for determining the mechanical properties. During the test the dent-shaped indentation is situated in the middle of the pull strip.

2.4 Panel Stiffness

The panel stiffness is defined as the resistance of a panel to elastic deformation. This is the ratio of the exerted force and deflection (i.e. initial slope of the force-deflection curve). Figure 3 is a typical stiffness plot showing three stiffness regions in a curved panel and the point at which the oil-canning response occurs.

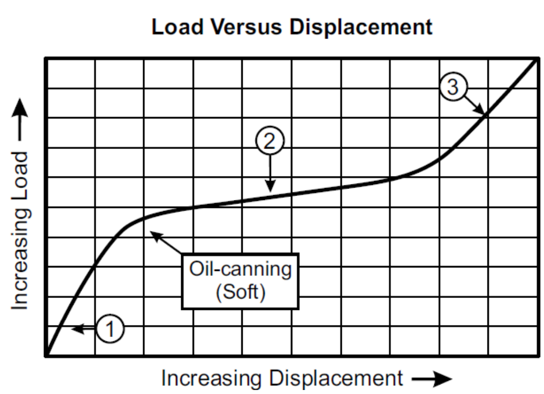

Figure 3: A typical auto body panel stiffness plot [Dylan Thomas, 2001]

3. RESULTS AND DISCUSSION

3.1 Formability of BH steel

Figure 4 shows the formability diagram of different high strength automotive steel grades. It can be seen that the FLC of BH steel is very close to that of high strength interstitial free steel (HIF). Formability of BH 180 is found to be a little more than BH 220 due to the fact that higher strength in BH220 reduces its formability.

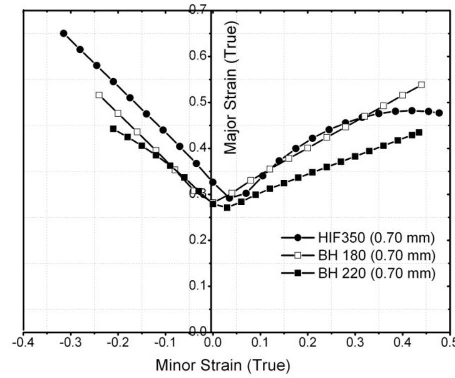

Figure 4: Forming Limit Diagram

3.2 Effect of pre-strain and curvature on dent resistance

Figure 5 shows the force required to produce a permanent deformation of 0.1mm on product with various pre-strain and curvature. It can be observed that an increase in pre-strain level and curvature of the product increases the dent resistance level of the formed component. For a pre-strain level of 2% when the product curvature is increased from 2000mm to 4000mm, the force required to make permanent deformation of 0.1mm increased by 10%. Similarly for a product curvature of 2000mm, an increase in pre-strain level from 2% to 4% resulted in an increase in dent resistance by 22%. From this it can be concluded that the effect of pre-strain on dent resistance is more than the product curvature. Plastic deformation during the forming process results in work-hardening of the material. This work-hardening means that the yield stress is increased for subsequent loading. The increase in yield stress is beneficial to the dent resistance. This is supported by the study of Stefan Holmberg and Per Thilderkvist [2012].

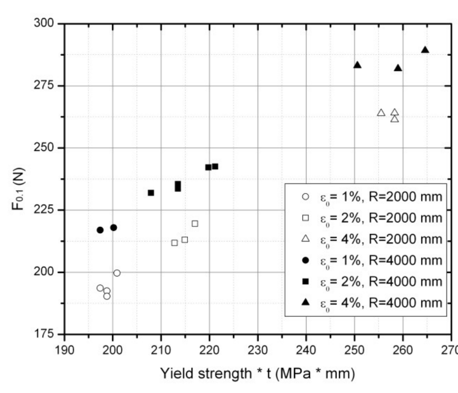

Figure 5: The dent resistance force as a function of the panel yield strength multiplied by the panel thickness.

Table 2: Static Dent Resistance test results

Specimen No	pre-strain (ε_0) [%]	Curvature(R) [mm]	Yield Strength [MPa]	$F_{0.1}$ [N]
1	1%	2000	282	194
2	1%	2000	284	192
3	1%	2000	284	190
4	2%	2000	304	212
5	2%	2000	307	213
6	2%	2000	310	220
7	4%	2000	369	261
8	4%	2000	369	264
9	4%	2000	365	264
10	1%	4000	282	217
11	1%	4000	286	218
12	2%	4000	297	232
13	2%	4000	305	234
14	2%	4000	314	242
15	4%	4000	378	289
16	4%	4000	358	283
27	4%	4000	370	282

3.3 Effect of pre-strain on increase in yield strength

Figure 6 shows a comparison of the yield strength of the pressed component with the initial strength level in the virgin material at corresponding strain levels. Initial yield strength of BH grade was 240MPa. The bake hardening process increased the strength of the components by 54%. Increase in strength also depends on the amount of pre-strain. The yield strength observed for 1%, 2% and 4% pre-strain were 285MPa, 310MPa and 370MPa respectively. The fact that strength increases due to strain hardening during stamping and bake hardening processes is reinforced.

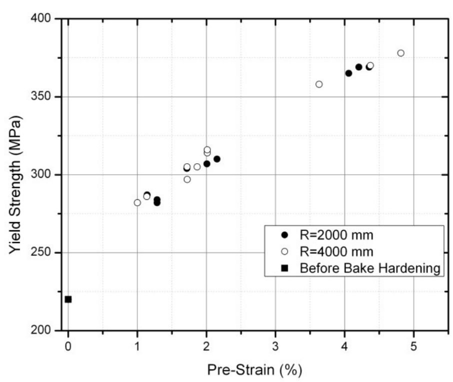

Figure 6: Effect of pre-strain on yield strength after bake hardening

Strength increment after baking process is attributed to diffusion of carbon atoms to the core of the dislocations formed during cold deformation that will result in pinning of dislocations, thereby preventing their movement**.** The effect of curvature on improvement of yield strength is much less pronounced, that for a given pre-strain even an increase of 2000 mm in curvature resulted in no significant improvement in yield strength. The effect of pre-stain and curvature on yield strength is shown in Table 2.

3.4 Effect of pre-strain and curvature on panel stiffness

Figure 7 shows the load and displacement cycle during the entire test for different levels of pre-strain and product curvature including the elastic displacement and oil canning effect. Results show that, panel stiffness is mainly dependent on product curvature and thickness. Panel stiffness increases with reduction of curvature from 4000 mm to 2000 mm. Over all, the panel stiffness increases with decrease in pre-strain from 4% to 1%, the reason being variation in thickness according to pre-strain. Same phenomenon observed in the study of Gunnar Ekstranda, 1998**.** But static dent energy absorption is good for 4% pre-strained component owing to higher strength due to work hardening.

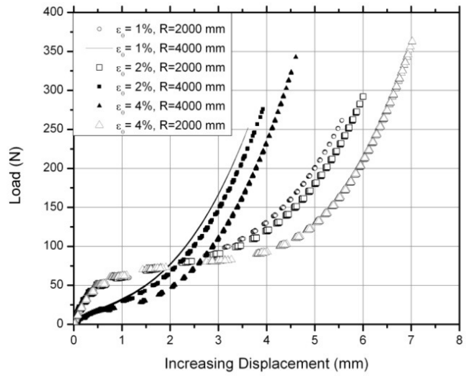

Figure 7: Panel Stiffness

From this study, it is understandable that by changing the product curvature and pre-strain level one can improve either panel dent resistance or stiffness, sacrificing the other in that process. This is supported by the study of Dicello and George [1974]. A possible way of improving dent resistance without affecting stiffness is switching over to higher strength material. On the other hand, stiffness is not strength dependent and hence improving this is possible only by increasing the initial thickness which subsequently increases the final thickness of the panel.

3.5 Effect of bake hardening on material property

Bake hardening process increases the yield strength of the as received steel. Figure 8 shows the plot between true-stress and true-strain for as received and pre-strained, bake hardened steel. While forming, some ductility of the material is utilized and subsequently strength is also improved to certain level by bake hardening treatment. Stretcher strain is observed in bake hardened steel in the load–displacement curve.

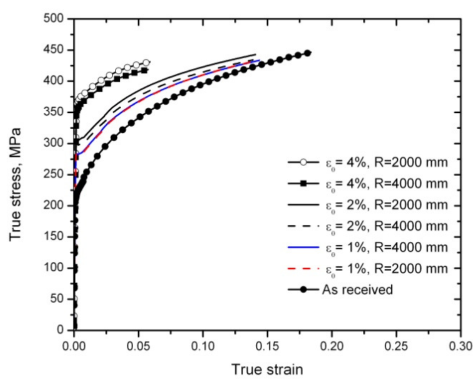

Figure 8: Effect of back hardening on Mechanical properties

From the previous section we could understand that curvature does not play a major role on strength. A same phenomenon is observed in this study as well. Irrespective of the product curvature, subsequent yielding of all the products follows similar work hardening behavior for a given pre-strain and bake hardening process.

3.6 Effect of pre-strain and curvature on each loading cycle.

Load required to make permanent deformation on the product for every loading cycle is shown in the figure 9. It shows that load required for the pre-strain level of 4% is higher than the 1% and 2% due to the higher amount of work hardening in case of 4% pre-strain. Similarly the load required for curvature of 4000mm is higher than for 2000mm. same trend has been observed in the SDR test results as well.

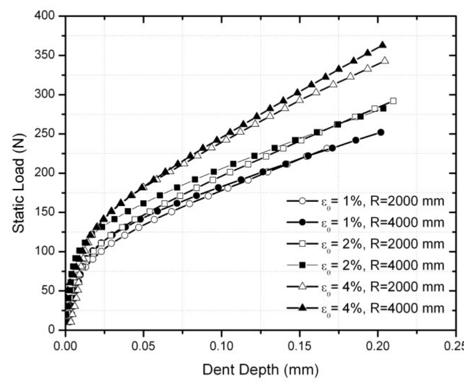

Figure 9: Static load on each cycle

3.7 Validation of SDR regression formulae with experimental results

These test results validate the empirical model developed by TATA Steel for predicting the force required to initiate a dent [12].

$$F_{0.1mm} = b_{grade} * \left(YS_{p0.2} * t\right)^{\alpha} * R^{\beta} \quad \text{---(1)}$$

Where:

$F_{0.1mm}$ = Local Static Dent Resistance [N]

$YS_{p0.2}$ = Actual Yield Point, $YS_{p0.2}$ after forming and baking [MPa]

t = Actual thickness from tensile test [mm]

R = Actual product curvature [mm]

b_{grade} = Grade depending factor

HIF Grades: $b_{IF\text{-}HS} = 0.158$

BH Grades: $b_{BH} = 0.182$

α = 1.18

β = 0.102

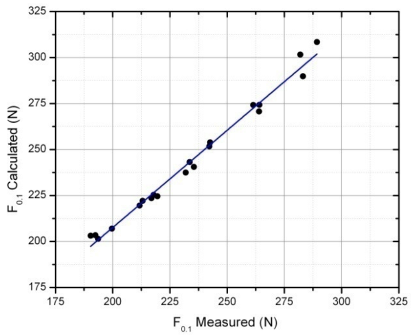

Figure 10: Validation with SDR regression formulae

It can be observed from figure 10 that both the results coincide very well. Experimentally finding static dent resistance force is time consuming and a costly process. It has been proven that empirical SDR regression model could predict the dent resistance as well as experiments. So, for a comparison of two different grades, this theoretical method can be applied to save time and cost.

3.8 Comparison of dent resistance between BH 220 and HIF350

Figure 11 shows the dent resistance force for both BH (0.7mm) and HIF (0.7mm) steel calculated by SDR regression formula. It is clear that the BH steel provides better dent resistance than the high strength IF steel, similar to experimental findings. This model also shows that dent resistance of the component is directly proportional to the pre-strain and product curvature.

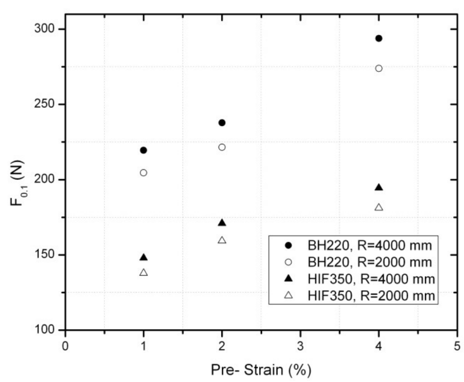

Figure 11: Calculated dent resistance force with SDR regression formulae

4. CONCLUSIONS

The experimental forming limit curve was plotted for BH180/220 (0.7mm) grades and compared with that for high strength interstitial free steel. Static dent resistance test was conducted after baking at 180^{o}C for about 20 minutes in various pre-strain conditions and curvatures. From the experimental test results following conclusions could be arrived at.

- Formability of BH steel grade is close to that of high strength interstitial free steel.
- Dent resistance is directly related to yield strength. Yield strength of the product increases with pre-strain level. Stiffness on the other hand is directly proportional to final product thickness and inversely proportional to product curvature but independent of the strength of the component. High stiffness does not always entail high dent resistance. In short, dent resistance is mostly material strength dependent and stiffness is component design (curvature and final thickness) dependent.
- If a component requires both high dent resistance and high stiffness, an elegant solution is to select a material with higher yield strength.
- Significant increase in strength level of the component was observed after bake hardening of BH220.When compared with HIF 350 steel; it was found that BH steel is a better option for the component that requires high dent resistance.

From this study it is evident that weight saving and better dent resistance can both be achieved by choosing BH grade, which will enable us to save energy and enhance safety with greater dent resistance of vehicle panels.

References

1) Blake Hodgins. (2001), A thesis on Numerical Prediction of the Dent Resistance of Medium Scale Aluminum Structural Panel Assemblies, University of Waterloo.
2) Dylan Thomas. (2001), A thesis on Numerical Prediction of Panel Dent Resistance Incorporating Panel Forming Strains, University of Waterloo.
3) G. S. Cole, A. M. Sherman. (1995), Lightweight Materials for Automotive Applications. Elsevier Publication, Ford Motor Company, Dearborn, Ml 48121-2053.
4) Gunnar Ekstranda, Nader Asnafib. (1998), On testing of the stiffness and the dent resistance of auto body panels. Materials and Design,Vol.19, pp.145-156.
5) Geoff Davies., (2003), Materials for Automobile Bodies, Elsevier publication, P.31.
6) H. Alihosseini, K. Dehghani. (2012), Bake hardening of ultra-fine grained low carbon steel produced by constrained groove pressing. Material Science and engineering A.
7) Hisashi Hayashi, Takeo Nakagawa. (1994), Recent trends in sheet metals and their formability in manufacturing automotive panels. Journal of Materials Processing Technology, Vol. 46, pp.455-487.
8) ISO 12004-2. (2008), Determination of forming-limit curves in the laboratory, First edition.
9) Internal report no: IJTC/AUT-MPP/K/R/6504/02/Z, Empirical Relation for Local Static Dent Resistance, Tata Steel, Ijmuiden, Netherlands.
10) J.A. DiCello, R.A. George. (1974), Design criteria for the dent resistance of auto body panels. SAE 740081.
11) Stefan Holmberg, Per Thilderkvist. (2002), Influence of material properties and stamping conditions on the stiffness and static dent resistance of automotive panels. Materials and Design.
12) Y. Yutori. (1980), Studies on the static dent resistance. Memoires Scientifiques Revue Metallurgie, Vol.77, pp.561– 569.

ACKNOWLEDGEMENTS

The authors acknowledge the experimental support of Product Application Center, Netherlands, Tata Steel Europe. They are also thankful to Tata Steel for the permission to publish the results.