INFLUENCE OF BAKE HARDENING TREATMENT AND STRAIN AGEING TIME ON DENT RESISTANCE OF DIFFERENT AUTOMOTIVE STEEL GRADES.
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Abstract
An investigation of dent resistance was performed with respect to the isolated and superposed influence of time - temperature history on dent resistance of different automotive steel grades (DDQ, HSS and AHSS). The steel sheets were stamped to a semi-industrial shape similar to car door panels. After different time delays between stretching and testing as well as baking procedures dent resistance tests were carried out on tensile samples. Conventional tensile test data as well as stress-strain curves of the various tensile tests were examined and correlated with the obtained dent resistances. Several significant and interesting results were obtained especially concerning the already known strong influence of the flow stress curve shape at low strain values which shows a strong function of time history and baking procedure. Localized strain level of the dent-deformation area was investigated by means of numerical simulations. The influence of the baking procedure of various bake-hardenable steel grades was confirmed, an equivalent strong impact of time history after straining on dent resistance was found correlating with the stress-strain curve shapes at low plastic strain values in the order of magnitude of 0.01% that were obtained by the various baking and strain ageing procedures. The results characterize various automotive steel grades with respect to their applicability for exposed parts of the body-in-white.

Key Words: Dent resistance, bake hardening, time-temperature history, strain, stress-strain curve shape

1 Introduction
Bake hardenable steels have been exploited for several years especially for exposed parts with improved dent resistance of the body-in-white in the automotive industry. The driving force is the well-known general necessity of reduction of the mass of the body-in-white of automotive vehicles due to the commitment to reduce fuel consumption in combination with the aim to improve dent resistance, stiffness and crash safety.

Efforts of various authors [1, 2] focused on the investigation of the influence parameters such as geometric variables of the final part (thickness, panel curvature, span length and edge restraint conditions), nominal material properties (yield strength, bake-hardening value including general strain-hardening of the plane material) and stamping and forming characteristics (final strain level, strain path) in combination with the paint-baking procedure. It has been shown by Sadagopan [2] that dent resistance in addition to the strong influence of initial yield strength, thickness of the used material and baking treatment, is affected by the combined effects of panel curvature, strain and strain path. The conclusions which were pointed out in [2] are as follows:
The dent resistance of highly constrained and curved regions is relatively independent of material properties, whereas shallow regions of panels are significantly dependent on stress, strain path and bake hardening. The dent resistance of bake-hardenable steels is relatively independent of the strain path, whereas for non bake-hardenable steels, the strain path is very important. Bake hardenable steels show a lower dependence of dent resistance on the strain path, i.e., with bake-hardenable steels it might not be necessary to obtain a biaxial stretch to maximize dent resistance. For most exposed applications, the increase in dent resistance is relatively independent of the BH1-value for a wide range of forming conditions.

Okamoto et al. [1] investigated dent resistances of bake-hardened and non bake-hardenable steels at different strain levels as well as at different strain paths with the following results:

Dent resistance is not simply assessed by the yield strength of uniaxial tensile test. The 0.2% offset yield strength by uniaxial tensile test with a sample cut out from stamped panel does not affect the dent resistance of the panel. If 0.02% offset stress for the yield strength instead of 0.2% offset stress is chosen, the dent resistance shows good correlation with the yield strength of the tensile test. The dent resistance improvement by baking is largest when stamping is performed by equibiaxial stretching. The bake-hardening effect of showing a sharp yield point or a steep and straight elastic modulus is the key factor for improving the dent resistance.

The aim of the hereinafter-described experimental and numeric simulation activities is as follows:

- Estimation of the dent resistance of the various steel grades stamped to reality-near panels
- Estimation of an average equivalent strain level of the panel in the area of the dent (plastic deformation of 0.1mm caused by a specific load, commonly defined as the "dent resistance")
- Influence of time history and bake-hardening on Young’s modulus, strain-stress curve and dent resistance.
- Investigation of the stress-strain curve shapes of samples cut out from stamped panels especially at low strain levels
- Correlation the stress-strain curve shape with dent resistance.

The investigations were carried out using both non bake-hardenable steels and bake-hardenable steels, including AHSS grades such as dual-phase and TRIP grades.

2 Experimental procedure
2.1 Materials
Five materials with a thickness of approximately 1.4mm were used in the experiments. The mechanical properties are listed in Table 1. The IF grade DX56D was chosen as a non-bake-hardenable steel, two bake-hardening grades (low carbon continuously annealed and EG, ultra low carbon HDG) and two AHSS (dual-phase and TRIP grade, both HDG).

<table>
<thead>
<tr>
<th>Material</th>
<th>LL</th>
<th>a</th>
<th>YP</th>
<th>TS</th>
<th>UEL</th>
<th>EL</th>
<th>r6</th>
<th>r10</th>
<th>r15</th>
<th>n10</th>
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<td>232</td>
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<tr>
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<tr>
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<td>0.22</td>
<td>0.21</td>
<td>0.21</td>
<td>197.6</td>
</tr>
</tbody>
</table>

LL: Testing direction (Q = transversal, L = parallel to rolling direction)

- Strip thickness

BH0: Bake-hardening index without pre-strain calculated as to SEW904 (BH0 = Rr0.2% / 200)

BH2: Bake-hardening index after 2% pre-strain calculated as to SEW904 (BH2 = Rr0.2% / 200)

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2.2 Stamping procedure and strain measurement
The sheets were stamped to panels on a semi-industrial scale. Fig. 1 shows an as-stamped panel (dimension: overall length 1000mm, width 400mm). The orientation was chosen in such a way that the rolling direction is parallel to the longer side of the part. The parts were formed on a double-acting hydraulic press with a maximum drawing force of 6300 kN and a maximum blankholder force of 2500kN. The deformation status of the part was characterized by means of strain analysis software (ARGUS System, GOM).

Fig. 1 Stamped panel, forming analysis on the 4 dent resistance measurement

As shown in Fig. 1, the strain was been measured on 4 specific points and at the panel wall. Dent resistance measurements were performed on these 4 points (B1, B3, B5 and B7). As at the points B1 and B7 the dent test is geometrically very much affected by the border influence (higher stiffness due to radii), the main emphasis was laid on the analyzing the points B3 and B5. During stamping the blankholder force and lubrication were varied depending on the steel grade in order to reach similar strain levels. The achieved mean strains in rolling and normal to rolling direction (major and minor strain) are shown in Table 2.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Typical strain on the stamped panels at the 4 dent resistance measurement points</th>
</tr>
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<tbody>
<tr>
<td>Grade</td>
<td>B1</td>
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<tr>
<td>DX56D</td>
<td>7%  1%</td>
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<tr>
<td>H220R+Z/E</td>
<td>8%  1%</td>
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<tr>
<td>H220R</td>
<td>9%  1%</td>
</tr>
<tr>
<td>HT650X0</td>
<td>3%  1%</td>
</tr>
<tr>
<td>HT650TD</td>
<td>6%  1%</td>
</tr>
</tbody>
</table>

2.3 Dent resistance measurement device
The dent tests were performed using a 100mm diameter hemispherical indenter. The indenter is positioned normal to the surface of the panel and is vertically moved by means of an electrical cylinder with an AC servo gear drive which is equipped with an incremental position as well as a force transducer as displayed in Fig. 2. The stroke of the electrical cylinder (150mm) is controlled via force transducer. Under the panel an inductive position transducer is installed, which is calibrated prior to each dent resistance measurement.

A load-controlled loading and unloading sequence (with incremental load of 20 or 40N) is conducted until the plastic deformation reaches 0.1mm. Thus the load to cause a permanent 0.1mm deep dent after unloading is defined as dent resistance (commonly used measure of dent resistance for exposed panels).

2.4 General experimental procedure
For each steel grade the following procedure was carried out according to Fig. 3:
1. Characterization of the main properties of the plane material including bake- and work-hardening values
2. Stamping the panels at the press with the following parameter set-up:
   o Drawing depth: 100mm (same geometry for all grades and samples)
   o Lubrication status of plane material and blankholder force were varied to achieve similar strain levels, especially at points B3 and B5
3. Further actions (dent test, tensile samples) were performed after the following ageing and heat treatment:
   o Immediately (without and with heat treatment (HT) of 170°C, 20min)
   o After a natural ageing treatment of 24 hours (without and with HT - 170°C, 20min)
   o After a natural ageing treatment of 1 week (without and with HT - 170°C, 20min)
4. Dent test and tensile tests with samples cut out from the panel after the ageing treatment
5. Investigation and correlation of dent resistance values and mechanical properties that were obtained from the samples cut out from the various panels.
displacement of the reference node for the dent tool was increased up to a value of about 2.5 mm. In the next analysis step the corresponding reaction force at this reference node was gradually released to zero. As a result of plastic deformation a permanent dent formed.

3 Results

3.1 Dent resistance of the investigated materials

The results of the dent resistance measurements for the stamped panels, which were tested immediately after stamping (general experimental procedure see Fig. 3), with and without heat treatment (170°, 20min), are illustrated in Fig. 6.

As expected, the IF grade shows no significant influence due to the heat treatment, reaching a dent resistance value (at 0.1mm plastic deformation) of approx. 500 N. The dent resistance value of the other grades with “bake hardening potential” (see Table 1), again as expected, increases significantly after the baking procedure. The ULC-based bake-hardening grade H220BD reaches 800 N, the LC-based grade 700 N. The grade H220BD in baked condition shows a remarkably low plastic deformation up to 400 N. The AHSS grades HT600XD and HT600TD show an outstanding increase due to the baking procedure, especially the TRIP grade, where the dent resistance increases from app. 700 N to over 950 N. Even HT600XD - although having a rather modest BHb-value (Table 1) - enhances the dent resistance after heat treatment by more than 270 N reaching 855 N.

3.2 Influence of time history and bake-hardening on dent resistance

To investigate the influence of strain ageing time superposing bake hardening treatment a procedure according to Fig. 3 was carried out as follows:

Stamping, ageing and heat treatment, dent test and finally tensile tests of samples cut out from the panels in transversal direction and parallel to the main strain direction (as illustrated in Fig. 1).

From the results, illustrated in Fig. 7 and 8, except for the IF grade that of course shows no influence, a significant influence of the time history can be observed. Especially the LC-based H220+B-ZE and the DP grade HT600XD show a high time dependence at room temperature strongly affecting the dent resistance curve.

The heat treatment (bake-hardening procedure: 170°C, 20min) provides an additional increase of the dent resistance curve. One remarkable feature is that the influence of the time between stamping and measuring of the LC-based H220+B-ZE and the HT600XD grade is almost as large the one of baking treatment.

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As heat treatment panels were subjected to a simulated paint bake ageing treatment by putting the formed panels in a temperature-controlled furnace at 170°C for 20 minutes.
Fig. 7 Influence of ageing time and heat treatment on dent resistance: bake hardening grades

H220B+ZE

H220BD

HT600XD

HT600TD

Fig. 8 Influence of ageing time and heat treatment on dent resistance: AHSS-grades

Fig. 9 Influence of ageing time and heat treatment on dent resistance: Comparison of bake hardenable grades

3.3 Numerical Simulation (FE) – estimation of the typical average strain level in the dent – deformation area and dent resistance analysis

Numerical simulations were conducted parallel to experimental work with the following aims:

- Modeling the dent resistance test and comparison with experimental results (tuning)
- Estimation of the typical mean equivalent strain in the area of the resulting deep dent
- Analysis of the influence of the flow curve at small plastic strains, particularly that of the steepness of the flow curve at low strains (extreme case: ideal plastic behavior)

Concerning the first point, Fig. 10 shows the resulting load / permanent displacement curves for three steel grades with the finite element model in comparison to experimental results. It can be observed that the calculated dent resistances (dent with a depth of 0.1 mm) are in satisfactory agreement with the experimentally obtained values. However, there are some discrepancies for smaller loads and smaller dent depths. This may be due to the idealization that is assumed for the analysis model, e.g. a constant deformation field from the forming process and no softening due to cyclic loading.
Fig. 11  Numerical simulation (FE) of dent test:

One particular question refers to the extent and the level of plastic deformation near the position of the denting tool. Fig. 11 displays the variation of the equivalent plastic strain of a 0.11mm dent for the bake hardening steel grade H220BD. The plastic zone size which exceeds the level of 0.001 (0.1%) is in the order of 14mm, whereas the size for the respective strain level of 0.001% is 30 to 40 mm. This means that the plastic deformation occurs in a small area in the denting test. Of course this depends on the geometry of the tested part. The plastic components in a longitudinal and transverse section are shown in the two diagrams besides the contour plot. The two curves (section plots, Fig. 11) are the strains on the two surfaces of the dented panel. As the strain curves for the two strain curves (upper and lower surface, "...a", "...b") are almost identical, it can be concluded that the basic deformation mode is membrane, the bending deformation is of minor importance.

In order to obtain an average strain level of the plastic deformation due to the denting test the following evaluation procedure is applied. After summing up the plastic work (energy) over all the plastically deformed elements of the modeled sheet integrating also the volume of these elements, an assumed level of (mean) yield strength (according to Fig. 13) finally leads to the mean equivalent plastic strain according to Fig. 12. Eventually, if the assumed mean yield strength differs significantly from that in the flow curve corresponding to the obtained strain (Fig. 13), an iterative procedure may be used.

Fig. 12  Formulas used for the estimation of mean strain via energy theorem

The results for the evaluation for the H220BD material (acc. to the procedure of Fig. 12) are shown in Fig. 13. The mean equivalent plastic strain is 0.015% which is an order of magnitude smaller than the normal reference strain of Y.P. at 0.2%. It can be noted that the area of actual plastic deformation arising from the above-mentioned method is somewhat larger than the above-mentioned zone size for an offset value of 0.01% (acc. to Fig. 11) as volume elements with strain smaller than 0.01% are considered as well.

Fig. 13  Estimation of mean equivalent strain in the dent area via energy theorem: result for grade H220BD

3.4 Influence of Young's modulus and flow stress curve

Additionally to the dent resistance measurements on the panels, investigations with tensile samples from plane sheet were conducted to study the impact of the pre-straining level, as well as time influence after pre-straining and the superposed bake ageing treatment on Young's modulus and flow stress curve (investigation of Young's modulus on samples from the panels doesn't lead to reliable results due to the curvature of sample shape). As far as the experimental procedure is concerned, the same procedure as for dent resistance tests was applied according to Fig. 3. The only difference was that the longitudinal stretch was not produced in plane strain modus via panel stamping, but by means of uniaxial tensile test modus.

The results, as illustrated in Fig. 14 - 16, first of all confirm the known effect of decreasing of Young's modulus (hereinafter Y.M.) due to pre-straining.
For the IF grade DX56D (Fig. 14) the already low level of the Y.M. decreases as a function of the rising pre-strain ratio, and shows practically no recovery after natural ageing with different time as well after subsequent baking treatment. In contrast, Y.M. of the bake-hardenable grades H220B+ZE (LC, EG) and H220BD (ULC, HDG) recovers continuously as a function of ageing and completely after baking treatment (Fig. 15). For both grades, natural ageing for a sufficient time leads nearly to the same result as an artificial ageing treatment with 170°C, 20min. A similar behavior can be noted for the AHSS grade HT600TD according to Fig. 16 with slightly less recovery at high strains. The Y.M. of the DP grade HT600XD, however, recovers more slowly with ageing time and generally does not recover fully to the initial Y.M. value, even after baking treatment. The slower ageing kinetics correlates quite well with the slower increase of dent resistance function shown in Fig. 8.

Fig. 14 Influence of pre-straining ratio and ageing time on Y.M.

Fig. 15 Influence of pre-straining ratio and ageing time on Young's modulus

The above Y.M. values gained from plane sheet tensile tests were correlated with the respective dent resistances of Fig. 9 showing a clear, but not very sharp correlation (Fig. 17).

Thus, regarding the influence of Young’s modulus, a first conclusion might be: dent resistance correlates clearly with Y.M. and its recovery after ageing, but the function misses a little bit of “sharpness” and additionally suffers from the well-known uncertainty of Y.M. measurement. To meet the requirement of achieving a clearer function of the influencing parameters on dent resistance, a more detailed investigation of the flow curve was deemed to achieve the desired result.

3.5 Investigation of the flow stress curve shapes of samples cut out from stamped panels especially at low strain levels and correlation with dent resistance

From the panels tested with respect to dent resistance according to Fig. 3, in close proximity of the region where dent tests B3 and B5 (see Fig. 1) had been carried out, tensile test samples were cut out parallel and transversal to the rolling direction and thus to plain strain forming direction. Tests were performed, including acquisition of the stress-strain curves during the tensile tests.

These flow curves, after having been separated from the elastic portion of the flow curve, are displayed and analyzed for the steel grades H220BD and HT600TD in Figs. 18 and 19. Examining these curves in Figs. 18 and 19 the following conclusions may be drawn:

Due to the main strain direction in L-direction (plane strain) in the panels (see Table 2) the flow curves in L-direction are strongly and much more affected by the strain ageing and bake paint ageing treatment than the Q-curves. Both directions show a strong influence of the baking treatment; in addition, the L-curves show a gradually rising influence of the ageing time. Remarkable detail: if analyzing the 0.2% offset yield strength, almost no difference between ageing time “immediately”, “24 hours” and “1 week” is observable because the curves converge.

Y.M. with dent resistance
at this strain level, whereas if 0.01% (or less) offset yield strength is investigated, the yield strength values differ significantly. E.g. for HT600TD, for "immediately" / "24h" / "1 week" the values are 320 / 364 / 464 MPa, which means 56% / 64% / 81% related to the value of 570 MPa of the baked sample (see Fig. 19). A similar behavior is observed for the grades H220BD (Fig. 18), H220B+Z and HT600XD.

Reviewing the chapter “numerical simulations” and the results showing that the mean equivalent strain over the deformed area (for a 0.1mm-deep dent) is in the order of magnitude of 0.01% to 0.02% (according to Figs. 11-13) the dent resistance increasing mechanism is clearly explainable by the above-mentioned curves in Figs. 18 and 19.

This mechanism was also backed up via numerical simulation (Fig. 20), where two different flow curves were applied, the first a real one and the second a “fictive” one with ideal plastic shape at low strain values.

Although Young’s modulus analysis does account for that behavior to some extent, it is not as satisfactory as the above-mentioned method.

Thus, the flow curves analyzed at low strain values (ε_{eq} = 0.005% - 0.02%) show a clear increasing tendency with increasing strain ageing time finally approaching the steep (almost) ideal plastic flow curve behavior after baking treatment (Fig. 18 and 19, L-direction).

The increase of the dent resistance as a function of the ageing time shows a similar behavior and correlates well with the flow curves.

Fig. 18  Flow stress vs plastic strain curve H220BD  
Transversal (Q) and longitudinal (L) samples cut out of the panel  
Influence of ageing time and heat treatment on the flow curve shape at low strain ratios

Fig. 19  Flow stress vs plastic strain curve HT600TD  
Transversal (Q) and longitudinal (L) samples cut out of the panel  
Influence of ageing time and heat treatment on the flow curve shape at low strain ratios

Fig. 20  Numerical simulation (FE) of dent resistance:  
Influence of steep flow curve at low strain (real vs ideal plastic curve)

To investigate whether the measured dent resistances according to procedure in Fig. 3 correspond with the various offset yield strengths (Y.P.) (R_{op}, [x = 0.1%, ... , 0.01%]) all data from the 5 grades for all ageing treatments were correlated for transversal and longitudinal samples with the following results:

- Dent resistance vs 0.2% offset yield strength does not correlate as in satisfactory manner.
- Consequently, the values, which are calculated with 0.2% offset Y.P., don’t do so either (BH-values).
- The lower the values of the offset yield strength (0.2%, 0.05% ... => 0.01% or 0.005%) applied, the better dent resistance and offset Y.P. will correlate (acc. to Fig. 21 and Table 3).

Fig. 21  Correlation of Y.P. at 0.2% and 0.01% with dent resistance: All grades – without and with ageing and heat treatment (longitudinal and transversal samples cut out from the panels)

Table 3  Correlation coefficient as a function of the offset yield strength for the function dent resistance vs offset yield strength (Y.P.) (R_{op}, [x = 0.1%, ... , 0.01%])

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<tr>
<th>Yield strength</th>
<th>Transversal direction</th>
<th>Longitudinal direction</th>
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<td>R_{0.01}</td>
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4 Conclusions
- Investigations with respect to dent resistance of near-to-reality stamped panels were conducted on five steel grades as a function of strain ageing time and paint bake ageing.
These investigations confirmed the well-known strong influence of the baking treatment on dent resistance also for AHSS steel grades, but showed a strong increase of dent resistance even for storage at room temperature as well.

- Dent resistance cannot be simply assessed by BH values or 0.2% offset yield strength.
- Numerical simulations (FE) of dent resistance test were carried out; the results are in satisfactory agreement with those gained from the experiments showing that the mean equivalent plastic strain of the deformed area of the dent is in the order of magnitude of 0.01%.
- Young’s modulus correlates roughly with the dent resistance, however more accurate correlations can be obtained by assessing dent resistance by means of the offset yield strength at low values in the range between 0.01% and 0.005%.
- Stress-strain curves (in the range of 0.01% offset yield strength values) resulting from tensile samples cut out from the panels correlate clearly with the measured dent resistances for all investigated steel grades.
- For the assessment of the suitability of bake-hardenable steel grades for application as exposed parts, BH values and the 0.2% offset yield strength give only rough indications, whereas offset yield strength values at low strains of pre-strained samples provide a more accurate criterion.

5 References


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