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Prediction of Bake Hardening Behavior of Selected Advanced High Strength Automotive Steels and Hailstone Failure Discussion

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Abstract: The purpose of the present study is three-fold. Firstly, it attempts to describe the bake hardening (BH) behavior of selected interstitial free (IF) and dual phase (DP) steels. Secondly, it predicts the BH behavior of the IF DX 51D and DP 500 HCT 590X plates of steel, and thirdly studies material failure prevention in scholarly sources. The research is aimed at investigating the increasing steel strength during the BH of these two high-strength sheets of steel used for outer vehicle body parts. Samples of steel were pre-strained to 1%, 2%, and 5% and then baked at 140–220 °C for 10 to 30 min. The BH effect was determined from three factors: pre-strain, baking temperature, and baking time. Research has shown that increasing the yield strength by the BH effect is predictable. Therefore, the number of experiments could be reduced for the investigation of BH effect for other kinds of IF and DP steels. The literature study of the hailstone failure reveals that the knowledge of BH steels behavior helps to calculate the steel supplier´s failure mode effect analysis (FMEA) risk priority number.

Keywords: bake hardening; dent resistance; failure study; polynomial regression; yield strength; automotive steels

1. Introduction

In Europe, there were about 25,000 fatal road accidents in 2016, of which passenger accidents accounted for more than 25.6% [1]. The European Union's environmental policy and high customer demands for car quality are forcing manufacturers to adhere to strict quality, safety, and environmental management standards. Therefore, becoming a new supplier in the automotive chain in today's busy market is extremely complex [2,3].

According to [4] many industrial applications, such as car bodies require steels with good formability and high strengths, taking into account safety, fuel efficiency, environmental performance, manufacturability, durability, and other quality properties.

According to the Eurostat 2018 study [1], such steels contribute significantly to reducing the number of fatal road accidents. The goal of car manufacturers is to increase the use of high-strength steels with minimized-thickness because it is necessary for preventing material failure and avoiding cost increases.

However, these requirements are often contradictory since the increase in strength must be achieved without compromising formability.

Due to a variety of requirements, different automotive parts utilize various steel types and grades to achieve the required properties [5]. For example, outer body parts should possess good surface quality, dent resistance, and also a good hemming ability.

Bake hardened steels have good formability before stamping and enhanced strength after baking. Hence, in recent years bake hardened steel has been widely used in vehicles components, thus leading to a reduction in vehicle weight and improved safety. Bake hardening steels derive their increase in strength from a strain aging [6].

Considering that the investigated bake hardenable steels are planned to be used for the automotive outer body parts, there is a high probability that during use, various damages will occur due to static or dynamic stone impact, e.g., hailstones. It is therefore worth considering for further research the increased number of hailstorms that have recently occurred in the world. There were 4611 hailstorms in the USA [7] and Europe per year. A report by Munich RE [8] shows that damage from individual events can exceed billions of dollars as the risk has increased in the past decades. Hail damage to properties, such as cars, becomes substantial when the diameter of hailstones approaches and exceeds 50 mm. Forecasts for the year 2019 say that world-wide hailstorms might cause record damage [9]. Therefore, steel sheets are required to have high dent resistance, which is closely related to high strength.

The aim of our research is to find out how to control a particular grade of interstitial free (IF) and dual phase (DP) steel by changing input parameters during bake hardening (BH) and to explore the possibility of generalizing this knowledge to other grades of IF and DP steels by microscopic analysis and predict their behavior by multi-polynomial regression. Hailstone failure of bake hardenable steels is studied in scholarly sources, and inclusion of increased frequency of occurrence and severity of hailstones into the failure mode effect analysis (FMEA) at the steel-maker company (supplier) is recommended.

2. Materials and Methods

Conventional bake hardening steels were initially developed and patented in 1977 to propose an increased strength in cold-formed sheet metal parts that require good formability [10].

BH effect can be observed in many different grades of steels, and this phenomenon is discussed in detail, e.g., in [11]. Bake hardening occurring in steel materials corresponds to an increase of the flow stress after a pre-strain followed by heat treatment (or annealing) within a specific temperature range [12]. Bake hardening uses the deformation aging process to increase yield strength. The maximum is reached at a temperature range between 150–220 °C according to [13,14].

The pre-strain is a permanent elongation of the sample. The sample was loaded to a given pre-strain elongation and unloaded at room temperature. The value of pre-strain is the percent of the length before elongation.

Bake hardening increases the yield strength by the deformation aging process of the formed part for increased dent resistance without a reduction in formability [12]. Typical applications are automotive outer body panels where increased dent resistance is required.

For press-formed car body structural components, the paint-baking treatment is the last process cycle which is performed at low-temperature. Paint-baking gives the car not only an aesthetic appearance but also positively affects the strength of the material and increases the dent resistance via the BH effect [15–17].

Two low carbon sheets of steel referred to as IF DX 51D and DP 500 HCT 590X that exhibit bake hardening effect were used in this study. According to the metallurgical designation, we can classify IF DX 51D and DP 500 HCT 590X as advanced high-strength steels (AHSS). AHSS have carefully selected chemical compositions and multiphase microstructures resulting from precisely controlled heating and cooling processes. Table 1 shows the chemical composition of the investigated steels.

Table 1. Chemical compositions of investigated steels (wt.%).

Steel	C	Si	Mn	P	S	Ti	Al_{TOT}	Cr + Mo	Nb + Ti	V	B
IF DX 51D	0.15	0.55	-	0.04	0.015	0.3	-	-	-	-	-
DP 500 HCT 590X	0.12	0.5	1.6	0.1	0.045	0.3	0.015–1.5	1.4	0.15	0.2	0.005

Most automotive components are subject to low stress during the final shaping operation before baking. Therefore, BH behavior experiments are performed by exposing the samples to a pre-strain range of 1–5% at 20 °C. Applying pre-forming to samples increased the density of dislocations [18,19]. After that, the sample was baked for a defined time at a specified temperature.

Bake hardening effects can be evaluated using a standardized concept of a bake hardening index. The value of BH_2 index for pre-strain 2% is given according to DIN EN 10325:2006 [20] by Equation (1):

$$BH_2 = Re_{L,t} \text{ (or } Rp_{0.2,t}) - Rp_{0.2,r} \quad (1)$$

where $Re_{L,t}$—is the yield strength of lower point when the stress-strain shows a sharp yielding point for the sample after baking; $Rp_{0.2,t}$—the yield strength of the crossing point of 0.2% offset line with the tensile test curve when the stress-strain does not show a sharp yielding point; $Rp_{0.2,r}$—the yield strength of the relevant pre-strain for the sample before baking.

The dislocations generated by the preformation are anchored by free soluble atoms that diffuse into the dislocation core during baking. The consequence of this process is an increased yield strength (YS) [20].

In general, the BH index is 30–40 MPa for IF steels [21] and 30–60 MPa for DP steels [22] after 2% pre-strain and baking at a temperature of 170 °C throughout 20 min. The magnitude of this phenomenon depends on the baking temperature and time [12,23].

3. Results

3.1. Bake Hardening Behavior of Investigated Steels

The mechanical properties of investigated steels before and after baking were tested using a tensile test according to [24]. The sample thickness for DP steel was 1.5 mm and was 0.55 mm for IF steel. The geometry of the samples used for the tensile test is given in Figure 1.

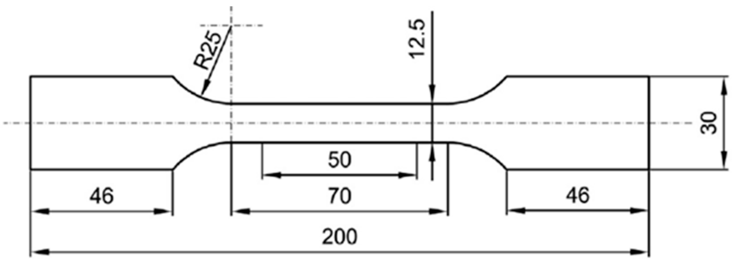


Figure 1. Sample geometry for tensile testing (unit: mm).

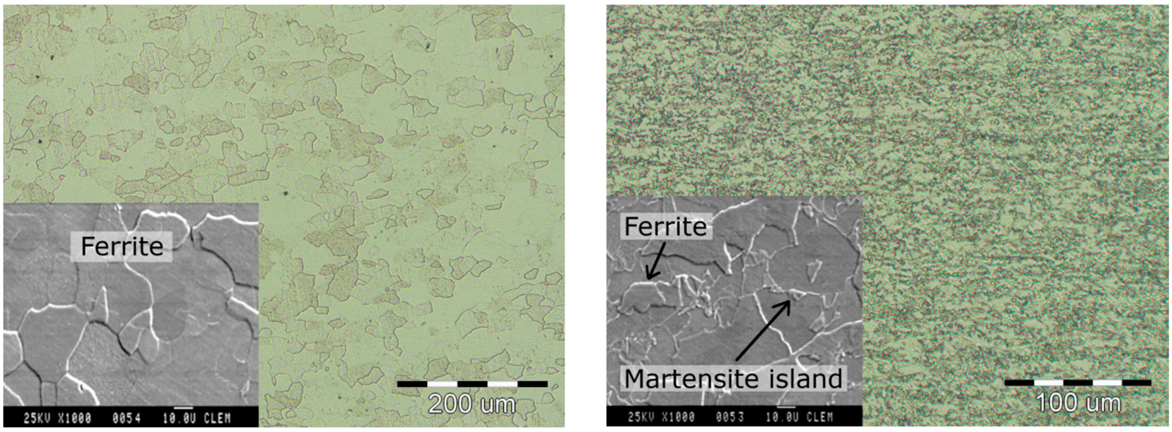
Table 2 shows the mechanical properties of investigated steels before baking.

Table 2. Mechanical properties of as-received steels.

Steel	YS (MPa)	UTS (MPa)	A80 (%)
IF DX 51D	220	350	36
DP 500 HCT 590X	340	590	20

YS—yield strength; UTS—ultimate tensile strength; A80—elongation 80 mm.

The microstructure of both materials was obtained by metallographic analysis. Samples were taken from cold rolled galvanized sheets in the rolling direction. Samples were produced for both types of steel by a standard metallographic procedure according to the internal procedure of the steel-maker [25]. Samples of tested steels were observed on the Olympus GX 71 microscope (Tokyo, Japan). Figure 2a and Supplementary Video S1 show the microstructure of the IF DX 51D steel before baking. The microstructure is formed by ferrite grains. Steel is purely ferritic without interstices as carbon (C) and nitrogen (N). The microstructure of the DP 500 HCT 590X steel before baking is represented in Figure 2b and Supplementary Video S1. The higher volume fraction of small martensite islands and small ferrite grains produces higher BH values. Solute carbon content in ferrite controls the speed of BH response [19].



(a) (b)

Figure 2. The microstructure of investigated steels: (**a**) Interstitial free (IF) DX 51D steel. (**b**) Dual phase (DP) 500 HCT 590X steel.

For tensile tests, a multiaxial material testing machine Zwick Z050 (Ulm, Germany) with optical strain measurement ARAMIS 5M and the rate-controlled device was used. First, three groups of samples were pre-strained to 1%, 2%, and 5%. Then, each sample was subjected to a baking process at the unique combination of temperature (140 °C, 170 °C, 190 °C, 220 °C) and time (10, 15, 20, and 30 min). After cooling down to room temperature the tensile test was performed, and measured values were recorded. Tables 3 and 4 show the selected measured values at a typical temperature 170 °C and time 20 min. The whole set of measured values of the BH index used in a model calculation in Section 3.2 is listed in Appendix A.

Table 3. Measured values of IF DX 51D, 170 °C/20 min.

Specimen	a_0 (mm)	b_0 (mm)	Re_L (MPa)	$Rp_{x,r}$ (MPa)	A80 (%)	BH_x (MPa)	Pre-Strain
E1_170/20	0.55	20.06	352	310	20.7	42	1%
E2_170/20	0.55	20.04	374	339	15.6	35	2%
E5_170/20	0.53	20.04	433	342	19.6	91	5%

a_0—sample thickness; b_0—sample length; Re_L—yield strength of lower point; $Rp_{x,r}$—yield strength of pre-deformation 1%, 2%, 5% before baking; A80—80 mm elongation; BH_x—bake hardening index.

Table 4. Measured values of DP 500 HCT 590X, 170 °C/20 min.

Specimen	a_0 (mm)	b_0 (mm)	Re_L (MPa)	$Rp_{x,r}$ (MPa)	A80 (%)	BH_x (MPa)	Pre-Strain
K1_170/20	1.47	20.09	486	418	23.8	68	1%
K2_170/20	1.47	20.01	548	477	22.9	71	2%
K5_170/20	1.46	19.77	630	567	19.9	63	5%

a_0—sample thickness; b_0—sample length; Re_L—yield strength of lower point; $Rp_{x,r}$—yield strength of pre-deformation 1%, 2%, 5% before baking; A80—80 mm elongation; BH_x—bake hardening index.

3.2. Multi-Polynomial Regression Model

The regression analysis was used for estimating the relationships between bake hardening values and independent variables: pre-strain, baking temperature, and baking time. The second-order multi-polynomial regression model was chosen from several tested models because it had the lowest value of the residual sum of squares [26,27]. The number of measurements taken was 48 for each type of steel, which is the number of a full factorial experiment. The model is given by Equation (2):

$$Y = C_0 + C_1X_1 + C_2X_2 + C_3X_3 + C_{12}X_1X_2 + C_{13}X_1X_3 + C_{23}X_2X_3 + C_{11}{X_1}^2 + C_{22}{X_2}^2 + C_{33}{X_3}^2 \quad (2)$$

where Y is BH (MPa), X_1 is pre-strains (%), X_2 is baking temperature (°C), and X_3 is baking time (min). The coefficients C_1 to C_{33} of the model are listed in Table 5.

Table 5. Summary of regression analysis results.

Coefficient	IF DX 51D	DP 500 HCT 590X
C_0	−67.2078	31.5670
C_1	−18.9102	−14.5249
C_2	1.4452	−0.1713
C_3	−2.5467	1.2129
C_{12}	0.0656	0.0320
C_{13}	0.2182	0.0066
C_{23}	0.0021	0.0006
C_{11}	4.3385	1.0295
C_{22}	−0.0045	0.0021
C_{33}	0.0765	−0.0218
Residual Sum of Squares	1926.8700	204.4950
Coefficient of Determination R^2	0.9528	0.9897

Table 6 contains the values of the coefficient of determination (R^2) for models which were calculated in the way mentioned above for the different number of measurements. The values were taken from the existing set of measurements. The number of measurements can be reduced three times from 48 to 16, and the R^2 value is still close to the original one. It must be said that good result are achieved by choosing a set of measurements where all distinct values of independent variables (pre-strain, baking temperature, and baking time) are presented.

Table 6. Coefficient of determination (R^2) for calculated models.

No. of Measurement	Coefficient of Determination R^2	
	IF DX51D	DP 500 HCT 590X
12	0.9486	0.9832
14	0.9472	0.9826
16	0.9498	0.9893
18	0.9511	0.9892
20	0.9507	0.9890

The coefficient of determination, R^2, in Table 6 is the proportion of the variance in the variable BH that is predictable by the model. The analysis shows that the model for DP 500 HCT 590X steel is more precise. Nevertheless, it can be concluded that the increased yield strength by the BH effect is predictable and can be described by the second-order multi-polynomial regression model with ten coefficients C_1 to C_{33}. The values of coefficients in Table 5 are valid for given sample geometry and thickness.

3.3. Yield Strength and a Dent Resistance—Findings from the Literature Study

There are extensive crash studies concerning the safety of outer vehicle body parts in the literature [28,29]. Less known and respectively less published are failure studies, which are related to smaller, non-life-threatening outer damage of sheets due to static and dynamic impacts of small hard objects (up to 100 mm), which reduce aesthetic properties of vehicles and require costly repair. More extensive dent resistance tests were done by [30,31]. A key distinction that is sometimes missing in dent resistance studies is the nature of the dent.

There are two types of denting, static and dynamic, according to F. Gatto & D. Morri [32]. Static denting refers to a gradually applied load over a small area typified by a hand pushing on a vehicle bonnet. Dynamic denting occurs under impact loading typified by a hailstone. The key difference between the two is the nature of load application. A static dent indicates a slowly applied force. A dynamic dent is driven by inertia and impact energy.

Burley et al. [33] confirmed that dynamic dent resistance is affected by factors such as panel density, modulus of elasticity, and curvature. Thomas D. presented the test of the AA6111 steel sheet. Results of this research were presented as "dynamic dent models" in [30].

Mehmet E. Uz [31], simulated the hailstone impact on G300 and G550 steels in laboratory conditions and investigated the dependence of dent size on steel grade, steel thickness, yield strength, and the size, speed, and impact force of ice balls. Experimentation reveals that the dent depth was inversely proportional to thickness and yield strength, while the dent diameter was found to be proportional to yield stress. As the yield strength of the steel sheet increased, the dent depth decreased for these specific materials.

In the literature [34–36] there are applications of failure studies in steel-maker organizations. The detailed procedure, according to [37,38] aims to guide quality engineers and practitioners and to offer consistent results towards failure prevention and quality improvement.

One of the most popular engineering techniques for failure prevention is a FMEA method [39]. FMEA is used for reducing the risks of failure and understanding the nature of preventive actions needed to be taken as measures of continuous improvement.

This method can reveal the risks at the early stage of product planning, reduce time, and save investment. For failure risk assessment the risk priority number (RPN) can be used and defined as the result of the three independent factors Equation (3):

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D} \quad (3)$$

where S is the Severity of the failure effect; O is the occurrence likelihood factor of the failure cause and D is for the detection likelihood of the occurred failure cause, failure or failure effect, respectively.

4. Discussion

4.1. Bake Hardening Behavior

The minimum BH index value for IF DX 51D steel is 12.2 MPa at 1% pre-strain, 220 °C, and 15 min, and the maximum value is 98 MPa at 5%, 220 °C, and 20 min. The minimum BH index value for DP 500 HCT 590X steel is 33.5 MPa at 5% pre-strain, 140 °C and 10 min, and the maximum value is 109.2 MPa at 1%, 220 °C, 30 min, as can be seen in Appendix A.

The BH effect for the IF DX 51D steel is less sensitive to temperature, which is evident in Figure 3. In contrast, the BH effect for the DP 500 HCT 590X steel is quite sensitive to temperature but almost insensitive to pre-strain (Figure 4). It could be stated that BH effect for IF DX 51D steel is dependent on pre-deformation as opposed to DP 500 HCT 590X steel, where BH effect increases with the rise of temperature. That is consistent with the findings in literature sources [19,23], which state that increasing of the BH effect significantly depends on the type of material and its structure.

4.2. Prediction of the Bake Hardening Behavior

Prediction of BH behavior is visualized in Figures 3 and 4. It is evident that different steels behave differently, which is apparent from the Supplementary Video S1. However, the assumption made about the predictability of bake hardening behavior allows for calculation of the model coefficients for different steels from a reduced number of measurements. In this case, the model coefficients are calculated by solving a system of linear equations.

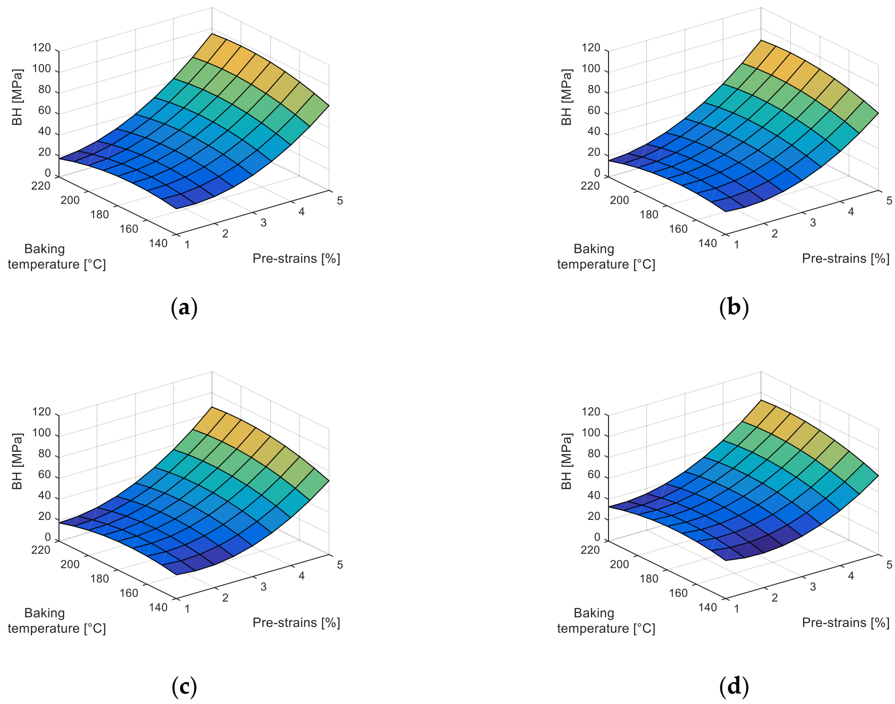


Figure 3. Bake hardening behavior of the IF DX 51D steel. (**a**) Baking time 10 min; (**b**) baking time 15 min; (**c**) baking time 20 min; (**d**) baking time 30 min.

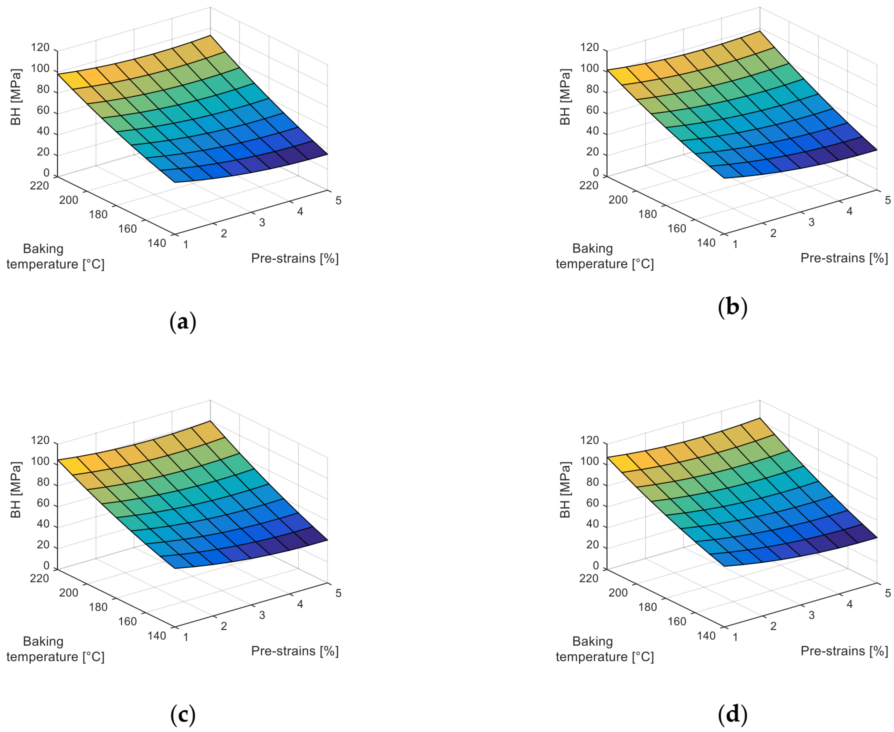


Figure 4. Bake hardening behavior of the DP 500 HCT 590X steel. (**a**) Baking time 10 min; (**b**) baking time 15 min; (**c**) baking time 20 min; (**d**) baking time 30 min.

4.3. Failure Caused by a Hailstone

According to the literature [6,12,34], BH steels have a high dent resistance. Nevertheless, we know cases when car roofs have been damaged during hailstorms as well as due to the stone impacts to the hood, doors, and mudguards. Illustration can be found in Supplementary Video S1.

According to our multi-polynomial regression model, it is possible to predict the yield strength only for sheet thicknesses shown in Tables 3 and 4. By measuring for different thicknesses, the same procedure could make the model generalizable for other thicknesses of the examined materials and thus contribute to the customer's decision on a particular sheet thickness with respect to dynamic dent resistance.

Then, implementation of failure analysis (FA) as a systematic procedure of an organization will help to identify the dent risks concerning of the outer vehicle body damage.

Since the studies mentioned above have shown dependence between yield strength and dent size caused by hailstones, the knowledge of work hardening and bake hardening effects can be used for estimating the RPN number by steel-maker organization.

Our further research will focus on the simulated hailstone in laboratory conditions and investigate steel grade dependence, steel thickness, yield stress and size, speed, and impact strength of ice balls on samples on outer vehicle body parts for IF DX 51D steel and DP 500 HCT 590X steel. FMEA will reveal the risks of hailstone damage for investigated steels at the early stage of steel research.

5. Conclusions

The subjects of our study were bake hardenable automotive body steels, for which the vehicle producer required good formability and high strengths. On the base of the producer request, we investigated the behavior of two steel types during bake hardening.

We examined the effect of pre-strain, baking temperature, and baking time on the bake hardening process, which is used for the strengthening of body sheets after the painting process.

The following conclusions can be drawn from the experimental part:

- IF DX 51D steel is created only by ferritic phase. DP 500 HCT 590X steel contains ferrite as the primary phase, and the secondary strengthened phase is formed mainly by martensite.
- Measured higher ultimate tensile strength of the primary material DP 500 HCT 590X steel is 590 MPa and elongation A80 is 20%, and for IF DX51D steel the ultimate tensile strength is 350 MPa and elongation A80 is 36%.
- The result of the regression analysis shows that the increase of yield strength by the bake hardening effect of investigated steels is predictable, therefore a reduced number of measurements are needed to describe BH behavior for another grade of IF and DP steels or for different steel sheet thickness.
- The literature review shows that there is a direct relationship between the dent depth, which is inversely proportional with thickness, and yield strength. Therefore, knowledge of BH behavior should be taken into account in the process FMEA of the steel-maker organization.

Supplementary Materials: The following are available online at http://www.mdpi.com/2075-4701/9/9/1016/s1, Video S1: Bake hardening behavior of the IF DX51D and DP 500 HCT 590X steels.

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Appendix A

Table A1. Measured values of BH index.

Pre-Strain	Temperature (°C)	Time (min)	BHx (MPa)			
			IF DX 51D	a_0	DP 500 HCT 590X	a_0
1%	140	10	26.0	0.55	54.0	0.47
2%	140	10	30.5	0.55	40.5	0.47
5%	140	10	80.5	0.53	33.5	0.46
1%	170	10	38.0	0.55	64.0	0.47
2%	170	10	32.0	0.55	60.0	0.47
5%	170	10	84.0	0.53	52.0	0.46
1%	190	10	32.2	0.55	79.1	0.47
2%	190	10	30.1	0.55	72.1	0.47
5%	190	10	90.8	0.53	66.8	0.46
1%	220	10	24.2	0.55	102.1	0.47
2%	220	10	26.1	0.55	92.1	0.47
5%	220	10	95.8	0.53	92.8	0.46
1%	140	15	14.0	0.55	54.0	0.47
2%	140	15	19.5	0.55	43.5	0.47
5%	140	15	77.5	0.53	38.5	0.46
1%	170	15	26.0	0.55	64.0	0.47
2%	170	15	21.0	0.55	63.0	0.47
5%	170	15	81.0	0.53	57.0	0.46
1%	190	15	20.2	0.55	79.1	0.47
2%	190	15	19.1	0.55	75.1	0.47
5%	190	15	87.8	0.53	71.8	0.46
1%	220	15	12.2	0.55	102.1	0.47
2%	220	15	15.1	0.55	95.1	0.47
5%	220	15	92.8	0.53	97.8	0.46
1%	140	20	16.0	0.55	56.0	0.47
2%	140	20	21.0	0.55	49.0	0.47
5%	140	20	81.0	0.53	44.0	0.46
1%	170	20	42.0	0.55	68.0	0.47
2%	170	20	35.0	0.55	71.0	0.47
5%	170	20	91.0	0.53	63.0	0.46
1%	190	20	22.0	0.55	81.0	0.47
2%	190	20	21.0	0.55	80.0	0.47
5%	190	20	93.0	0.53	76.0	0.46
1%	220	20	14.0	0.55	104.0	0.47
2%	220	20	17.0	0.55	100.0	0.47
5%	220	20	98.0	0.53	102.0	0.46
1%	140	30	25.0	0.55	60.0	0.47

Table A1. *Cont.*

Pre-Strain	Temperature (°C)	Time (min)	BHx (MPa)			
			IF DX 51D	a_0	DP 500 HCT 590X	a_0
2%	140	30	38.0	0.55	49.0	0.47
5%	140	30	72.0	0.53	42.0	0.46
1%	170	30	51.0	0.55	72.0	0.47
2%	170	30	52.0	0.55	71.0	0.47
5%	170	30	82.0	0.53	61.0	0.46
1%	190	30	38.3	0.55	86.2	0.47
2%	190	30	43.7	0.55	82.2	0.47
5%	190	30	84.7	0.53	76.2	0.46
1%	220	30	30.3	0.55	109.2	0.47
2%	220	30	39.7	0.55	102.2	0.47
5%	220	30	89.7	0.53	102.2	0.46

a_0—sample thickness. Shaded parts are minimum and maximum values of BHx.

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