https://doi.org/10.3311/PPtr.23794
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Periodica Polytechnica Transportation Engineering

Limit State of Bake Hardened Stamped Interstitial-free Steel Automotive Parts Caused by Local Thickness Reduction

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Received: 06 November 2023, Accepted: 07 February 2024, Published online: 26 April 2024

Abstract

Current trends in the complex shapes of modern automobiles lead to the need for extremely formable materials for deep drawing applications. In general Interstitial–Free (IF) steels present the solution for this purpose. In addition, the cold stamping process is influenced by a variety of input factors that must be correctly adjusted. An imperfection in one of the inputs may cause stamping defects even with deep drawing materials. Limit states may then appear in the form of cracks or unacceptable thinning in the critically stressed areas of the stamped parts. For this reason, a general focus is placed on the use of non-destructive methods and inspection of stamped parts after stamping for potential subsequent modification of the stamping process.

The presented work deals with the material analyses of stamped parts made of Bake-Hardened Interstitial-Free steel, including the local thickness reduction of the material, leading to the occurrence of crack propagation. The focus of the work was placed on the critical influencing factors resulting from the limit states presented. The evaluation of the material flow and the local plastic response was carried out using a cylindrical indentation method. In addition, the SEM analyses showed the importance of the deformation capacity of the surface coating which proved to be one of the decisive parameters for the occurrence of limit states.

Keywords

thickness reduction, local thinning, BH IF steel, limit state, stamped parts, stamping defects

1 Introduction

Actual design trends in the body forming of automotive outer panels force the producers to make complex stamped parts. These complex parts often include sharp edges that may cause stamping complications and limited distribution of plasticity leading to localized thickness reduction and undesirable consequences. In addition to this crucial stamping process input in the form of part geometry we can also mention, e.g., technological inputs in the form of stamping speed, temperature, or the amount of lubricant, which are also very important for success (Hsu et al., 2002). Input in the type of used coating is an actual problem as well (Li et al., 2018; Kurz et al., 2015). All these inputs must be correctly set and controlled for the given material so that the resulting stamped parts get the required quality. However, even with an apparently correctly set stamping process and its inputs, sometimes undesirable phenomenon in the form of unacceptable local thinning or crack occurs (Schmidová et al., 2023). The reason may be the part's complex shape leading to a complicated stress-strain state in combination with the effect of different friction in contact of the stamping tool and the coating. This phenomenon is very difficult to predict and not possible to simulate with commonly used tests. The friction may not be constant depending on the geometry of the part. In addition, the local thinning increases the strain rate of deformation, which may hardly affect the plastic capacity of the material (Verleysen et al., 2011). This opens the field for research of the new stamping simulation parameters and material research leading to quantifying the limit state of the plasticity, especially studying the microstructure evolution under the predefined stress-strain states. Emphasis is also placed on the non-destructive evaluation of these local defects.

The material used for stamping these complex outer panels must provide excellent formability. In general Interstitial–Free (IF) steels present the solution for this purpose. IF High Strength (IF-HS) or Bake Hardened (BH) steels are used as well, especially for their higher

Cite this article as: Klejch, F., Schmidová, E. (2024) "Limit State of Bake Hardened Stamped Interstitial-free Steel Automotive Parts Caused by Local Thickness Reduction", Periodica Polytechnica Transportation Engineering, https://doi.org/10.3311/PPtr.23794

strength and better dent resistance (Deva et al., 2021). IF steels provide excellent formability because of their inherent material characteristics. Low content of C and N interstitial atoms (< 0.003 wt% and < 0.004 wt%), and γ fibre (<111>||ND) crystallographic texture ensures high plastic anisotropy (r value) that supports ductility (da Rocha Santos et al., 2018). The stabilization is done by alloying elements of Ti and Nb, a description of the effect of these alloying elements was carried out by Hoile (2000). IF-HS steels are reached by adding alloying elements of P, Si, or Mn, IF, BH steels are prepared to be strengthened by the use of the bake hardening effect when the movement of dislocation is blocked by remaining carbon atoms. This procedure is done at the temperature of 150–200 °C during paint baking (Bhattacharya, 2011; Pereloma and Timokhina, 2017).

The presented study deals with a problem of localized thinning of stamped parts made of bake-hardened IF steel. A set of stamped samples with galvanized zinc Mg/Al coating including a different stage of stamping/amount of deformation, containing a local material thinning at the critical location, was analyzed. The thickness reduction measurement, EDX chemical microanalyses, and unconventional indentation method for obtaining the local plastic response of the material were done. Emphasis is placed on the description of the critical influencing factors of the investigated problem.

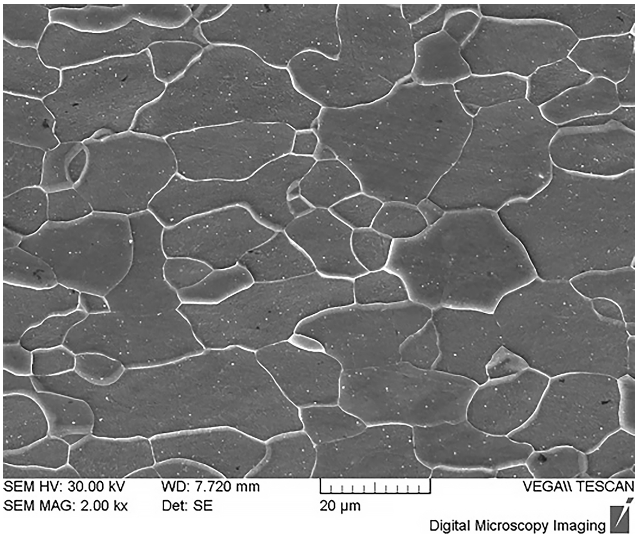
2 Material and Methods

The material used in this work is bake-hardened IF steel with a yield strength of 240 MPa and ultimate tensile strength of 330 MPa, commonly used for automotive outer body panels (doors, roofs, etc.). The chemical composition is given in Table 1. The initial thickness of the tested material was 0.7 mm, with a galvanized zinc Mg/Al coating thickness of 4 μm. Fig. 1 shows (a) the typical IF BH steel microstructure obtained by Scanning Electron Microscope (SEM) and (b) inherent material anisotropy in the normal direction (ND) obtained by Electron Backscatter Diffraction (EBSD) analysis.

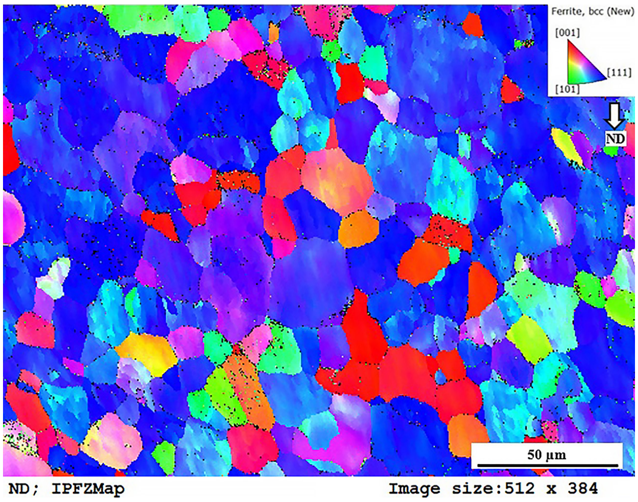
Scanning Electron Microscope (SEM) TESCAN VEGA 5130SB with EBSD analyzer Bruker e-Flash was used to examine the microstructural state of the material, the state of the surface layers, and to measure thinning in perpendicular sections of the stamped parts. For the evaluation of the surface layer's chemical composition, the microanalyses using EDX Bruker Quantanax 200 microanalyzer were used (Bruker, 2014). The etching for metallographic analyses was made using 3% Nital etchant. EBSD samples were prepared with the use of chemo-mechanical polishing with colloidal silica.

Table 1 Chemical composition of the tested IF BH steel [wt. %]

Elements	C	Mn	Si	P	S
	<0.01	0.35	<0.01	0.032	0.006
[wt. %]	Cr	Ni	Cu	Al	Ti
	0.025	0.02	0.015	0.041	0.011



(a)



(b)

Fig. 1 IF BH steel microstructure (a) and EBSD IPFZ Map image in ND – the presence of γ fibre (b)

To quantify a local plasticity response and distribution of the plastic flow of the material, unconventional indentation tests using the universal hardness tester ZWICK ZHU 2.5/Z2.5 with the continual force-displacement record and cylindrical indenter of 0.2 mm diameter were used. Based on the use of cylindrical indenters and the Hencky theory for plane strain indentation slip (Bowman, 2003), it is possible to calculate the indentation yield strength from the indentation force-displacement data. The indentation load-depth curve shows the interface between elastic and plastic material response, which is possible to use for indicating the local yield strength. The relation is shown in Eq. 1. To get comparable results the calibration using the tensile test yield strength is used.

$$\frac{F_y}{A_1} = 2.57 R_I \quad (1)$$

Where: F_y = force at yield point; A_I = indenter base area; R_I = indentation yield strength

3 Results

Analyzes were performed on a set of stamped samples containing a local material thinning at the critical location. Samples were prepared at different stages/amounts of stamping deformation. The critical location of the stamped parts was found to be in a position next to the stamped part's critical radius, where the main contact of stamping tools occurs. This position corresponds to a phenomenon that may occur during deep drawing of round and rectangular cups, presented by Kardes (2012) and Eshel et al., (1986). According to them, the material at the punch corner is the most common failure region because the portion of the sheet has the least strain hardening here (Kardes, 2012). On the other hand, in our situation when the material thinning starts to localize, the material also localizes the strain hardening into this position. The local strain rate is also rapidly increased during the deformation, which limits the material's ability to distribute plasticity and leads to failure. The material is also affected by friction in contact with the stamping tool, where in the case of predominant one-sided contact, uneven tensile stress occurs. This leads to the appearance of inhomogeneous thinning, which is shown in Fig. 2.

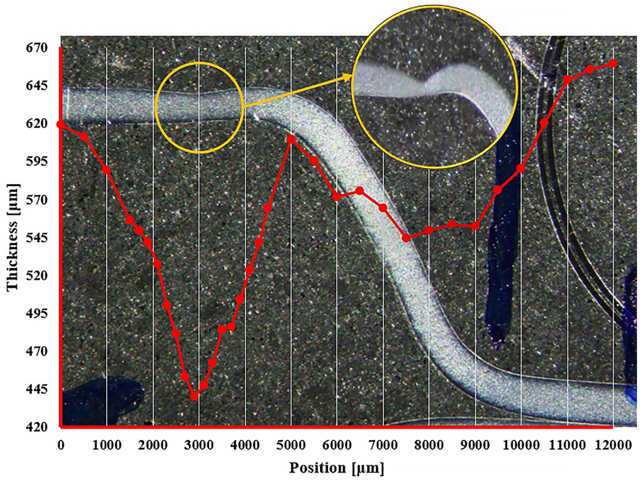


Fig. 2 The critical location of the stamped part including thickness reduction

Fig. 2 shows the critical location in the stamped part, including the thickness gradient. The state leading to failure is shown in detail. Maximum thickness reduction leading to the failure was found to be more than 60% compared to the initial thickness of the sheet. According to Schmidová et al., (2023), the limiting thickness reduction leading to plasticity degradation was found to be over 28%. The state in the figure shows the stage slightly over this critical value, steep thickness distribution is visible from the gradient. The detail shows the state just before the crack appeared. The unconventional indentation method using a cylindrical indenter was used to quantify local plastic response and plasticity distribution in perpendicular cuts. Measurements under the load of 45 N carried out in longitudinal sections enabled the evaluation of strain hardening according to thickness reduction and plasticity distribution. The measurements were done in two steps using a gap of 0.8 mm for each step. The second step was used to increase the sensitivity of the obtained gradient, which was not affected by the surrounding imprints. The minimal edge distance of 1 indentor *d* was used. The crucial importance of the stamping tool contact area and the possibility of material movement/flow over the edge of the tool with the sample and its surface layer was determined from the measurements. The possibility of the material flow allows wider plasticity distribution connected with less steep thickness reduction. This effect is shown in Fig. 3 where a failure would occur in the upper sample (N) but not in the bottom sample (O).

Sample N has a narrower and steeper gradient of the plastic response, also higher values of hardening were found. In comparison to the parent material, we can see the rise of local yield strength by 85%. This effect would be greater with higher deformation leading to failure.

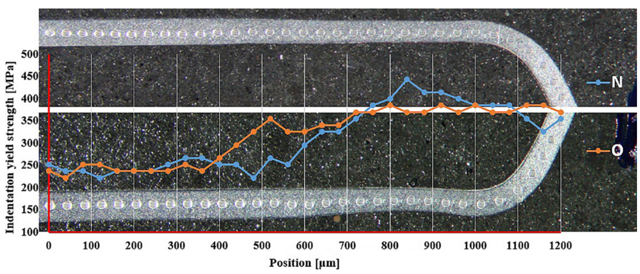
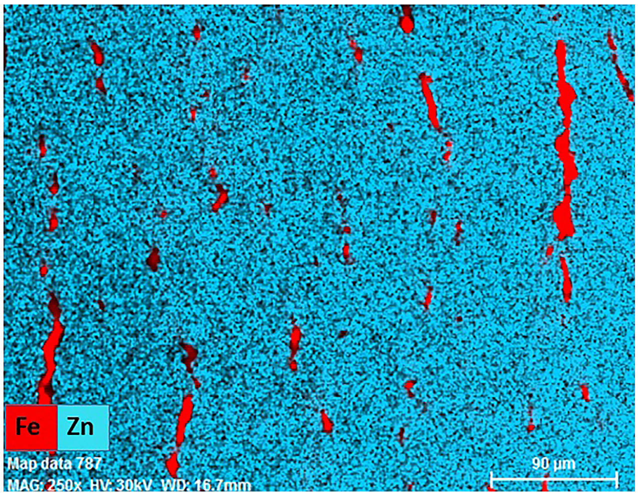


Fig. 3 Distribution of strain hardening in the critical region

Sample O has a wider plasticity distribution visible in the figure. This is closely connected to the state of the used surface layer. The next thing visible from the graphs is the absence of dramatic strain hardening in the 0 to 400 µm position, in this position the material undergoes uniform tensile deformation of small strains that do not affect the limits of plasticity.

The deformation capacity of the surface coating has a crucial role in the localization of deformation. When reaching the critical tensile stress on the outer side of the critical place, the surface layer starts to crack. This is connected to the effect of too high local friction, which doesn't allow enough flow of the material. Appearing cracks lead up to the interface of the sheet metal and the surface layer, where they accelerate the localization leading to failure. That is documented by EDS map Fig. 4 (a) and SEM picture in the position Fig 4 (b).



(a)

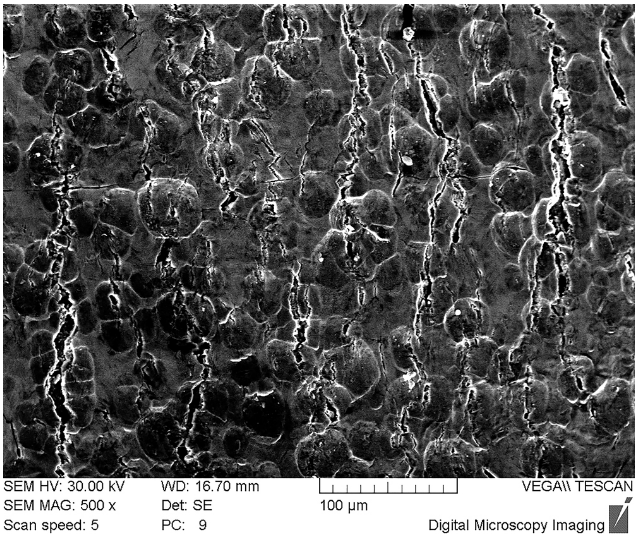


Fig. 4 SEM image of cracked coating (a) and EDX microanalysis in the same area (b)

4 Discussion

In this study, the effects and critical stamping process inputs leading to local thickness reduction were evaluated. Analyses done in the critical position of the stamped parts containing different stages of deformation bring important knowledge of limiting process inputs leading to localized failure. Material thinning in critical positions leads to localized strain hardening which affects the material behavior and especially its distribution of plasticity. This was studied by Ghosh (1977), who demonstrated the critical influence of strain hardening on sheet metal forming under uniaxial and biaxial deformation. The localization leads to microstructure deformation, where in the critical state, the interaction of dislocations leading to the formation of subgrains with low-angle boundaries occurs (Schmidová et al., 2023). The effect of localization and its influence on further deformation is also dependent on the geometry of the part. That was studied by Tasan et al., (2009) who found out that for IF steels the type of strain path has a significant influence on deformation after localization. The localization also causes the presence of a higher local strain rate, which has a significant influence on forming. Its significance was proved for IF steel by the research made by Verleysen et al., (2011).

The localization and distribution of plastic flow were found to be very influenced by the state of the surface layer. Friction in the contact of the stamping tool and coating limits the plastic flow distribution leading to cracks in the surface layer and subsequently in the sheet material. The coating does not only play the role of anti-corrosion protection, but is very important for the correct stamping process. This was proved by many authors, e.g. Evin and Tomáš (2022) and Gupta and Kumar (2006) studied the importance of friction coating of galvanized IF steels. The coating parameters need to be correctly selected to provide sufficient formability. Especially Zn Mg/Al coatings are prone to cracking, which was studied in detail by Ahmadi et al. (2021); Salgin et al., (2022). The importance of capturing this phenomenon and its importance also plays a role in simulations of forming, where it is very hard to take this effect into account. It is also very difficult to predict and not possible to simulate with commonly used formability tests. Wettability and friction coefficient instabilities as consequences of surface degradation represent current limitations in predicting true formability limits.

5 Conclusions

Critical parameters having one of the key roles in the stamping process were analyzed. The following conclusions can be derived from the performed analyses:

- The position of the local thickness reduction is influenced by the local stress state and material flow. The material is affected by friction in contact with the stamping tool, where in the case of predominant one-sided contact, uneven tensile stress occurs. This leads to the appearance of inhomogeneous thinning, which leads to this typical type of failure.
- Localization leads to a rapid local increase of strain rate, which limits the distribution of plasticity.
- Analyses revealed the critical importance of the material flow possibility over the edge of the stamping tool. This effect affects the plastic distribution leading to fracture.
- The deformation capacity of the surface coating was found to be one of the crucial parameters. Cracking of the coating limits material flow and leads to fast localization of deformation.

A prospective way to suppress such a complex problem should be based on the specification of limiting factors for the prediction of plasticity at real forming conditions, i.e. involving the forming limits of coatings along the standard evaluation of substrate forming response. Newly designed methods based on bending or tensile in-site tests reflect the current research orientation. The performed research has proved that the decisive trigger for hardening is the plastic flow localization due to the degradation of the coating layer. Thus, the real geometry together with friction instability needs to be specified and it is still the field for the next research.

Acknowledgement

This work was supported by the project "Current research topics from transport means and infrastructure solved at Faculty of Transport Engineering", realized at the Faculty of Transport Engineering; Number SGS_2023_014

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