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ANISOTROPY AND HARDENABILITY OF INTERSTITIAL FREE STEELS UNDER THE INFLUENCE OF LOCALIZED DEFORMATION

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Abstract:
Interstitial Free (IF) steels are nowadays commonly used for stamping complex parts of outer automotive bodies. Current requirements for fast production lead to the need of monitoring the real state of the material after stamping based on its real material conditions. It is desirable to describe and quantify the evolution of microstructure deformation and plastic conditions before and after the stamping process.
This paper presents Electron Backscatter Diffraction analyses of deformed and non-deformed IF steel, including the quantitative measurement of the localized plastic response of the real stamped part, using an unconventional indentation method. The effect of strain rate was evaluated using the high-speed tensile tests. The increased ratio of the Low Angle Grain Boundaries was found as a good parameter to quantify the depletion of plasticity.

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1. INTRODUCTION

Trends in the production of automotive outer body panels need a material that is capable of high formability and fast production rates. The requirement is also to maximize the utilization of the material capacity to achieve stiff, lightweight, and complex-shaped stamped parts. All while achieving high production rates. The resulting quality of stamped parts is influenced by many factors entering the production process. These factors must be correctly set, e.g., the shape of dies, lubrication, temperature, speed of the stamping cycle, and the used steel [1].

Nowadays the Interstitial Free (IF) steels present the solution for this purpose. In general, the IF steels have great formability, which is necessary for stamping complex parts of outer automotive bodies. Great formability is caused by the interstitial free character of the steel and crystal structure [2]. The interstitial free character of the steel stands for the low amount of interstitial atoms, especially carbon and nitrogen (< 0.003 wt% and < 0.004 wt%). To achieve a low content of these elements, vacuum degassing technology is used during continuous casting [2]. The steels are also microalloyed with Ti and/or Nb elements in a controlled way, which ensure a stabilizing effect by forming suitably formed and distributed precipitates [3,4]. Also alloying with the elements of P, Si, and Mn enables to reach the high strength types of IF steel (IF-HS) [2,5]. Important is also the crystal structure that allows plastic anisotropy to be achieved. A high value of average normal anisotropy $\bar{r}$ correlates with good formability of thin sheets, a low value of planar anisotropy Δr is also important. Isotropic steels have an $\bar{r}$ value of 1, but deep drawing steels should have an $\bar{r}$ value higher than 1.8 [3]. To reach the high normal anisotropy, the presence of γ fiber/{111} crystallographic texture is important. A large number of grains with {111} planes parallel to the sheet plane supports the drawability [6]. The intensity of the recrystallization structure {111} also depends on the content of interstitial elements. A larger proportion of interstitial atoms leads to the formation of {110} and {100} type textures, which cause a reduction of drawability [2].

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Current requirements for the fast production also lead to an increase in the forming speed, i.e. an increase in the speed of working tools and strain rates. Therefore, the material has high requirements in terms of its plastic capacity. The limits of plastic capacity may lead to crack propagation and are one of the main points of current research, not only for the IF steels [7-9].

The plastic capacity and its limits are influenced by many parameters that affect the local condition of stamped parts. In addition to the material anisotropy and chemical composition/metallurgical quality, is it for example the local strain rate and strain path.

Even in common forming techniques, such as deep drawing or rolling, high strain rates are locally achieved. This differs from the commonly used strain rates for determining the mechanical parameters of materials [10,11]. The effect of high strain rates on the formability of different types of steel sheets was investigated by Verleysen et al. [10], where a significant drop in formability (Forming Limit Diagram) of deep-drawing steel (DC04) under dynamic conditions was found.

The influence of strain path is a very researched topic and has an inherent influence on the limit state and failure of the material. In the case of stamping, there is a combination of different states of deformation according to the shape of the stamping dies, as well as their local changes during the stamping process [12]. The strain path has also an effect on the phase transformation or even the development of crystallographic textures under the loading [13]. The Strain path studies are mostly based on the available testing methods, i.e. the Forming Limit Diagram (FLD) methods or biaxial tensile tests. An extensive study of different strain path influences on the behaviour of IF and Dual Phase (DP) steels using FLD methods was carried out by Tasan et al. [14].

The presented study deals with real stamped automotive parts made of IF steel and its localized plastic response in the critical point of the part. The plastic response was measured by an unconventional indentation method, using a cylindrical indenter. Indentation was made in the critical area of the stamped part and also on the tensile test samples, using different strain rates up to 666 s^{-1}. Electron Backscatter Diffraction (EBSD) outputs, considering undeformed, stamped and cracked material are presented, as well.

2. MATERIAL AND METHODS

The material used in this work is the IF steel typically used for stamping automotive outer body panels. The chemical composition is given in Table 1. The thickness of the tested sheets was 0.8 mm, including electrolytic zinc coating. The mechanical parameters were evaluated by the standard tensile test using a ZWICK/ROEL Z-030 machine, obtaining the average yield strength of 157 MPa and ultimate strength of 287 MPa, $\bar{r}$ value reached 1.835, Δr was found to be 0.61.

The dynamic tests were made using an AH 40-100 M062 electro-hydraulic system with an Inova TestControl control system at two loading rates – 5 m/s (333 s^{-1}) and 10 m/s (666 s^{-1}). The EBSD analyses were made by SEM TESCAN VEGA 5130SB with EBSD analyzer Bruker e-Flash. As a last step of the EBSD samples preparation, chemo-mechanical polishing with colloidal silica was used.

The unconventional indentation method was used for the quantitative measurement of the local plastic material conditions. The universal hardness tester ZWICK ZHU 2.5/Z2.5 with the continual force-displacement record was used and local yield strength was evaluated by using a cylindrical indenter with 0.3 mm diameter. Based on the Hencky theory for plane strain indentation slip, it is possible to calculate the real yield strength using a cylindrical indenter. The ratio of indentation yield strength to normal yield strength is 2.57 according to Hencky equations [15]. Indentation force in the yield position, (Fig.1) divided by the cylindrical base area is equal to 2.57 normal yield strength.

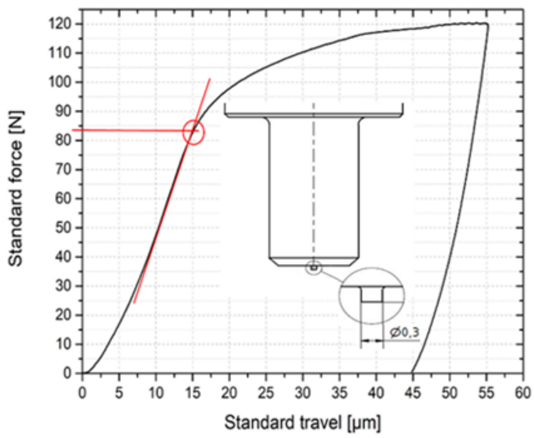

Fig. 1. Indentation curve with the yield force position

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

Elements	C	Mn	Si	P	S	Cr	Ni	Cu	Al	Ti
[wt.%]	0.0018	0.11	0.024	0.0062	0.0076	0.033	0.036	0.026	0.051	0.056

To get the precise results for tested steel, the calibration using the real yield strength, obtained from the static tensile tests, was made.

3. RESULTS AND DISCUSSION

A typical IF steel anisotropy in the parent stage of deformation, i.e. in the stage of the undeformed sheet, revealed by EBSD is shown in Fig.2a and b. Similarly, the parent state initial anisotropy was confirmed by Vadavadagi et al. [16], who compared IF and IF-HS grades of the steels.

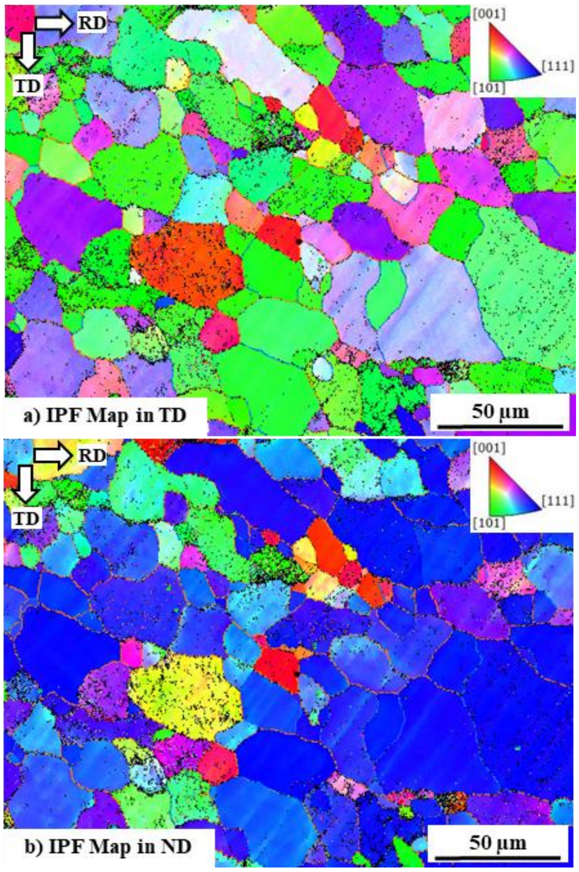

Fig. 2. EBSD analyses of the undeformed sheet

The preferential orientation, i.e. the γ fiber, has been observed in Normal Direction (ND), contrary to „blended“ crystallography orientation in Transverse Direction (TD) and Rolling Direction (RD). Increased γ fiber constituents were revealed in the TD using the tensile samples as a reference towards the limiting rotation due to uniaxial loading conditions. The increased ratio of the Low Angle Grain Boundaries (LAGB) was found as a suitable quantitative parameter to assess the depletion of plasticity, while all the other material parameters (metallurgy quality, grain size inhomogeneity etc.) bring particular collaborative effects.

The crucial influence of the localized stress-strain conditions was revealed in the case of the real „auto-body“ stamped parts (Fig.3). Grains show a significant deformation in the direction of the main plastic flow. Restriction of a tendency to „free torsion“ is connected with the suppressed anisotropy evolution during the forming process. The increased plasticity and the hardenability, as a consequence of localized plastic flow (strain path), are the natural consequences as well.

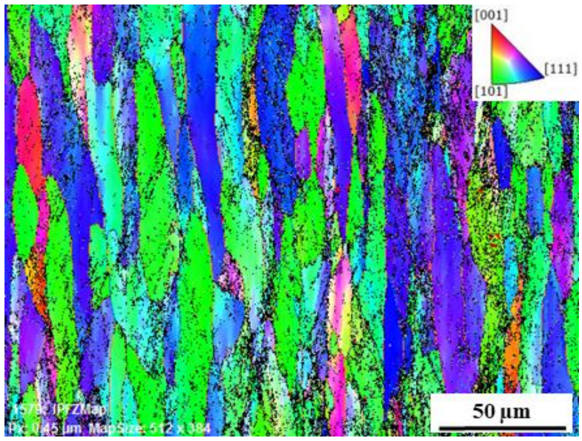

Fig. 3. EBSD analysis of the stamped part

Exemplary grain boundary misorientation graphs are depicted in Fig.4. The extreme increase of LAGB (5-15°) was captured near the fracture of the stamped part. For the comparison, stamped part without fracture is shown, as well. The amount of low angle grain boundaries is related to the degree of deformation of the material grains, respectively deformation hardening of the material in the analyzed region. The relation between LAGB and grain deformation during the differential speed rolling (DSR) process of IF steels was demonstrated by Ko et. al. [17]. A decrease in the amount of LAGB and an increase in High Angle Grain Boundaries (HAGB) of deformed grains during recrystallization annealing was demonstrated by Xu et. al. [18]. In the case of different local deformations of the material, the increased ratio of the Low Angle Grain Boundaries represents a good parameter to quantify the depletion of local plasticity.

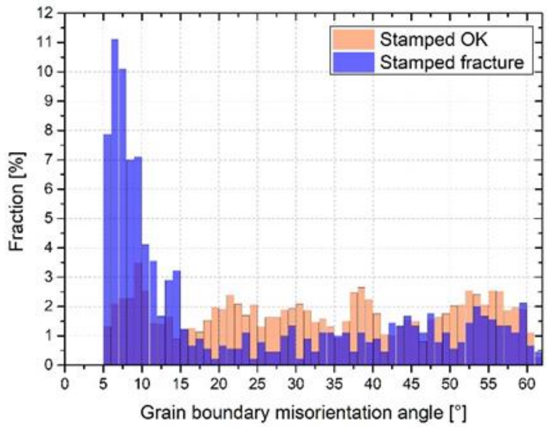

Fig. 4. Fraction of grain boundary misorientation angle

Two parameters have to be considered as distinctive for formability limitation under particular technology parameters – a strain-rate sensitivity and the ability of steel to distribute plastic strains. An activation volume plays a key role in the rate-controlling mechanisms during deformation. Indentation methods, mainly nanoindentation are commonly used ways to assess the local mechanical properties and also became a frequently used technique to determine strain-rate sensitivity. Abrupt changes in strain rate during the indentation process, allow determining the sensitivity of the strain rate for probing lower strain rates [19].

A systematic comparison of the different micromechanical techniques has been performed by Wehrs et al. [20], to investigate the strain rate sensitivity to establish the consistency of their results: nanoindentation, miniature tension, and micropillar compression; for all used techniques a good agreement was shown.

When the cylindrical indenter is used, the material response is still affected by non-uniform stress-strain fields underneath the loaded indenter, but it becomes closer to macroscopic regimes, i.e. including the grain size influence.

Depending the stage of plastic deformation, the underlying mechanisms of deformation behavior can be related to different contributions of dislocation slip, grain boundary sliding [21,22], up to the decohesion, and failure. Intrinsic deformation mechanisms can be derived based on the sensitivity to the strain rate (m) and apparent activation volume (v) of the material [23-25].

The performed analyses have shown a steep increase in LAGB, so dislocation rearrangement in the grain interior is dominant under analysed conditions of the forming process.

To evaluate the real processes, which should be considered as a simultaneous effect of particular strain rate and triaxiality, the first set of indentations was made in the critical part of the stamped part and compared to the undeformed sheet state. The measurements were made perpendicular to the surface along the three lines: near the critical bending (radius) position, in the radius, and in the maximum thickness reduction next to the radius. The average obtained yield strength of the undeformed sheet was 157 MPa, which corresponds to the yield strength from the standard tensile test. Compared to this, a large increase in the obtained yield strength in the stamped part critical area was measured; in the maximum thickness reduction position yield strength was 129 % higher and in the position of the radius and near the radius was about 90 % higher. This shows that the stamping process has a significant effect on the local strengthening of the material. It reaches maximum values in critical places, where after the depletion of plasticity, failure may subsequently occur. Analogous strengthening of IF steels was discovered by Ko et.al. [17], who performed tensile tests after varying conditions of DSR processes.

To see the effect of strain rate on the hardening gradient and plastic capacity distribution of the material, the second set of indentations was made. As the operational strain rate is defined by speed of the forming dies together with localized plastic flow, the actual conditions of the real stamped parts deformation should be taken in the testing parameters. Based on the localized plasticity along the sharp bending parts, the range of localized strain rate was considered in order up to hundreds s^{-1}. Uniaxial tensile tests were performed under 0.002 s^{-1}, 333 s^{-1} and 666 s^{-1} strain rates, reflecting the used combination of loading rate vs. deformed length of samples. A comparison of static and dynamic tensile tests is shown in Fig. 5. The strain rate dependence is obvious from the graph, for the evaluation of the dynamic test, a standard approach was used to obtain the tensile strength response from the dynamic oscillations. Based on this approach dynamic tensile strength was found to be about 400 MPa in comparison to 290 MPa from standard static test.

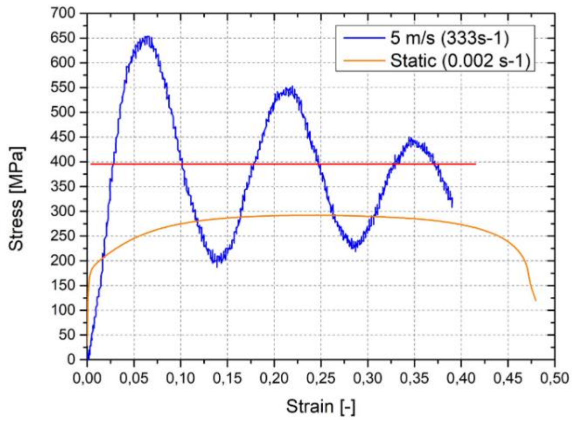

Fig. 5. Static vs. Dynamic tensile test curves

The indentation gradients are depicted in Fig.6. The yield strength in the position near the fracture of the samples shows about a 97 % increase compared to the yield strength of the undeformed sheet and also to the undeformed part of the tensile samples. The reach of the plastic flow reflects the strain rate influence that is visible in comparison of static and dynamic results, and also in tensile test curves. No substantial difference was found in the tested dynamic conditions. Hence, one can conclude that the decisive plastic spread restriction is associated with the 333 s^{-1} strain rate (loading rate 5 m/s). A much wider experimental series with differing the strain rate range is necessary to confirm this assumption. This will be subsequently done in next research work.

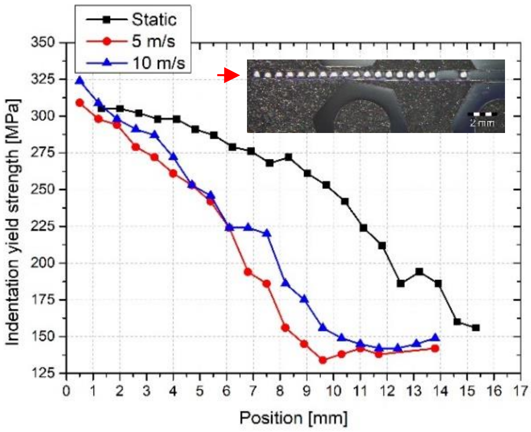

Fig. 6. Indentation gradients of tensile samples

4. CONCLUSIONS

The following conclusions can be derived from the performed analyses:

- A much higher hardening effect was measured in the case of the real critical stamped parts, compared to the uniaxial tensile tests. The real plastic restriction of the stamped part made of the IF steel is connected with different stress-strain conditions and increased strain rates;
- The localized yield strength, obtained by the unconventional indentation method was about 129 % higher in the position of maximal thickness reduction, compared to the undeformed sheet state;
- The required type of anisotropy was confirmed in the parent stage of the analyzed steel. The main tendency to rotation under the loading is sensitive to the real strain condition in the critical stamped parts. The increased γ fiber constituents have been observed in TD during the uniaxial loading, contrary to that, strong limitations of this kind of crystallography rotation were revealed in the case of the real critical loading conditions;
- The increased ratio of the Low Angle Grain Boundaries (LAGB) was found as a suitable quantitative parameter to assess the depletion of plasticity;
- The particular effect of dynamic hardening was measured under defined dynamic conditions; the decisive plastic spread restriction could be associated with a 333 s^{-1} strain rate (loading rate 5m/s).

Further experimental analyses will be done to confirm mainly the quantitative expression of investigated processes.

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