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Microstructural Influence on Fracture Toughness of IF Steel and DP Steel

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Abstract. Interstitial free steels (IF) and Dual-phase (DP) steels are widely used in the automotive industry, their specific application is driven by requirements to optimize the strength-to-weight ratio. Utilizing the full capacity of their plasticity and strain hardenability requires an assessment of edge fracture susceptibility and flangeability. In this work, the ability of the mentioned steels to spreading of deformation along initiated cracks is evaluated by structural and fractographic analyzes. Microstructural restrictions of plasticity are correlated with fracture toughness results, adopting the essential work of fracture (EWF) methodology. Crystallographic analyzes (EBSD) are focused on the role of anisotropy and the deformation texture evolution, affecting the development of plasticity and thus the energy consumption to the fracture.

1 Introduction

Interstitial-free (IF) steels are widely used in the automotive industry. The excellent formability, based on the plastic anisotropy (r) and absence of Lüders bands are the characteristics, which made the IF steel an excellent option for deep drawing of various stamped automotive outer body components. Increased strength of high strength grades of IF steels is reached by an increased presence of the secondary phases by micro-alloying, or even the presence of pearlite micro volumes. Therefore, the localized inhomogeneous micro-plasticity leads to preferential crack initiation and so the deformation limit is becoming lower.

Dual-phase (DP) steel, as a variety for some autobody parts with higher required strength, has a good strength-to-weight ratio, simple thermal processing, absence of Lüders bands, and modest formability. The strength of DP steel is attributed to the martensite fraction, while the ferrite helps in keeping ductility[1,2]. The high early strain hardening and high ratio of ultimate to yield strength of DP steel[3,4] make it an alternative to IF steel. However, DP steel possesses a lot of challenges to stamping, such as a spring back effect, lower flangeability, and many more stamping-related problems.

Thus, precise evaluation of energy consumption and resistance to crack propagation is of increasing importance. Comparing the fracture toughness is very essential, as it has a direct influence on the formability, edge fracture, and flangeability. The presence of low crack-tip constraints and the fixed thickness of rolled sheets are the restrictions for the standard fracture toughness test methods.

In the previous part of the study[5], the essential work of fracture (EWF) methodology has been utilized to determine the fracture toughness of IF and DP steel. For both the steels, the values of plastic anisotropy and strain hardening are key parameters decisive for crack propagation. To enable formability prediction, it is necessary to identify the acting degradation process during localized plasticity along the crack path. The structural analyses presented in this work are focused on the effects on the distribution of microplasticity, as the trigger for better energy consumption expressed by the EWF methodology. Crystallography parameters are emphasized in their role to limit plasticity.

2 Materials and methodology

The chemistry of DP450 and IF steels used in this research work are given in Table 1. The average grain sizes of the DP450 and IF steel are 5.81 µm and 16.5 µm, respectively. Table 2 shows the results of the standard tensile tests for the DP450 and IF steel in the transverse direction (TD) and at a strain rate of 0.002 s^{-1}.

Table 1. Chemical composition (weight %) of DP450 and IF steels.

	C	**Mn**	**Si**	**P**	**S**	**Cr**	**Ni**	**Cu**	**Al**	**Ti**
DP	0.083	1.72	0.026	0.021	0.0049	0.209	0.0097	0.014	0.056	0.163
IF	0.0018	0.110	0.024	0.0062	0.0076	0.033	0.036	0.026	0.051	0.056

Table 2. Mechanical properties from standard tensile tests.

	σ_y**(MPa)**	σ_u**(MPa)**	**Ag%**	**A50%**	**n**	**r**
DP	309	499	18.82	28.57	0.18	0.58
IF	177	284	24.52	43.16	0.22	1.82

To define specific energy consumed in the fracture process zone, the essential work of fracture (EWF) was measured in the initial experimental study [5] in comparison IF vs. DP steel. The methodology was proposed by Cotterell and Reddel [6] based on Broberg's [7] concept of separating energy zones at the crack tip. In the essential work of fracture method (EWF), the total energy absorbed by the specimen to fully fracture (W_f) is measured by a uniaxial test at a defined strain-rate. Two parts of the absorbed energy are distinguished - essential energy (We) consumed in fracture process zone (FPZ) and energy consumed for the plastic deformation in the outer plastic zone (W_P). The essential energy (We) is proportional to the ligament area. Samples of different ligament lengths are loaded up to fracture and the values of specific work of fracture “w_f” (W_f divided by the area of fracture) are plotted as a linear function of the ligament length. Then, the specific essential work of fracture “w_e” is presented in energy value at zero ligament length. The detailed characterization of the used methodology including the limitations for correct application is described in the research work [8]. In the EWF test, both notched and pre-cracked samples of the DP 450 and IF steels were tested. Double edge notched tension (DENT) specimens (crack propagation is along the rolling direction) are used in the EWF tests - Figure (a).

To describe the microstructural background of the fracture response, complex structural, fractography and crystallography analyses (EBSD) are conducted.

The DP450 and IF steel samples were prepared before and after EWF tests. The position of EBSD analysis after the EWF test is just outside the fracture zone (necking zone). The samples for structural analyses are prepared using mechanical grinding and polishing, followed by electro-polishing for EBSD. In this work, grain boundary misorientation of 5° to 15° is considered a low angle grain boundary (LAGB), and above 15° is considered as high angle grain boundary (HAGB).

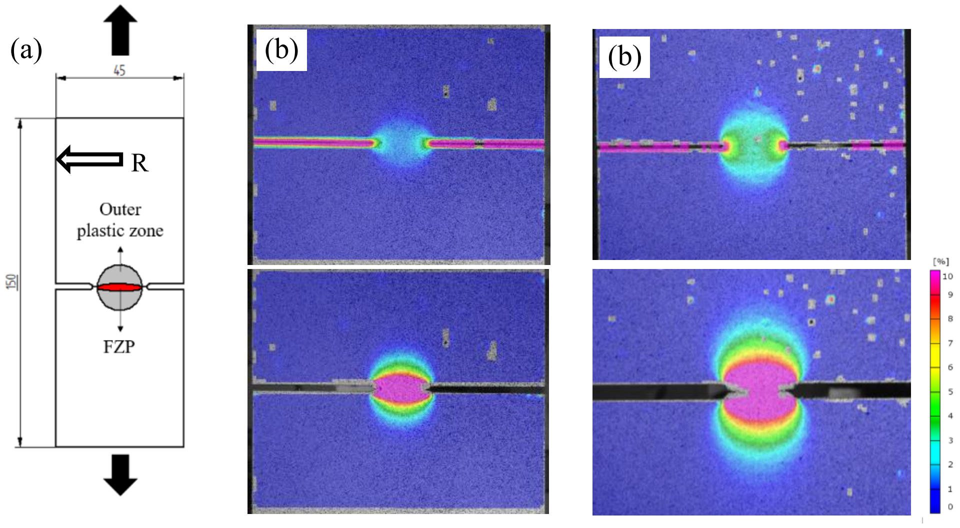

Figure 1 (a) Graphical representation of double edge notched tension specimen of EWF tests (mm); (b) Von Mises strain development during the EWF test for ligament length 8.86 mm of DP450 steel (c) IF steel.

3 Strain localization analyses

The strain hardening exponent and plastic anisotropy are significantly higher for the IF steel compared to the DP450 steel. This indicates that DP450 steel will experience high strain localization and early thinning by necking during stamping compared to the IF steel.

Generally, increased deformation hardening (expressed by "*n*" values in this case) means the effective process to restrict the localization of microplasticity. A successful transfer of micro plasticity through grain boundaries is accompanied by the gradual depletion of the plasticity of individual grains. A distribution of microplasticity to a large section, supported by the local work hardening is a natural precondition for better formability.

The fracture toughness, expressed by energy consumption in the fracture process via EWF methodology, should be closely correlated with hardening capacity. It was confirmed for both types of samples in initial tests. For the notched samples, the IF steel has about a 6% higher value of the specific essential work of fracture ("w_e") than the DP450 steel. For the pre-cracked samples, the IF steel has about 27% higher "w_e" value than the DP450 steel [5]. However, better plasticity distribution with increased strain hardening may not be true for fracture resistance. D. Frómeta et al.[8] have tested two DP1000 steels in the EWF method; the steel having lower total elongation and strain-hardening exponent had better fracture toughness. In this research work, the IF steel has a higher strain exponent, total elongation, and fracture toughness as well. The DP450 steel, compared to the IF steel, lost more resistance to fracture due to increased stress concentration due to fatigue pre-cracking. In AHSS, fracture toughness is highly influenced by the presence of multiple phases and the difference in strain compatibility of the phases.

The efficiency of microplasticity spreading is conditioned by interconnected microstructural processes. Depletion of plasticity within the grains with the best orientation of the slip system is followed by a rotation of neighboring grains. Thus, the initial orientation characteristics together with local grain size are the crucial microstructural parameters. The evolution of primary crystallography characteristics, such as the stability of positive prevalence of γ-fibre in ND in the fracture process zone, is decisive for the ability to spread the plasticity and thus for the energy consumption. The selected structural and crystallography parameters are further discussed in their functionality within the localized plastic deformation and in the fracture process zone.

3.1 Limiting effects on the strain distribution

Local misorientation identified by KAM maps reflects the dislocation density and localization within a grain. The evolution of the dislocation density and arrangement is displayed in Figure 2 in comparison of the initial stage vs. the stage of localized deformation along the crack propagation for both analyzed steels. In the DP450 steel, for the as-received condition, the misorientation count is high in comparison to the IF steel. Due to the volumetric expansion of the martensite during quenching, a higher misorientation is present in the DP steel before the deformation. This leads to an increased dislocation density along the martensite-ferrite grain boundary and finally to an intensive strain localization near the crack tip. The mentioned process has been reported as a source of early strain hardening for dual-phase steels[9,10]. KAM map in the deformation zone after the EWF test (Figure 3) displays an inhomogeneous deformation reflecting the grain boundaries. The deformation is concentrated mainly near the grain boundaries, while the center portion of the ferrite grain experiences minor deformation.

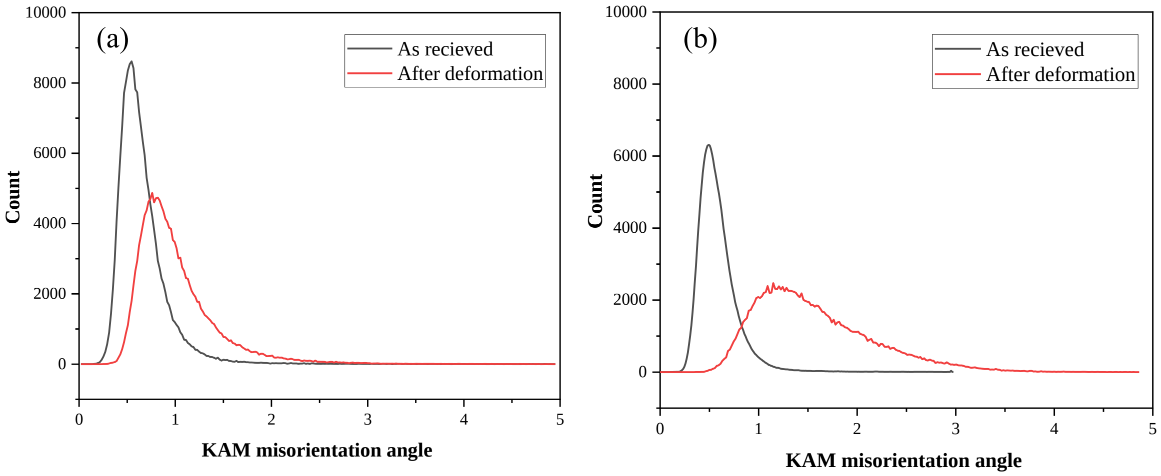

Figure 2. KAM misorientation angle before and after the localized deformation: (a) DP450 steel; (b) IF steel.

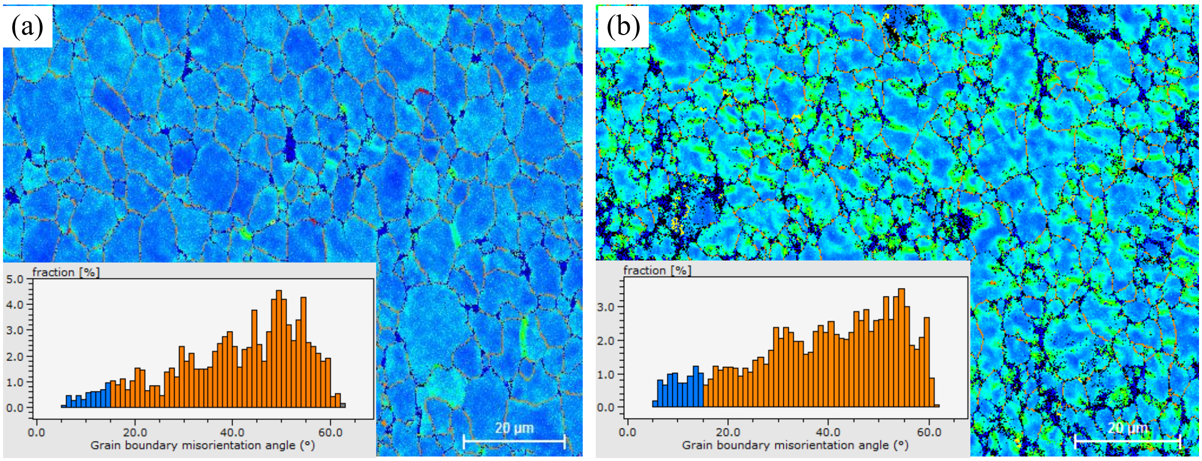

Figure 3. KAM map (0º-5º) of DP450 steel vs. LAGB/HAGB presence: (a) as received; (b) after the EWF test

The primary mode of void generation in analyzed DP450 steel is by ferrite-martensite decohesion (Figure 4(a)). Ahmed et al. [11] have also reported a similar void formation mechanism for low volume fraction martensitic DP steel, while the higher volume fraction of martensite in DP leads to martensite cracking. The difference in plastic strain compatibility between the two phases is the primary reason for the decohesion [12]. The ferrite-ferrite decohesion appeared only in proximity to the martensite. Kadkhodapour et al.[13] have predicted that the presence of higher carbide density along the ferrite-ferrite grain boundary weakens the grain boundary. Voids appeared along the ferrite-ferrite grain boundary between the closely situated martensite in the analyzed DP steel.

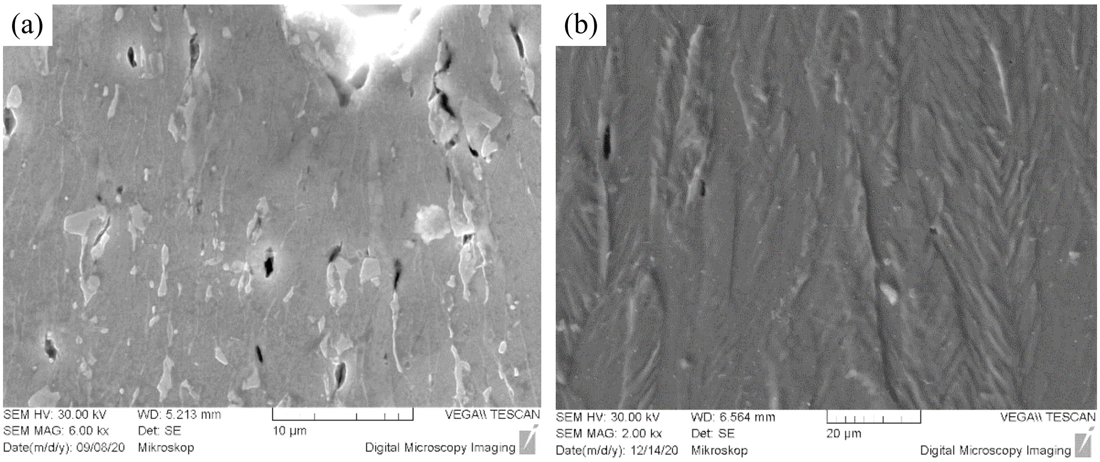

Figure 4. (a) Voids formation due to ferrite-martensite boundary decohesion in necking region of DP450 steel. (b) Slip bands formed inside heavily deformed ferrite grains.

For IF steel, a different process of deformation localization and crack propagation was observed in the EWF test. In the stage of the localized deformation, a substantially higher increase in misorientation value was found for the IF steel compared to the DP450 steel (Figure 2(b)). Contrary to the DP steel, a stepwise increase in LAGB was observed as a direct consequence of localized deformation – Figure 5. An apparent increase in the low angle grain boundaries is attributed to the formation of sub-grains during deformation. In the IF steel, the absence of hard secondary phases and uniform plastic flow (Figure 5(b)) allowed the extension of plasticity at the crack tip to a wider area.

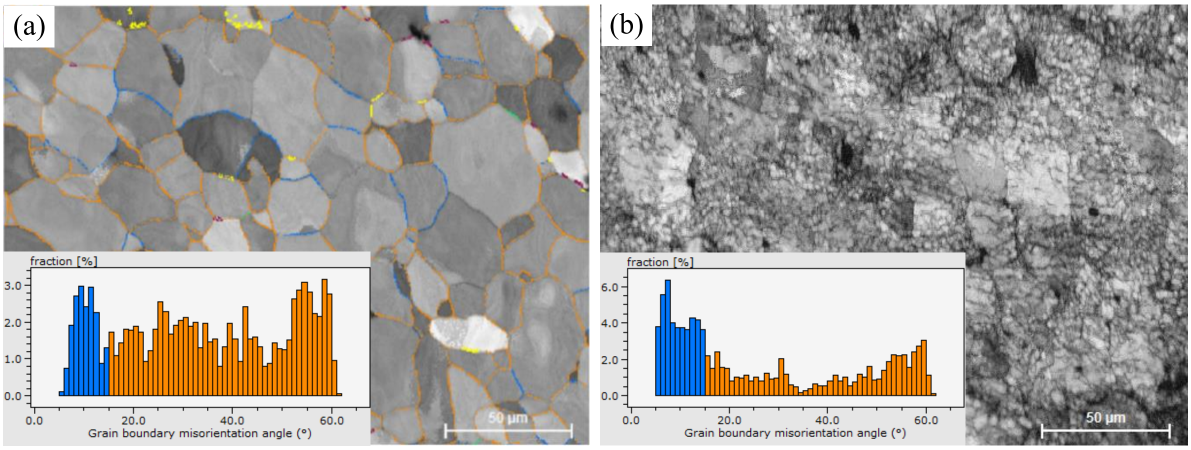

Figure 5. Low angle grain boundary evolution due to localized deformation of IF steel: (a) as received; (b) after deformation from EWF test.

4 Conclusions

The microstructural effects on fracture toughness for the DP and IF steels expressed by the EWF method led to the following conclusions:

- The primary mode of void generation in the DP450 steel is the ferrite-martensite decohesion, alternatively in ferrite separated by micro volumes of martensite.
- In the IF steel, increased misorientation evolution within the grains in the plastic zone was observed due to missing other retarding processes of propagation of microplasticity (unlike DP steel with the interphase borders). Voids are formed preferentially at the grain boundaries in case of small secondary phase distribution.
- During plastic deformation, the DP450 steel experience heterogeneous deformation within the ferrite grain due to the neighboring of martensite fraction.
- The sub grains are formed in the IF steel in the zone of the localized plastic deformation.

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