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Effect of punching and stress concentrations on mechanical behaviour of electrical steels

Dennis Van Hoecke[1], Sigrid Jacobs[2], Lode Vandenbossche[1],
Bastien Weber[3], Emmanuel Attrazic[4]
[1]ArcelorMittal Global R&D Gent, OCAS NV, Technologiepark 935, B-9052 Zwijnaarde (Gent), Belgium
[2](corresp. author) ArcelorMittal Global R&D, Technologiepark 935, B-9052 Zwijnaarde (Gent), Belgium,
sigrid.jacobs@arcelormittal.com
[3]ArcelorMittal Global R&D Maizières-les-Metz, Voie Romaine BP30320, 57283 Maizières-les-Metz, France
[4]ArcelorMittal Saint-Chély d'Apcher, Rue des Martyrs du Maquis, 48200 Saint-Chély d'Apcher, France

Abstract

ArcelorMittal supplies advanced mechanical and magnetic material data for its iCARe^{TM} line of electrical steels to enable customers to optimise the design of their e-machines . This paper gives an overview of the experimental methodologies to assess the effect of stress concentrations and punched edges on the fatigue behaviour of thin gauge electrical steel sheets. The link between the mechanical properties and the microstructural and metallurgical features of the different materials is discussed.

Keywords: materials, motor design, optimisation, vehicle performance

1 Introduction

As previously reported in EVS presentations, ArcelorMittal has a specific electrical steel product line that optimises the performance of automotive traction electrical machines [1]. This product family is called iCARe^{TM}. It declines in Save grades allowing weight reduction, in Torque grades allowing higher torque and Speed grades for high speed rotors.
The machines used in automotive traction now already have been going through several optimisation steps, in the consecutive generations of hybrid vehicles on the market. These optimisation cycles had not only to answer more stringent requirements in power density but also cost reduction. Both of these machine aspects are linked to the amount and type of the core material.
Additionally, machine design is switching from a pure electromagnetic design with simplified mechanical constraints towards a coupled electromagnetic and mechanical design approach.

To allow an optimal mechanical design of a machine, the structural integrity of the stator and rotor core needs to be predicted based on in-service load and temperature cycles, manufacturing aspects, component geometry and statistical material data obtained by experimental testing. This material data comprises the mechanical properties under both static and dynamic loading (fatigue properties).
ArcelorMittal supports its customers with the mechanical design by providing these advanced mechanical characteristics for its electrical steels. This advanced characterization takes into account the effect of temperature and the effects of the manufacturing aspects like punching and notching.

In a first approximation of the temperature effect, the static mechanical property data (yield strength, tensile strength and elongation) are extended from room temperature to machine operation temperatures up to 250°C.

These data can then be applied to model the fatigue properties at elevated temperatures based on the available fatigue limits at room temperature.

Machine manufacturing operations can also influence the mechanical properties of the core laminations. The insertion of notches leads to stress concentrations and influences both static and dynamic properties. Punching influences mainly the fatigue properties by introducing defects at the punched edges.

This paper presents the methodologies which were developed for the advanced mechanical characterisation of electrical steels as well as the obtained results on the effect of punching and stress concentration (notches) on the fatigue properties of thin gauged electrical steels.

2 Effect of temperature on mechanical behaviour

An important parameter to assess the ability of the rotor to withstand constant centrifugal force is the yield stress at the operating temperature. The yield stress of various non-oriented electrical steels grades which are often applied in automotive traction machines was experimentally determined for temperatures up to 250°C on standardized smooth samples [2,3]. It can be observed in Figure 1 that the yield strength drops fast up to 100°C after which it further monotonously decreases slowly at temperatures up to 250°C.

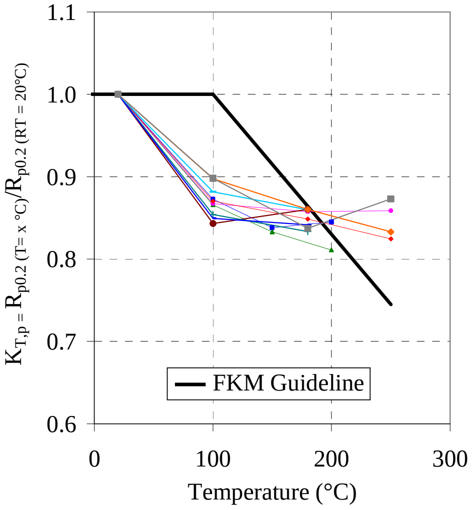

Figure 1: Yield stress ratio T vs. RT compared to experimentally determined values

If no data are available, customers often revert back to general design guidelines, e.g.[4], to dimension their machines. In Figure 1, the values in this particular guideline are compared to experimental results.

As can be seen from Figure. 1, the general design guideline assumes no change in yield stress up to 100°C, which results in a non-conservative design. The difference depends on the specific grade and can mount up to 15%. It is to some extent attributed to the high Si concentration in electrical steels which has a pronounced effect on the yield stress in that temperature range [5].

Former work [2,3] has also shown that the tensile strength of these steels behaves non-linearly with temperature. After a first drop at 100°C, the tensile strength increases again with temperature. This phenomenon is attributed to a combination of dynamic strain ageing and short-range ordering of Si atoms.

In general guidelines the fatigue properties are often derived from the tensile strength. Therefore care should be taken with the estimation of fatigue properties at elevated temperature seen the non-linear behaviour of tensile strength with temperature.

The fatigue limits at elevated temperatures of these electrical steels are also planned to be determined experimentally

3 Effect of stress concentrations on fatigue behaviour

In reality, the electrical motor laminations are punched and contain notches giving rise to stress concentrations. These are of particular interest for sharp geometries for particular teeth / slot edges and permanent magnet geometries.

An experimental campaign to characterize the behaviour of electrical steel under stress conditions was set up as little quantitative data has been published on this subject for this steel type. The aim was to investigate if guidelines for steel in general as described for example in [4] are still applicable to (high alloyed) electrical steels and to investigate the associated fracture mechanisms.

3.1 Experimental procedure

In stress based design approaches, which assume only elastic behaviour, the design ensures that the stress in a critical area is lower than a maximum allowed stress. If the design is limited by fatigue, this stress will be compared to the fatigue limit obtained on smooth samples at a specified amount of cycles. However, this can result in a very conservative design if the critical area is in the vicinity of a notch. In these cases, the fatigue strength is not reduced by an elastic stress concentration factor K_t, but with a fatigue notch factor K_f ($K_f < K_t$). This can be explained by the theory of reduction of peak stress through cyclic yielding at the notch root [6]. The exact value of K_f depends on the mechanical properties of the material. Therefore, notch effects on M330-35A electrical steel were experimentally assessed using axial force controlled fatigue experiments on notched samples with an elastic stress concentration factor K_t = 2.2. (Note that the M330-35A is a general base reference for electrical machines in automotive traction applications.) The test parameters are shown in Table1 and the sample geometry in Figure 2.

Table1: Test parameters

Loading type	Axial force controlled
Test machine type	Servo hydraulic
Test frequency	30 Hz
Load ratio R (S_{min} / S_{max})	0.1

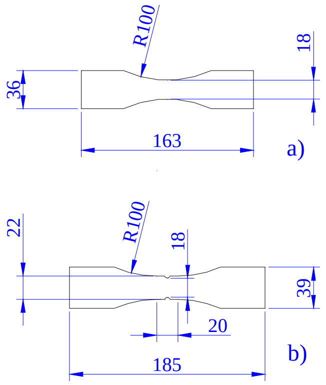

Figure2: Sample geometry a) smooth, b) with notch, K_t = 2.2

3.2 Results

The results of the comparison of fatigue limits on smooth and notched M330-35A samples are shown in Figure 3. The S_{max} stress values are calculated based on the net section, i.e. using a nominal width of 18 mm.

For non-notched samples and a load ratio of 0.1, the guideline [4] predicts an endurance limit of 470 MPa. This prediction is based on the ultimate tensile strength of the material but is well in line with the experimentally determined fatigue limit of 464 MPa.

Concerning notch sensitivity, the fatigue experiments give a fatigue notch factor $K_{f,,exp}$= 464/268 = 1.7. The guideline in reference [4] estimates K_f based on R_m and the related stress gradient in the vicinity of the notch using formulas (1) and (2).

$$\overline{G}_\sigma = \frac{1}{\sigma_x^e}\cdot\left(\frac{d\sigma(x)}{dx}\right)_{x=0} \approx \frac{2}{r} \qquad (1)$$

$$\frac{K_t}{K_f} = 1+\sqrt{\overline{G}_\sigma\cdot mm}\cdot 10^{-\left(a_G+\frac{R_m}{b_G\cdot MPa}\right)} \qquad (2)$$

For the considered case, the design guideline predicts K_f = 1.9. This is slightly non-conservative with respect to the experimental results. It should be noted that these values should only be applied to quasi elastic conditions where the stresses remain elastic with little plasticity in critical locations.

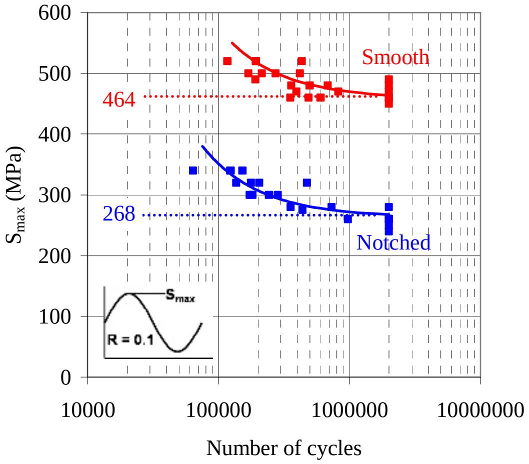

Figure3: Fatigue results on smooth (red) and notched (K_t = 2.2, blue) M330-35A samples using R = 0.1 and f = 30 Hz, Stromeyer fit

3.3 Fracture surface analysis

To interprete the obtained experimental data, the fracture surface was investigated using Scanning Electron Microscopy (SEM). The locus of the fatigue crack initiation is shown in Fig.3a.

This area is limited in size and exhibits fatigue striations smaller than 5 µm. In a the larger surroundings, a fracture appearance as in Fig.3b was observed. The fracture mode in this area is cleavage-transgranular with striations every 7-12 µm. The cleavage transgranular nature indicates a fast propagation of the crack which could have been influenced by the loading conditions. In this study, a test frequency of 30 Hz is used to limit the test duration whereas the mechanical loading frequencies in real operation conditions are much lower (< 1 Hz). Theoretically, this difference in test frequency and thus strain rate could lead to too conservative input data since steels with a high Si content (~3wt%) have been reported to exhibit twinning under these specific conditions [7]. This is of importance because the early fatigue damage mechanisms, linked to the persistent slip band appearance and coming from the edge and screw dislocation activities under cyclic loading, could be disordered by twinning. Since the initiation phase is shorter for notched samples, these can be more affected by this effect. This theory is subject to further investigations as the exact fracture mechanism can depend on other microstructural features like grain size, inclusions and crystallographic orientation [8,9].

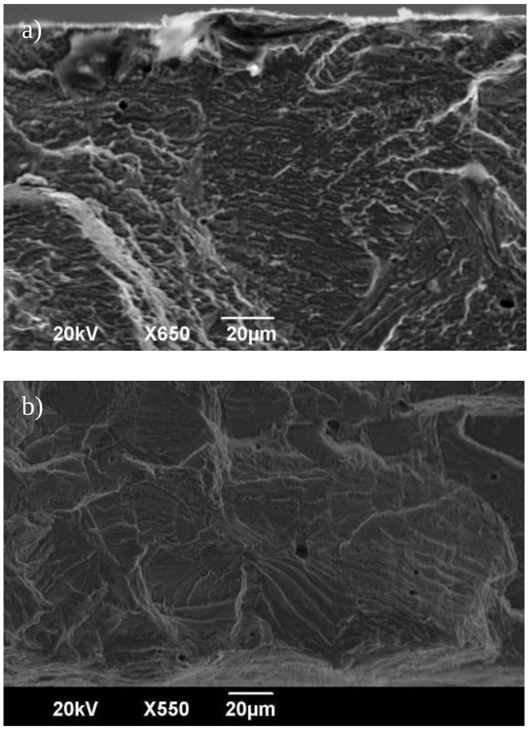

Figure4: SEM analysis of fracture surface a) initiation area, b) example of propagation area

The crystallographic orientation is reported to be less relevant for the crack propagation path. Shimojo [9] reports that the fatigue striations are not formed crystallographically on special planes, but are formed provided that fatigue cracks grow perpendicular to the loading direction regardless of crystallographic orientation.

Opposite to common brittle fracture theories, no preferred crack propagation along {100} crystallographic planes was observed by EBSD analysis of a cross section of a fatigue fracture surface of a M235-35A sample. Figure 5 shows a trough thickness Inverse Pole Figure (IPF) mapping along the normal direction near the fracture surface (left edge of the mapping. The fatigue crack has initiated in grain “g1” and has propagated trough the sample. The absence of orientation gradients near the fracture surface indicates that the fracture was brittle, except for the bottom grain, supposing a ductile rest fracture. The orientation of the fracture directions are ,indicated by the solid arrows, were determined and are plotted in a separate stereographic projection. It shows that the crack direction is of the type <uuw> with Miller indices u and w different from zero. The latter excludes that cracks are propagating along {100} directions. It rather indicates that the crack propagates along {110} planes which was also observed in [10].

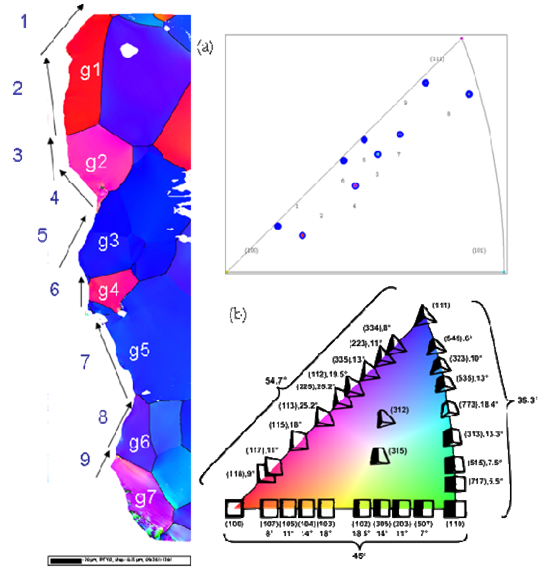

Figure 5: IPF mapping in the thickness direction of the fracture surface and stereographic projection of the fracture directions.

4 Effect of punching on fatigue behaviour

The fatigue behaviour of punched electrical steel is largely determined by the quality of the punched edge. The effect of cut edges on fatigue properties was characterised before for automotive structural steels. The S-N curve of punched samples is expected to drop app. 20% compared to the one of polished samples. Based on this experience, a preliminary estimate for the effect of punching on the endurance limit of a M330-35A electrical steel is given in Figure 6.

To confirm the location of the assessed fatigue curve, a limited number of fatigue tests have been performed on samples produced by Electro Discharge machining (EDM).

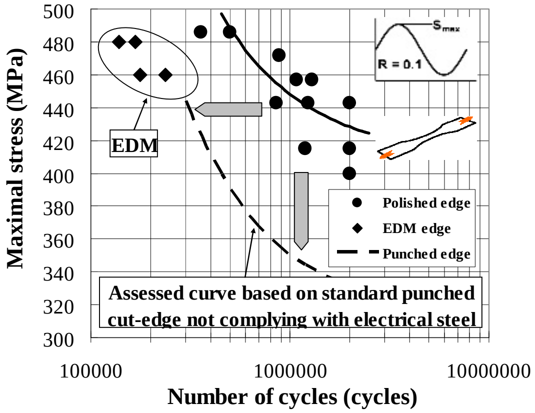

Figure 6: Estimate for the punched edge effect on fatigue behaviour of M330-35A(R = 0.1, f = 30 Hz)

The edges of such samples generally have a shallow hardened layer of molten material and contain many microscopic cracks whereas a punched edge generally has a work hardened zone with very few cracks. Therefore the EDM samples are assumed to be at the lower boundary of the fatigue curve. As can be seen from Fig.6 these obtained results were indeed found to be conservative.

To provide more accurate data for the effect of a punching on fatigue, a tool enabling the manufacturing of laboratory fatigue samples with representative punched edges is needed. Therefore, a dedicated tool was produced by Bourgeois, an experienced puncher in the field of electrical steels (Fig.7).

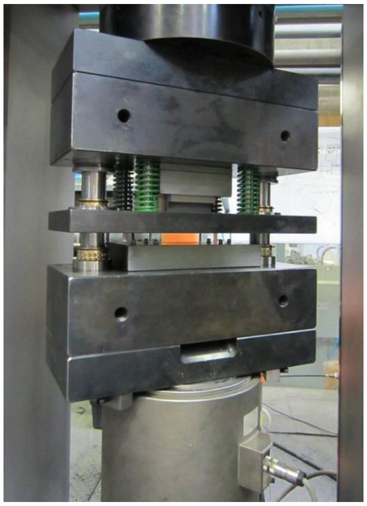

Figure7: Laboratory tool for manufacturing of fatigue samples with representative punched edges

The tool can be mounted in an instrumented high speed laboratory hydraulic press allowing realistic punching speeds up to 1 m/s. By comparing the data with data generated on samples with polished edges, the effect of punching on the fatigue will be quantified.

5 Conclusion

ArcelorMittal has not only developed new line of electrical steel grades for automotive traction machines, called iCARe^{TM}, but also provides its customers with advanced magnetic and mechanical characterisation data. This allows machine designers to make tighter machine designs, by replacing general design rules with accurate calculations, allowing to operate nearer , yet below the limit of the material performance..

Compared to the design rules in a commonly used guideline [4] and based on the experimental results till date, it was found that:

- The dependency of the yield strength on the temperature is not correctly taken into account for the investigated electrical steels.
- The predicted median endurance limit is in line with experimental results.
- The prediction of the effect of a notch on fatigue behaviour is slightly non conservative due to non-standard fracture mechanics which are typical for high Si steels.

The effect of punched edges has been estimated based on experience on other steels and will be investigated in more detail in future.

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Authors

Ir. Sigrid Jacobs graduated in electro-technical engineering at Ghent University and obtained an MBA at the Vlerick School for management, Belgium. After developing electrical steels at the metallurgy lab of the Ghent university, she joined the ArcelorMittal group and was involved in engineering projects. Now she is portfolio director of the group’s R&D activities in Electrical Steels.

Dr. ir. Lode Vandenbossche graduated in electromechanical engineering at Ghent University. He studied the link between magnetic properties and the microstructure of steels at the UGent Electrical Energy Lab, resulting in a PhD about magnetic non-destructive evaluation of material degradation. Currently he works at ArcelorMittal Global R&D Ghent, where he is performing research on electromagnetic applications and electrical steel solutions.

Ir. Dennis Van Hoecke graduated in mechanical engineering at Eindhoven University of Technology. After starting his career at an engineering office, he joined the ArcelorMittal group as a research engineer. Now he is team leader applications and solutions taking care of the advanced mechanical characterisation of ArcelorMittal products in the Ghent R&D lab.

Dr-Ing. Bastien Weber gratuated in mechanics engineering and PhD in durability from the National Institute of Applied Sciences of Lyon (France). After five years spent in the development of steel solutions for packaging in ArcelorMittal, he joined the Arcelor-Mittal Automotive Products research centre as research engineer in durability. Now he is program leader in Fatigue, Crash & Fracture for the Automotive R&D activities.

Emmanuel Attrazic is a superior environment technician. After acquiring production experience in the electrical steel production site of St.-Chély d’Apcher (ArcelorMittal), he joined the plant’s metallurgy-quality lab. He further specialised in mechanical and magnetic measurements, beyond the needs of routine production.