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Fatigue behaviour of thin Fe-Si steel sheets for electric motor production

G Fortese[1], G Nicoletto[1] and E Riva[1]

[1] University of Parma - Department of Engineering and Architecture,
Parco area delle Scienze, 181/A, 43124 Parma (Italy)

Corresponding author's e-mail: giovanni.fortese@unipr.it

Abstract. The on-going evolution toward electric/hybrid traction requires the development of high-performance electric motors. The rotor of electric motors is made from a stack of thin steel sheets and a complex configuration of magnets. Electric steels are typically Fe-Si alloys where Si addition controls grain size. Mechanical durability assessment of electric motors is based on the fatigue performance of Fe-Si steels.
This contribution reports a thorough mechanical characterisation of a Fe-Si alloy in the form of thin (i.e. 0.2 mm) sheets. Numerous tensile tests were performed to characterize the reference static properties and their respective scatter. A suitable fatigue testing procedure for thin sheets was developed and used in an extensive campaign aimed at investigating the directional fatigue behaviour of the Fe-Si steel. Comparison with literature data confirms that the fatigue response of thin sheets is affected by different factors related especially to the method of extraction.

1. Introduction

The increasing interest in environment protection and in pollution reduction over the last years, has led to consider different propulsion systems in transportation industry, which is responsible of almost 50% of worldwide carbon monoxide production. Increasing adoption of electric motor power in vehicle propulsion is motivated by a reduction of external impact, [1]. Nonetheless, performance and reliability remain design concerns that drive innovation.

There are different technologies employed for electric motors production, but the most common considers the use of Permanent Magnets (PM) inside the rotors [2]. Such rotors, see an example in Figure 1(a), are obtained by stacking thin electrical steel sheets, typically thickness of a few hundred microns, with the presence of openings in which magnets of different shapes are fixed with adhesives, Figure 1(b).

Depending on the material, the PM technology can ensure high performance and low electromagnetic losses. The most widely used magnetic material is neodymium iron boron (NdFeB), which belongs to the so-called rare-earth magnets. Such magnets typically have a very high remanence (i.e. residual magnetization in a ferromagnetic material after an external magnetic field is removed) and, therefore, are particularly suitable for high torque and high-power-density applications. Nevertheless, the high price and limited availability can request, for some low-cost application, their replacement with ferrite magnets. Their reduced electromagnetical performance lead to lower torque and speed ratings at equal size and weight. Besides, as emphasised by Sarlioglu et al. [1], the higher the temperature the more difficult is the demagnetisation of ferrite magnets whereas rare-earth materials show opposite behaviour. For these reasons, rare-earth materials are typically employed in high-performance environments [3], whereas ferrite magnets are the optimal choice where costs saving is the priority.

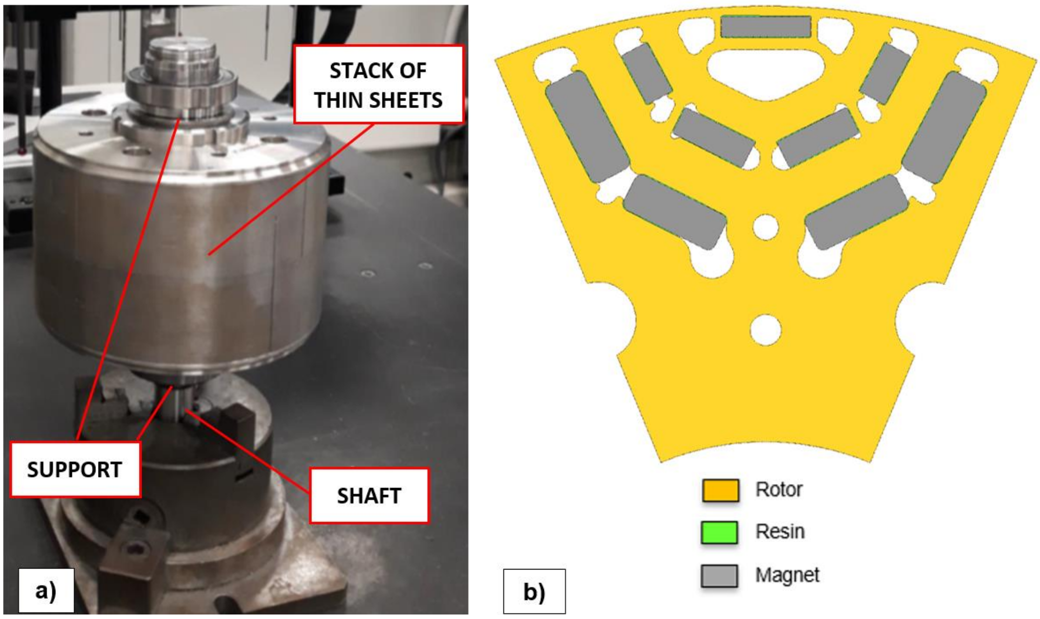

Figure 1. Rotor schematisation (a) and portion of rotor thin sheet (b).

From the electromagnetical point of view, Lovelace et al. [4] underlined how bridges surrounding the magnets cavities create a sort of magnetic short circuit, reducing the performance of the steel sheets. On the other hand, from the mechanical point of view, the same bridges are required to sheet continuity and to adequate thermo-structural resistance, especially in high-performance situations. High speed rotation typical of electric rotors generates centrifugal forces. Since PMs are less stiff than the electrical steel, their deformation due to centrifugal forces translates into additional loading of the steel bridges, [4].

A compromise between electromagnetic and thermo-mechanical behaviour is sought through a shape optimisation process and this paper is concerned with the mechanical implications. Parameters that can influence shape optimisation are discussed in [4-7] in terms of stress reduction: radius of holes, which acts as stress concentrators; addition of ribs to lamination geometry, which opposes to centrifugal stresses; rotor sheet material, which affects yield stress and core losses; maximum rotor speed, and finally rotor diameter. In particular, the latter influences the radial deflection, and so the deflection of the boundaries which directly affects the stress concentrations near bridge edges. An example of the FEA stress field contour of a rotor steel sheet during service condition is shown in Figure 2. Clearly, a preliminary complete knowledge of the thin sheet material response is needed to set critical conditions for the shape optimisation process.

Electrical steel can be described as a mild steel (i.e. low carbon content) rich in Silicon (generally 3%) and with a rather coarse microstructure (grain size of the order of 0.1 mm). As a consequence, a thin sheet contains only few grains in the thickness, and their interaction with the surrounding may be more relevant with respect to thicker materials [8].

Manufacturers know how to tailor both the mechanical and the electromagnetical behaviour of electrical steels by modifying Si content, increasing grains size and reducing sheets thickness [9,10]. From the electromagnetical point of view, the higher the Si content, the higher the electrical resistance and the lower the power loss. However, if Si content increases, magnetic saturation induction decreases and therefore torque decreases. So the Silicon content is chosen depending on the application.

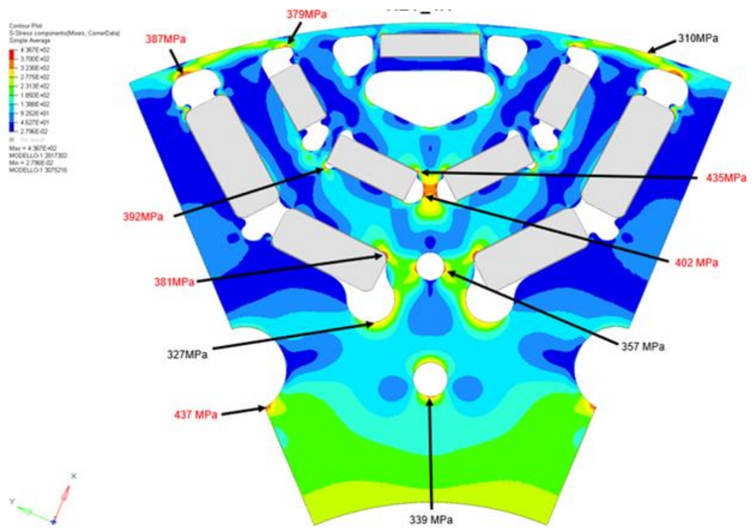

Figure 2. Example of FE stress field contour of a rotor steel sheet during service condition.

From the mechanical point of view, several factors can affect the mechanical performance of electrical thin sheets. First, they are usually shaped with punching operations, to reduce time and fabrication cost. Punching represents the most economic cutting technique [10], but also particularly affects the edge quality, both geometrically and material-wise. Several studies show that considerable geometrical defects can form at edges thus negatively affecting especially the fatigue behaviour [8,10-13]. In fact, such defects play the role of stress concentrators, and consequently may represent crack initiation points, reducing fatigue life [10,13]. Haefele et al. [14] studied the effect of different cutting techniques, and found that punched specimens show fatigue strength reduction up to 30% with respect to polished ones. Similar results are found by Dehmani et al. [15,16], who observed that removing visible defects with simple silicon carbide paper, after punching operations, can significantly improve fatigue strength. This is mainly due to geometrical defects removal and modification of residual stresses. Same authors [16] found that by annealing specimens after cutting processes can improve fatigue strength of punched specimens but, at the same time, slightly reduce fatigue strength for polished ones. This evidence is proposed to be probably due to the recrystallization of a region 50μm deep, transforming large grains into small ones and significantly reducing hardening in such a region. Punching operations may induce localised high level of hardening due to plastic strains and crystal dislocations: this aspect can lead to a deterioration of both magnetic and mechanical properties [12,17-20], and reducing fatigue life of the entire component. A consequence is the presence of non-negligible residual stresses at edges that may significantly affect the fatigue behaviour [10,12,18,21]. Secondly, electrical thin sheets are generally produced by rolling processes and, according to Moses [22] electrical steel sheets can be: i) grain-oriented, typically employed in static working conditions where designers can take advantage of best performance in the rolling direction; ii) without grains orientation, usually chosen when stress condition does not have a preferred orientation. For rotors of electric motors, due to their centrifugal state of stress, isotropic grain solution is usually chosen. Thirdly, openings for magnets accommodation represent stress concentration zones [23], independently of the cutting processes. This aspect is to be considered in designing electrical steel rotors, [24], because localised plasticity favours cracks initiation.

In recent years, the development of high performance electric motors has introduced stricter design requirements such as: weight and size reduction, increased speed range, high reliability without unexpected failures and, last but not least, reduced production costs. Therefore, a thorough understanding of electrical steels mechanical and fatigue behaviour appears of fundamental importance for the design of reliable electric motor components.

The main objective of the present contribution is to report a thorough mechanical characterisation of a commercial electrical steel, in the form of very thin sheet (i.e. 0.2mm), under static and fatigue loadings. Comparison with literature data highlight different factors affecting fatigue life, first of all the extraction method which may produce defects and induce residual stresses.

2. Material

The material analysed in this study is a non-oriented grain (NO) electrical steel, named NO20-1200 in accordance with EN10303 standard. More precisely, such electrical steel belongs to the category of ultra-thin electrical steel, a recently developed version of classical NO electrical steel that is characterised by very small thickness but, at the same time, maximum magnetic permeability and minimum power loss. Such characteristics make NO20-1200 electrical steel particularly suitable for high speed electric rotors. It is provided in the form of rolled sheet, with nominal thickness of 0.2 mm, and coated with a thin insulating layer which was not removed during the present tests, to preserve real application conditions.

For the experimental campaigns described in the next sections, smooth specimens were extracted from thin sheets by laser cutting along three different directions with respect to the rolling direction: 0°, 45° and 90°. The specimens' geometry is defined from ASTM E-8M-08 standard and shown in Figure 3. This geometry is employed for both static and fatigue tests. Light manual polishing of specimen edges with silicon carbide sandpaper was sometimes required to remove macroscopic defects.

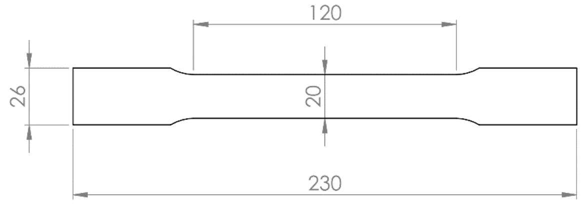

Figure 3. Geometry of the specimens employed for both static and fatigue tests.

3. Experimental campaign

The objective of the experimental campaign was to adequately determine mechanical and fatigue parameters of the electrical steel sheets to understand their behaviour and to provide experimental data to be used in FEA modelling, to accurately simulate rotor working conditions in service. Therefore, monotonic tensile and high cycle fatigue tests were performed and are described in the next sections.

3.1. Tensile tests

Monotonic tensile tests were carried out at different temperatures, by employing an MTS810 servo-hydraulic testing machine, with digital control system RT3 developed in LabView environment. Between the tested specimens and the jaws of the fixed and the movable heads, pieces of the same tested electrical steel were interposed to efficiently apply machine loads and to avoid unwanted failures at the clamped zones. Tests were all carried out under movable head displacement control at a speed equal to 0.02 mm/s. Applied forces, displacements of movable head and strain measurements of an extensometer placed in specimens' net zone, were continuously measured and recorded.

3.1.1. Room temperature. Tests at Room Temperature (RT) were performed on:
- 10 specimens with rolling direction at 0°;
- 3 specimens with rolling direction at 45°;
- 4 specimens with rolling direction at 90°.

The high repeatability of tests at 45° and 90° rolling directions (RD) justifies the reduced number of tested specimens, being sufficiently representative of the analysed direction.

Mean values of Elastic Modulus, E, yield stress, R_{p02}, and maximum stress, R_m, are reported in Table 1 together with standard deviations, in brackets, for every rolling direction: apparently the specimens at

45° RD show the best performance. The percentage difference with respect to the other RD is also given in Table 1. Data show that both yield stress R_{p02} and maximum stress R_m are only slightly dependent on RD, whereas the elastic modulus E shows more marked difference, about 22%, between worst and best RD.

Table 1. Mechanical parameters for different RD and difference respect to best RD.

	Mean values *(Std. Dev.)*			**Difference respect 45° RD**		
RD	***E***	***R_{p02}***	***R_m***	***E***	***R_{p02}***	***R_m***
	[GPa]	[MPa]	[MPa]	[%]	[%]	[%]
0°	156.7 *(3.4)*	427.1 *(3.8)*	523.7 *(3.4)*	-22.2	-5.6	-3.8
45°	201.6 *(1.8)*	452.6 *(0.2)*	544.4 *(2.4)*	-	-	-
90°	183.7 *(3.4)*	438.4 *(0.4)*	538.3 *(0.9)*	-8.9	-3.1	-1.1

3.1.2. High temperatures. Because of real electric motor application, monotonic tensile tests were also performed at temperatures different from RT, that is 100°C and 150°C. The experimental setup was analogous to previous tests at room temperature, with the addition of an extra-system for specimens heating, shown in Figure 4.

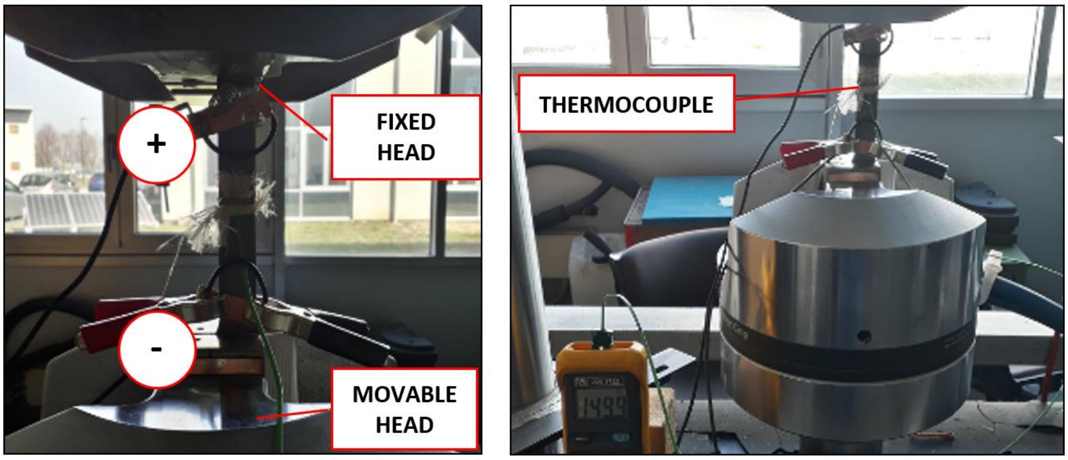

Figure 4. Experimental setup for monotonic tensile tests at both 100°C and 150°C.

The system consisted in a power-supply with a voltage regulator connected to the specimens. Exploiting Joule's law, electric current flowing through the specimen heated it up and the voltage was accurately regulated to reach and maintain the desired temperature, by the use of a thermocouple.

Tests were performed on 10 specimens per temperature, considering only 0° RD being such a direction the one that experienced worst performances at RT. Results are summarised in Table 2. Apparently the test temperature has a slight effect on elastic modulus E and maximum stress R_m, whereas the reduction of yield stress R_{p02} is considerable with increasing temperature (i.e. a 15% reduction at 150°C).

Table 2. Mechanical parameters for different temperatures and comparison with RT.

	Mean values *(Std. Dev.)*			**Difference respect RT**		
Temperature	***E***	***R_{p02}***	***R_m***	***E***	***R_{p02}***	***R_m***
[°C]	[GPa]	[MPa]	[MPa]	[%]	[%]	[%]
100	146.7 *(8.2)*	372.7 *(3.5)*	504.7 *(10.7)*	-6.4%	-12.7%	-3.6%
150	149.8 *(8.8)*	361.7 *(6.4)*	519.0 *(8.8)*	-4.4%	-15.3%	-0.9%

3.2. Fatigue tests

Fatigue tests were carried out at RT on a resonant fatigue testing machine schematically shown in Figure 5. Such a machine exploits the resonant principle and applies a cyclic loading at high frequency (dependent on mass and stiffness of the system) with an important test energy reduction (about 90%) compared to a traditional fatigue machine.

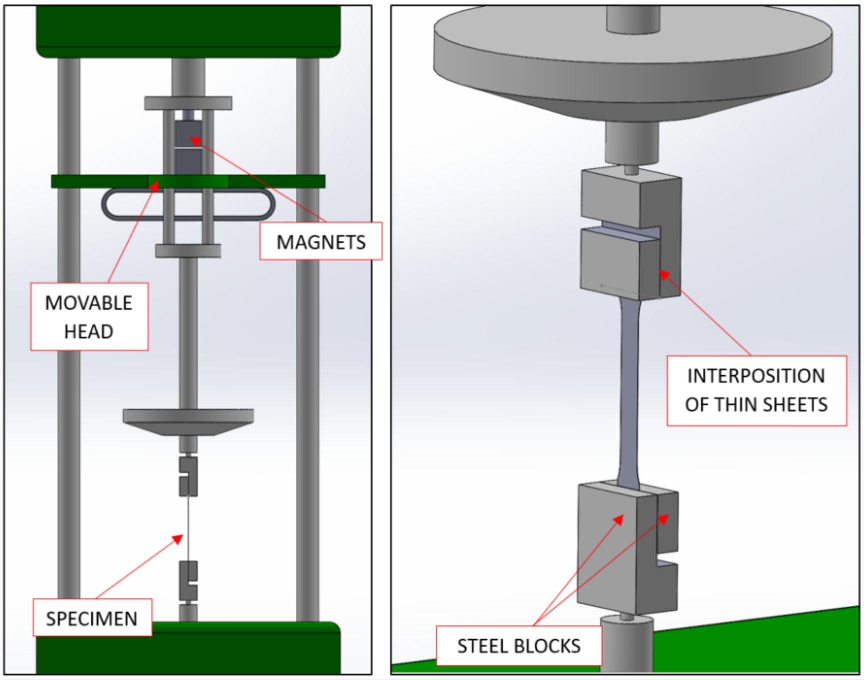

Figure 5. Schematic representation of experimental setup for fatigue tests.

Fatigue tests were conducted in the high cycle regime under load control. By considering the specimen sensitivity to buckling and loading conditions of electric rotors, pull-pull tests with a load ratio R=0.1 were performed. All tests were conducted at a loading frequency of about 74Hz. Tests were stopped at specimen failure (visible crack with a reduction of test frequency greater than 2Hz) or when a run-out (RO) of 10^6 cycles was reached without specimen failure.

Mean stress was applied by translating the movable head, retroacting the measurement of a load cell until the desired value was reached. Stress amplitude, instead, was applied by the excitation of magnets, placed in the upper part of the machine. The specimen was clamped at each end between two steel blocks pressed together by bolts, by interposing a layer of thin sheet (the same of tested specimens). This method avoided unexpected failures in clamping zones. Fatigue tests were performed on:

- 6 different levels of loading for RD equal to 45°;
- 2 different levels of loading for RD equal to 90°;

For each level of loading, at least 5 specimens were tested.

3.2.1. Results and comparisons. Experimental results, in terms of maximum stress vs number of cycles to failure, are shown in Figure 6 in black (45° RD) and in grey (90°RD). It can be seen that the S-N curves are very close, but the one related to 90° RD is slightly translated down with respect to 45° RD. Such curves can be described by the equation $S=CN^{\alpha}$, being α and C two parameters describing the slope and the intercept of the curves with the ordinate axis. Values of α and C are reported in Table 3 for each RD considered, together with fatigue limits at different reliability levels. The influence of RD is quite limited: 45° RD data show a fatigue limit slightly higher (about 1%) with respect to 90° RD data, and the same may be said for S-N curve slope.

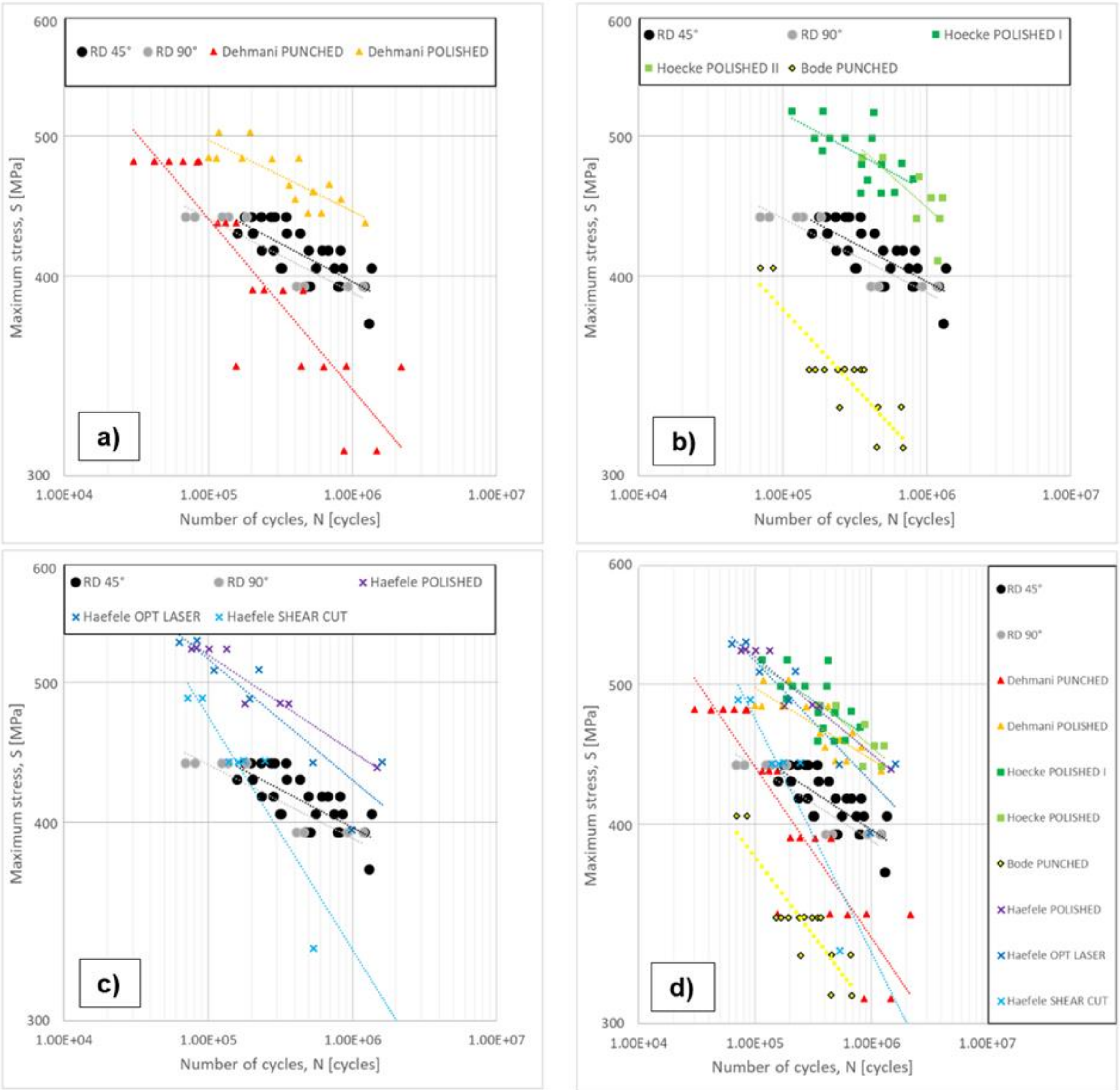

Figure 6. S-N curves comparison between results obtained by the author and: Dehmani et al. [16] (a); Van Hoecke et al. [23] and Bode et al. [9] (b); Haefele et al. [14] (c); and all previous Authors (d).

Table 3. Parameters of S-N curves and fatigue limits at different reliability level.

RD	*C*	*α*	σ_{LF} *(10%)* [MPa]	σ_{LF} *(50%)* [MPa]	σ_{LF} *(90%)* [MPa]
45°	808.5201	-0.0505	419.3	402.4	388.5
90°	777.6757	-0.0488	408.9	396.3	384.1

The different plots of Figure 6 show comparisons of the present test results with experimental results obtained by different authors, related to similar materials tested in similar ways but with different cutting processes. In particular, Dehmani et al. [16] tested a M330-35A electrical steel, punched-and-polished and only punched. Results are compared in Figure 6(a). As can be expected from literature evidence, laser cut specimens tested by authors stay inside the area enclosed by polished specimens and punched ones, being these alternatives forming techniques characterised by smaller and larger defects, respectively, compared to laser cutting. Figure 6(b) shows a comparison of the present data with M330-35A polished specimens tested by Van Hoecke et al. [23] and a NO electrical steel tested by Bode et al. [9] and obtained by punching. In this case as well, specimens tested by authors lie between polished and punched specimens. Haefele et al. [14] carried out a relevant experimental campaign on NO30-15 specimens extracted by polishing, punching and laser cutting techniques with optimized parameters. The comparison shown in Figure 6(c) demonstrates that specimens extracted with general laser parameters tested by the present authors show lower fatigue strength with respect to both polished and optimized laser cut specimens tested by Haefele et al. As Haefele suggests [14], this aspect is strictly linked to surface roughness generated during extracting technique particularly severe on fatigue life.

Figure 6(d) summarizes all experimental results considered in the previous comparisons: clearly, despite tested materials are similar, the fatigue behaviour can vary consistently, as a consequence of different defects generated along specimen edges. In fact, the scatter is more pronounced in punched specimens, with respect to polished ones.

So specimen forming technique has a fundamental role in fatigue behaviour of this kind of thin electrical steel: Figure 6 points out that fatigue strength of punched specimens can drop by 30% with respect to polished ones and the same holds for S-N curve slope. Figure 6(d) also shows that a linear trend can be clearly defined for polished specimens, whereas the same cannot be said for laser cut and punched ones.

3.3. Comparison with FKM guidelines

Experimental results shown in previous paragraphs are in this section compared with FKM guidelines. The objective is to understand if FKM recommendations are applicable to thin sheet components design, thus confirming FKM as a suitable design tool and avoiding expensive experimental campaigns.

Regarding tensile behaviour, yield stress trend with temperature reported in Table 2 clearly shows a considerable reduction from RT up to 100°C decreasing then slowly until 150°C. Figure 7(a) shows the present results along with those found by Van Hoecke et al. [23] on a similar material named M330-35A according to EN10106 standard. General design behaviour provided by FKM guidelines [25] is also shown. Results are expressed in terms of Yield Stress ratio, assumed as the ratio between yield stresses at a specific temperature against yield stress at RT. It is interesting to note that Van Hoecke and the present experimental results are in good agreement, whereas prediction provided by FKM assumes that yield stress remains constant up to 100°C, resulting in a non-conservative design at this temperature. As Van Hoecke et al. suggested [23] such a difference can be attributed to the high content of silicon in electrical steels, considerably affecting yield stress in this temperature range, in accordance with Leslie [26]. Moreover, some studies available in the literature [27,28] show that maximum stresses, after a first drop typically around 100°C, can slightly increase with temperature as with the experimental results shown in Table 2. Authors suggested that this phenomenon can be attributed to a combined effect of dynamic strain ageing ordering of Silicon atoms in the short range.

Regarding the fatigue behaviour, experimental results obtained from tests presented in the previous section are compared with FKM S-N curves provided for a typical non-welded steel. FKM guidelines generally provide S-N curves related to a fully reversed condition, that is R=-1. Therefore, for an adequate comparison, experimental results are scaled from a R=0.1 to a R=-1 exploiting Haigh's relation. The comparison is shown in Figure 7(b), together with Juvinall suggestions [29] for the same material. For high cycle fatigue regime (that is, cycles > 10^5), FKM prediction always underestimate the fatigue strength of the present material, thus being conservative. Nevertheless, the slopes of S-N curves are rather different: FKM curve is more sloped than the experimental ones leading to an underestimation of about 46% of the fatigue limit at 10^6 cycles. On the other hand, Juvinall's prediction shows always a conservative response but the slope is very similar to experimental evidence so the fatigue limit at 10^6 cycles is underestimated by 29%.

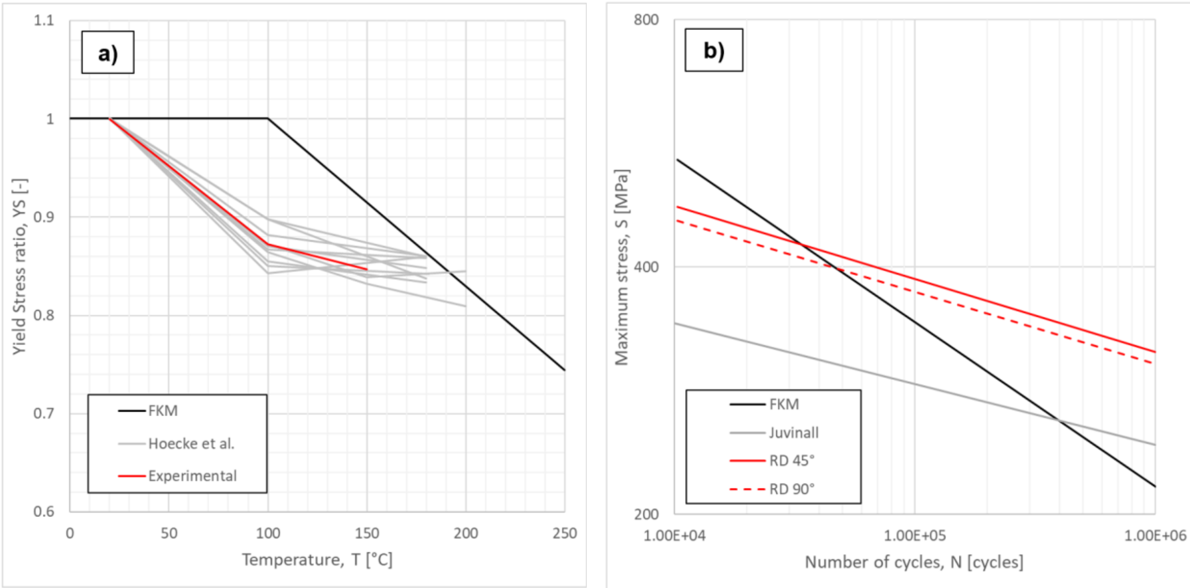

Figure 7. Comparison with FKM guide: yield stress ratio vs. temperature (a) and S-N curves (b).

It is interesting to note that both FKM guidelines and Juvinall suggestions are too conservative in the prediction of the fatigue behaviour of thin steel sheets. This can be due to different aspects, as a consequence to relevant differences between standard specimens employed to define guidelines and thin specimens here studied. First of all, the geometry: thin sheet specimens are not round specimens typically considered by guidelines, and for sure in specimens with very low thickness, grains dimension and position may affect damage mechanisms in a more important way [9]. Then, cutting technique plays also a fundamental role, as previously highlighted, and may induce important residual stresses on edges [10,16], which may have either a beneficial or a detrimental effect.

This comparison suggests that, for a preliminary design, guidelines can be helpful to designers of thin sheets components but at the detailed design stage, specific knowledge of material behaviour, passing through the collection of ad-hoc experimental data, may be needed.

4. Conclusions

The increasing interest in high-performance electric motors has led to an in-depth mechanical durability assessment of all their components: key among them, the rotors. Such rotors are made from a stack of electrical thin sheets with complex magnets configurations. In this contribution, a thorough mechanical characterisation of an electrical NO steel sheet has been carried out. The main conclusions are as follows:

- The static and fatigue response are largely independent of orientation with respect to rolling direction;
- The elastic modulus depends on test temperature in the range RT - 150°C;
- The high cycle fatigue behaviour is strongly influenced by thin sheet specimen extraction technology because of its impact on edge quality;
- Comparison of present data with literature defines the following ranking in fatigue strength: i) punching and edge polishing (best); ii) optimized laser cutting; iii) standard laser cutting and iv) punching (worst);
- FKM guidelines are conservative and acceptable at preliminary rotor design stage only, while component durability assessment requires actual thin-sheet-technology-dependent properties.

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