Experimental evaluation of the punching impact on the dynamic magnetic performances of M330-35A SiFe steel

Oualid Messal[1], **Afef Kedous-Lebouc**[1], **André Youmssi**[2]

1. Univ. Grenoble Alpes, CNRS, Grenoble INP, G2Elab, 38000 Grenoble, France*
oualid.messal@g2elab.grenoble-inp.fr

2. Université de N'gaoundéré, BP. 455 N'gaoundéré, Cameroun

ABSTRACT. *The punching induces stress in electrical steels. This stress contributes to the degradation of their soft magnetic properties. The high-speed machine design step, specifically, for on board applications (automotive, aircraft generators, etc.), requires the consideration of the influence of both punching and frequency on the magnetic properties of the material. In this paper, thin SiFe soft magnetic characteristics are investigated. To do so, series of rectangular samples of variable width have been industrially punched and then measured based on a mini-Epstein frame. The measurements have been conducted from 50Hz to 1kHz and from 0.3T to 1.7T. Both longitudinal and transverse directions have been explored and the results are presented in an effort to supply the most relevant conclusions concerning the degradation of the dynamic magnetic characteristics.*

RÉSUMÉ. *La découpe mécanique par poinçonnage des aciers électriques induit une détérioration de leurs caractéristiques magnétiques et en particulier les pertes, propriété capitale dans un contexte d'efficacité énergétique. Ainsi, la compréhension et la maîtrise de ce couplage mécanique-magnétique et son évaluation précise constitue une tâche incontournable afin d'intégrer correctement la dégradation due au poinçonnage des alliages dans l'étape de conception et d'optimisation des machines électriques. Dans ce contexte, cet article s'inscrivant dans le cadre du projet GIRTOM, évalue les effets combinés du poinçonnage et de la fréquence sur les performances magnétiques des aciers FeSi, utilisés typiquement dans les applications embarquées. Pour cela, nous avons dû notamment mettre en œuvre un dispositif expérimental adapté et réalisé de nombreuses caractérisations. Les études ont été menées entre 50 Hz et 1 kHz et de 0,3 T jusqu'à la saturation.*

KEYWORD: *electrical steels, frequency, high-speed machines, magnetic characteristics, punching.*

MOTS-CLÉS : *aciers électriques, caractérisation magnétique, fréquence, machines électriques haute vitesse, poinçonnage.*

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Extended abstract

☛ The electrical steels are usually submitted during their industrial process for the manufacture of electrical machines to a succession of many mechanical operations and handlings such as the punching. The latter induces stress in electrical steels. This stress contributes to the degradation of their soft magnetic properties. The high-speed machine design step, specifically, for on board applications (automotive, aircraft generators, etc.), requires the consideration of the dynamic behavior of the materials as well as the degradation of their properties due to this operation. Herein, the influence of punching and frequency on thin SiFe soft magnetic characteristics is experimentally evaluated. To do so, four series of rectangular samples of variable width have been industrially punched and then measured based on a mini-Epstein frame. The measurements have been conducted from 50Hz to 1kHz and from 0.3T to 1.7T. Both longitudinal and transverse directions have been explored and the results are presented in an effort to supply the most relevant conclusions concerning the degradation of the dynamic magnetic characteristics.

1. Introduction

The electrical steels are usually submitted during their industrial process for the manufacture of electrical machines to different mechanical operations and handlings such as cutting, punching, stacking, welding, gluing, and the final assembly step of the machine. Some previous works have reviewed the impact of the manufacturing processes on magnetic properties. Some of them have focussed on the effect of the punching on steel laminations (Carlberg, 1971; Gmyrek *et al*., 2013; Hanyu *et al*., 2017; Kedous-Lebouc *et al*., 2003 ; Kedous-Lebouc *et al*., 2017 ; Moses *et al*., 2000; Nakata *et al*., 1992; Rygal *et al*., 2000; Schmidt, 1976; Schoppa *et al*., 2000a; Schoppa *et al*., 2000b). The latter induces stress inside the electrical steel. This stress is of a sufficient magnitude to cause or contribute to the degradation of the soft magnetic characteristics near the cutting edge region as shown for example in (Rygal *et al.*, 2000). On the macroscopic scale, as revealed for example by (Schmidt, 1976; Moses *et al.*, 2000; Nakata *et al.*,1992), the iron losses and permeability are affected. Microscopically, the dislocations, the internal stresses and the grain morphology are affected. Particularly, the grain size promotes the extent of the degradation (Rygal *et al.*, 2000). Indeed, the degraded area in large-grain size material is much larger than in small grain materials. In certain materials, the degradation can extend few millimeters from the cut edge. This depends on the material itself (Rygal *et al.*, 2000; Carlberg, 1971). Therefore, in the area of on board applications, the design of high-speed electrical machines could involve problems of electromagnetic nature. Indeed, the stator core made of rigid and fine teeth would be subjected to an increase in losses (Kedous-Lebouc *et al.*, 2003; Takahashi, *et al.*, 2008; Liu *et al.*,2014) that can significantly reduce the efficiency.

The iron losses and the ac permeability are important properties in the design of machines with high efficiency. Thus, in order anticipate the change in magnetic characteristics due to the punching in the machine design step, it is necessary to characterize and quantify it. In this framework, the GIRTOM project has sponsored the full evaluation of the punching & frequency impacts on some materials in order to supply basic data on their performances.

Herein, the combined effect of punching and frequency on the magnetization curve and core losses in thin SiFe soft magnetic sheets is experimentally quantified. First, four series of rectangular samples of 15, 10, 5 and 3mm width have been industrially punched. Then, magnetic characterizations have been performed using a mini-Epstein frame. The measurements have been done from 50Hz to 1kHz and from 0.3T to 1.7T (near saturation). Both longitudinal (LD) and transverse (TD) samples have been explored.

2. Sample preparation and experimental procedure

The studied SiFe steel is the M330-35A commercial alloy. It was provided in a strip form of [300×300mm] as shown in Figure 1. To evaluate the effect of the punching on its magnetic properties, four series of mini-Epstein rectangular samples of 15, 10, 5 and 3mm width have been industrially punched and extracted from these strips as shown in Figure 1. Both LD and TD directions was considered. Table 1 gives and compares the maximum relative permeability measured at 50Hz in both LD and TD for a standard Epstein samples. The usage magnetic characteristics of the punched LD and TD samples have been measured. To do so, a mini-Epstein frame dedicated to small laboratory samples of maximum dimensions of 15×100 mm has been used. The latter is associated with the measuring system shown in Figure 2 which combines analog and digital technologies. The measurements have been performed while maintaining sinusoidal induction waveform from 50Hz to 1kHz and from 0.3T to 1.7T.

Notice that the 15mm width punched samples are considered as the reference samples due to the fact that their measured magnetic characteristics were not degraded in comparison with those of the standard Epstein samples of 30 × 300 mm.

Herein, the results at 50Hz are first presented and discussed. After that, we focus on that obtained at higher frequencies. They are presented in an effort to supply the most relevant conclusions concerning the degradation of the magnetic characteristics.

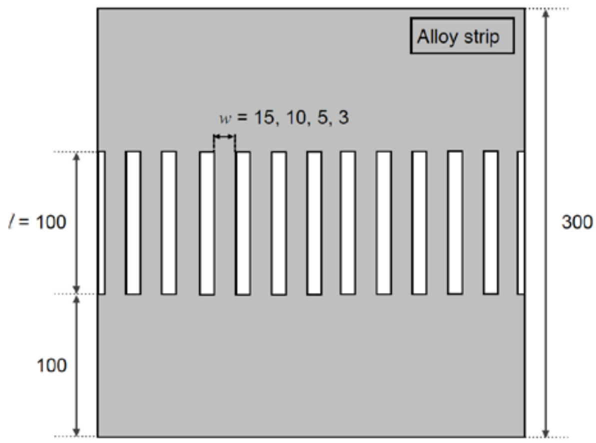

Figure 1. Punched samples preparation (the unit is millimeter)

Table 1. Maximum ac relative permeability (50 Hz) in LD and TD for the investigated grade

Maximum relative permeability		
Grade	LD	TD
M330-35A	8600	4000

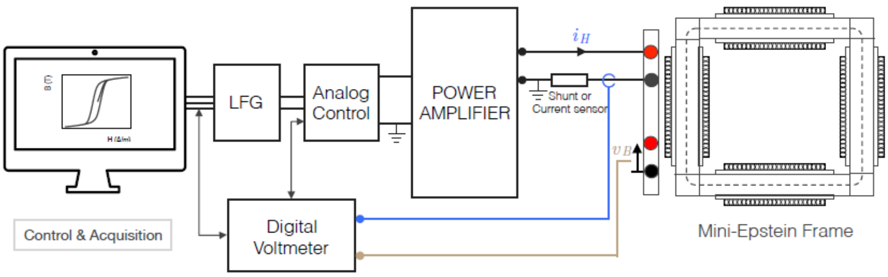

Figure 2. Scheme of the experimental setup

3. Magnetic characterization of the punching impact at 50 Hz

3.1. 50 Hz magnetization curves

Figure 3 displays the 50Hz normal magnetization curves for the M330-35A material respectively measured in LD and TD punched laminations. Let us recall that the lamination width varies from 3 to 15mm.. The curves show clearly that the permeability decreases with the sample width. A similar trend is observed in both LD and TD directions.

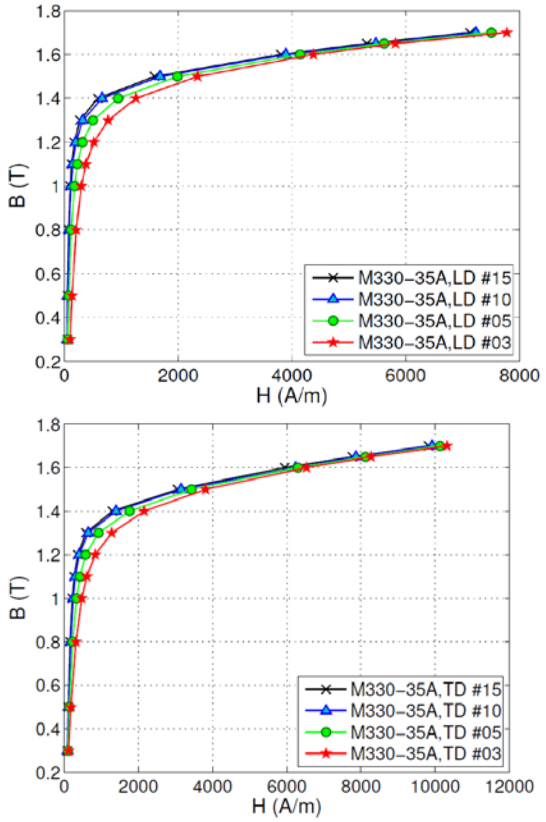

Figure 3. 50 Hz normal magnetization curves of the M330-35A alloy measured in both LD and TD directions (# w denotes the width of the sample in mm)

Figure 4 shows the increase in the applied field strength ΔH/H (in %) for the 3 mm width LD and TD samples. It is evaluated referring to the field applied for the reference samples (15mm width) for the same test frequency and the same direction. ΔH/H is more important in LD than TD and it is maximum around 1.2 T.

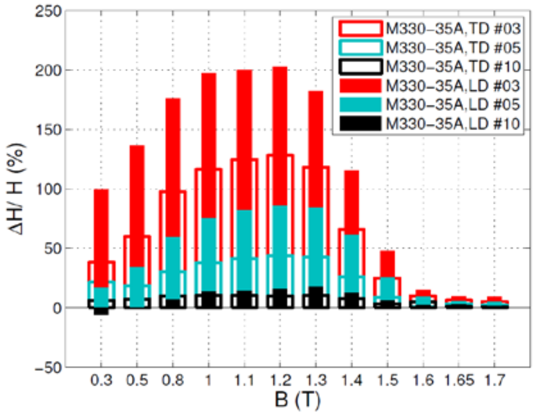

Figure 4. The increase in the applied field strength at 50Hz

3.2. 50 Hz core losses

Figure 5 displays the 50Hz core losses versus induction curves respectively obtained in LD and TD punched samples of the M330-35A alloy. These figures report the normal characteristics of increasing losses with increasing induction.

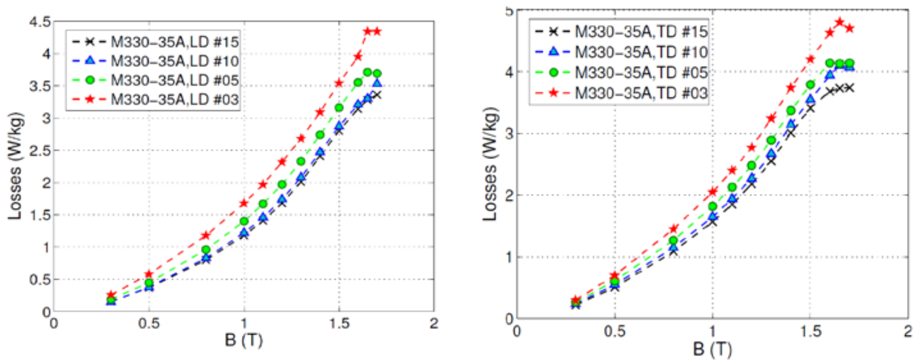

Figure 5. 50Hz loss vs induction curves of the M330-35A alloy measured in both LD and TD directions

3.3. 50Hz loss degradation factor

The degradation of losses induced by the punching can be quantified using a loss ratio ΔP/P defined in relation to the losses obtained in the reference sample of 15 mm width punched laminations. As mentioned before, the magnetic characteristics of 15mm width samples were not deteriorated in comparison with the standard

Epstein sheets. ΔP/P in (%) is called the loss degradation factor. It is analyzed as a function of induction for each sample in Figure 6.

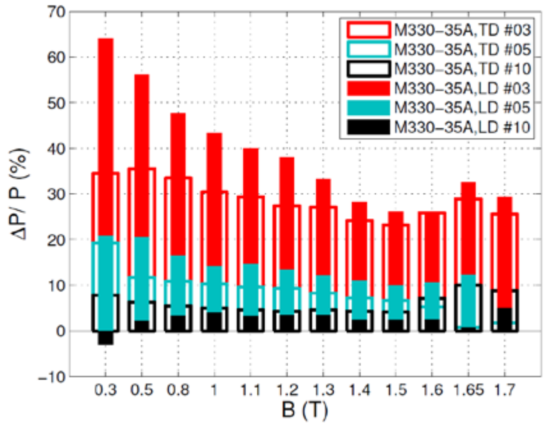

Figure 6. Loss degradation factor of the M330-35A alloy at 50 Hz

On the whole, we can observe ΔP/P varying up and down regularly as a function of induction following a quasi-linear curve for each of the samples. In both LD and TD, as the width decreases, the loss degradation factor increases. Nevertheless, ΔP/P remains higher in LD samples. For the most affected samples of 3mm width, the losses are increased to about 64% of their value at 0.3T. ΔP/P decreases then from 64% to 30% at the maximum induction test value (1.7T). While, in TD it decreases from 35% to about 25%.

4. Joint punching and frequency effect

In this section, we focus on the most degraded samples (of 3mm width) and compare their characteristics as a function of the frequency with the reference samples of 15mm width.

4.1. Magnetization curves

Figure 7 displays the magnetization curves for the M330-35A grade respectively measured in LD and TD samples at various excitation frequencies. It is apparent that the frequency effect is more important in LD than TD.

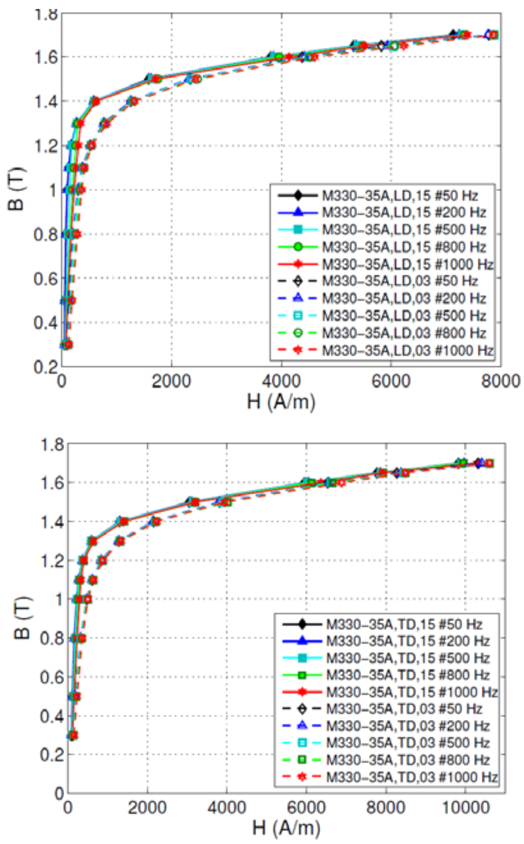

Figure 7. Frequency magnetization curves of the M330-35A alloy measured in both LD and TD directions

4.2. Losses and loss degradation factor

Figure 8 shows the core loss *versus* induction curves at variable frequency from 50Hz to 1kHz obtained in LD punched laminations, both 15 and 3mm. One observes the normal characteristics of increasing losses with increasing induction and frequency.

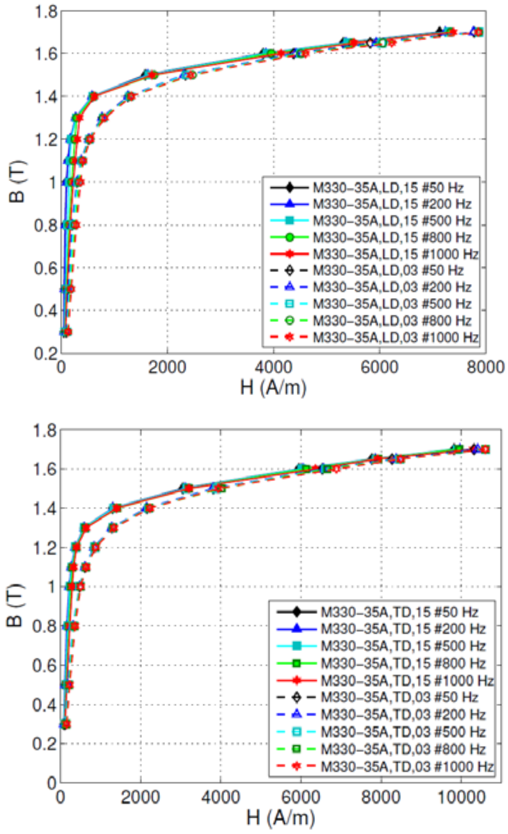

Figure 8. Core loss versus induction curves at various excitation frequencies for the M330-35A alloy measured in both LD and TD directions

5. Conclusion and prospects

In this paper, an experimental work has been performed to characterize the effect of both frequency and punching on magnetic properties of soft magnetic steel typically dedicated to high-speed electrical machines. The behaviour of the alloy punched into rectangular samples has been evaluated. The sample sizes for tests covered the width range [3-15mm] and both LD and TD directions have been explored. The measurements were taken from 0.3T to 1.7T and from 50Hz to 1kHz.

The M330-35A usage magnetic properties are dependent upon the punching to which the laminations were subjected. The results have shown that as the width decreases, the degradation of the magnetic characteristics increases. The 15mm width punched samples are the best in term of magnetic behavior. The observed deterioration was more pronounced in LD samples and at 50Hz.

The basic data shown here give some interesting indications about the influence of the punching and frequency on the magnetic properties of electrical steels. It is desirable to extend this work and include local measurements and microstructure analysis (Leuning *et al*., 2016) in order to see how far the degradation is extended in the material. All these data will be useful for the design phase of high-speed machines in terms of modelling (Kedous-Lebouc *et al*., 2017), parameter identification, analysis and validation.

Table 2. Loss degradation factor vs frequency for the most degraded samples (of 3 mm width) of the M330-35A

B (T)	ΔP/P (%)									
	50 Hz		200 Hz		500 Hz		800 Hz		1 kHz	
	LD	TD	LD	TD	LD	LD	LD	TD	LD	TD
0.3	64	34	54	36	51	36	49	35	49	35
0.5	56	35	48	35	47	32	47	34	47	34
0.8	47	33	38	32	39	31	40	32	41	33
1	43	30	34	30	32	29	32	29	32	29
1.1	40	29	33	28	28	28	27	27	26	27
1.2	38	27	32	28	25	25	22	26	21	25
1.3	33	27	29	26	22	25	18	23	17	23
1.4	28	24	25	23	19	22	16	19	14	20
1.5	26	23	22	22	17	20	13	17	12	16
1.6	26	25	21	21	15	19	11	14	8	17
1.7	29	25	18	22	6	20	0.5	12	7	10

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