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Manufacturing efficient electrical motors with a predictive maintenance approach

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ABSTRACT

To convert electric into kinetic energy within an electrical motor emerging magnetic fields have to be amplified by using electrical steels. The efficiency of this energy conversion is determined by the electrical steel's magnetic properties. Due to residual stress having a negative effect on an electrical steel's magnetic behavior, manufacturing processes like stamping that deform the material thereby decrease the electrical motor's efficiency. This paper presents a novel approach to predict stamping-related increased magnetic property deteriorations from in situ measured values. Using the approach can prevent an excessive efficiency decrease from increasing tool wear by just in time maintenance.

1. Introduction

Within electrical machines the magnetic cores of rotor and stator act as an amplifier for magnetic fields that emerge from copper windings or permanent magnets. These magnetic cores are build up from stacked electrical steel laminations. The quality of the materials used, directly affects the efficiency with which electrical energy is converted to kinetic energy and vice versa. This behavior can be explained by the ability to align internal magnetic moments of the electrical steel into the direction of the external magnetic field [1]. Parameters that influence this behavior are the grain size, the metallographic texture, the number of defects like dislocations or mechanical stress the material is subjected to [2].

To characterize a material's possibility to amplify external magnetic fields, specific magnetic properties are measured. They can be identified from the magnetic hysteresis of an electrical steel exposed to an alternating magnetic field. The magnetic behavior is exemplarily visualized by the three magnetic hysteresis in Fig. 1(a). The hysteresis shape depends on the maximum magnetic field strength to reach a certain magnetic polarization. Higher magnetic fields thereby always lead to higher polarizations. The amplification of an external magnetic field is limited by the materials saturation polarization that describes the point where every atom's magnetic spin is aligned towards the orientation of the external field.

From a mechanical engineering point of view, the maximum polarization J_{max} at a maximum field strength H_{max} can be linked to the mechanical moment an electrical machine can provide at a specific maximum current. In comparison the magnetic field's frequency is proportional to the rotational speed. A characteristic magnetic property that is indirectly shown in Fig. 1(a) is the specific iron loss P_S that emerges when magnetizing electrical steels. It is proportional to the area within a hysteresis and determines the efficiency of an electrical machine.

When processing an electrical steel to magnetic cores of electrical machines, magnetic properties are deteriorated by the used manufacturing processes [3]. Punching (Fig. 1(b)) thereby is the most influential production step [4]. As neutron grating interferometry investigations of punched electrical steels proof, the degradations result from the inverse magnetostrictive effect. Hence, punching-related magnetic property deteriorations can be mainly traced back to residual stress next to the cutting line (Fig. 1(c)) [5]. The induced stress always leads to hysteresis shearing and thereby to a maximum field strength increase to reach the desired maximum polarization as well as to higher specific losses [6]. The degree of degradation can be limited by controlling the punching parameters [7]. Especially, small cutting clearances (CCL) and low cutting edge (CE) wear significant reduce the extent of punching due to less induced residual stress [8,9].

Since measuring magnetic properties of rotor and stator cores within the manufacturing chain of electrical machines is difficult and not cost effective, varying magnetic properties due to alternating punching process parameters, like increasing tool wear, are not identified nor considered by now. The only parameter that has to be measured and that triggers a tool maintenance is the burr height h_B. It needs to be smaller than the rollover height h_R in order to prevent magnetic short cuts and therefore a loss increase when stacking the laminations [10]. A limitation of punching-related residual stress by an in-time punching tool maintenance is beyond the scope of magnetic core manufacturers due to its difficult industrial feasibility.

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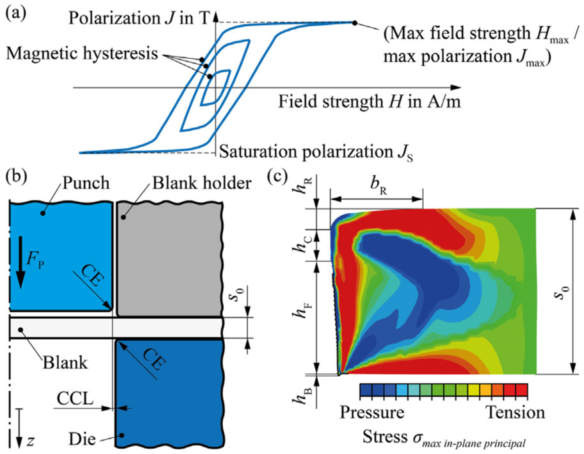

Fig. 1. (a) Magnetic hysteresis and characteristic magnetic properties; (b) Scheme of a punching tool setup; (c), cutting surface parameters and residual stress distribution of a punched electrical steel grid.

This paper presents two possibilities that allow deriving magnetic property deteriorations from in situ measureable punching process values. On the one hand a correlation of alternated magnetic properties and emerging cutting surface parameters such as rollover height h_R and width b_R, clean shear h_C, fracture height h_F and burr height h_B (see Fig. 1(c)) is depicted. On the other hand it is shown how evaluating the punch force F_P over punch travel z (see Fig. 1(b)) can help estimating production-related magnetic property variations. Since both, cutting surface parameters and punch force over punch travel curve correlate with the punching parameters used, either one of these two options allows to indirectly control the induced residual stress. This interdependence enables for a predictive maintenance of a punching tool to be carried out (see Fig. 2) [11,12]. Both approaches can help controlling the magnetic properties of the built magnetic cores and therefore support a manufacturer's ability to produce energy efficient electrical machines.

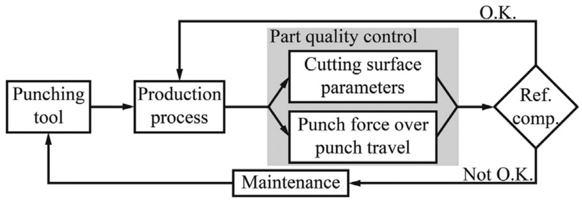

Fig. 2. Predictive maintenance approach based on either controlling cutting surface parameters or punch force over punch travel curve.

2. Experimental setup

2.1. Investigated materials

The investigation is carried out for the two different electrical steel grades M270-35A and NO30-16 having a thickness of 0.35 and 0.30 mm respectively. The materials have a silicon content of 2.7 wt.-%, a mean grain size of 87 and 108 μm, a yield strength of 494 and 485 MPa, an ultimate tensile strength of 613 and 595 MPa as well an uniform elongation of 9.1 and 8.4 %. Their specific losses are 1.3 and 1.1 W/kg at 1.0 T and 2.9 and 2.6 W/kg at 1.5 T. Both materials reach a maximum polarization of 1.5 T at 2500 A/m and 1.6 T at 5000 A/m. All of the mentioned magnetic properties have been measured at 50 Hz. The materials of punch and die are made from carbide having a tungsten carbide content of 87 wt.-% and a 12 wt.-% cobalt content.

2.2. Punching tool and punching process evaluation

A high-precision punching tool operated in an industrial mechanical single action press at 100 strokes per minute is used to manufacture electrical steel specimens for punching surface and magnetic property investigations. Exchangeable punches and dies allow different CCL and tool wear states to be analyzed. The electrical steel M270-35 A is punched with CCL of 7, 19, 35 and 35 μm with punch and die having sharp CE (S CE). In addition specimens are cut with a semi-worn (SW CE) and a worn CE (W CE) wear state for a CCL of 35 μm. The electrical steel NO30-16 is punched with tools having CCL of 15 and 35 μm with S CE and CCL of 35 μm with the W CE wear state [9].

To analyze the punching process a piezo force sensor and an inductive distance measurement system are used. This allows to calculate an average punch force over punch travel curve for each punching parameter setup from ten measurements recorded with a sampling rate of 110 kHz. The cutting surface parameters of the stamping grid's cutting lines is analyzed using a laser confocal microscope at thirty different position on five specimens each.

2.3. Magnetic measurement

The identification of punching-deteriorated magnetic properties is carried out by inserting specimens with constant mass but varying cutting line length and therefore varying residual stress affected material volume into a standardized single sheet tester (SST) (Fig. 3(a) and (b)). The SST is operated with a computer-assisted test setup according to IEC 60404-3. In order to demonstrate how punching affects the magnetic properties at different operating points, magnetic hysteresis are measured at maximum polarizations from 0.1 to 1.8 T in steps of 0.1 T and at frequencies of 50, 100, 400, 750 and 1000 Hz.

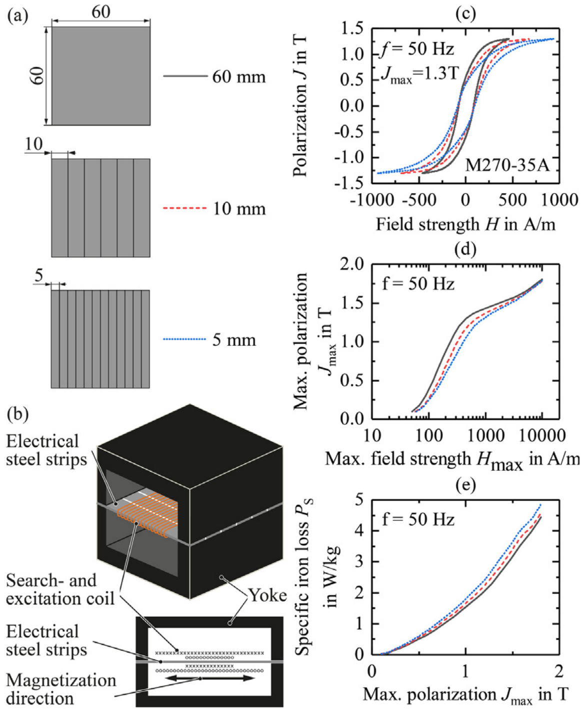

Fig. 3. (a) Sample arrangements with different specimen widths; (b) sample positioning in the SST; (c) (d) and (e) hysteresis shearing, max. polarization and specific iron loss increase due to punching-related stress.

The constant mass of the magnetically tested sample is ensured by either putting one 60 × 60 mm, six 10 × 60 mm or twelve 5 × 60 mm specimen into the SST. A detailed explanation on how these specimens of varying width w_s are produced can be found in Ref. [9]. Specimen positioning as depicted in Fig. 3(b) with the cutting line being parallel to the magnetic field ensures the analysis of a magnetic property degradation similar to the one in teeth of magnetic cores.

3. Results

3.1. Magnetic property deterioration

As depicted in Fig. 3(c) increasing the stress-affected material volume due to punching inside the SST leads to an elevated hysteresis shearing. This results in higher maximum field strengths to reach the same maximum polarizations and in increasing specific iron loss Fig. 3(d) and (e). While the loss gain can be noticed over the whole polarization range, the field strength increase diminishes for low polarizations and towards the saturation polarization. For an electrical machine this means the current supply as well as the overall energy consumption is higher when punching-related stress increases.

To better visualize how punching parameter variations affect the magnetic material properties the field strength factor C_{Hmax} and the specific iron loss factor C_S is calculated according to (1) and (2).

$$C_{Hmax}(J_{max},f) = \frac{H_{max}(J_{max},f,w_s = 5mm)}{H_{max}(J_{max},f,w_s = 60mm)} \tag{1}$$

$$C_S(J_{max},f) = \frac{P_S(J_{max},f,w_s = 5mm)}{P_S(J_{max},f,w_s = 60mm)} \tag{2}$$

Fig. 4 shows that both, increasing CCL as well as progressive CE wear yield in higher maximum field strengths and specific iron loss. Comparing the parameter variations to each other illustrates that the wear state influences the magnetic behavior to a larger extent due a higher residual stress induced [8]. Looking at the punching-effect at different maximum polarization levels the maximum influence on the field strength factor can be observed between 0.5 and 1.5 T where a high domain wall mobility impairment due to stress is present [5]. Regarding the specific iron loss factor a decreasing impact can be observed at rising maximum polarization levels independent of the punching parameters used.

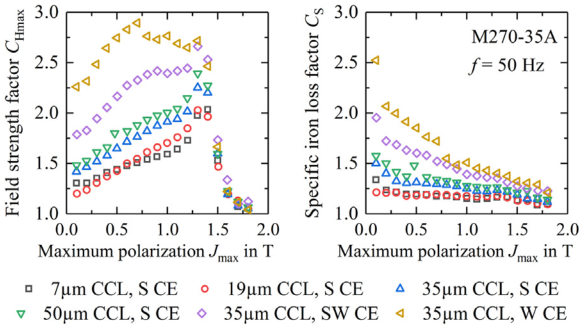

Fig. 4. Field strength and specific iron loss factor of M270-35A punched with different parameter setups at an excitation frequency of 50 Hz.

With respect to electrical machines that are deployed at different speeds, the effect of punching on the field strength and specific iron loss factor is shown in Fig. 5 for punching with 7 µm CCL and sharp CE and with 35 µm CCL and worn CE depending on the excitation frequency. It is obvious that rising magnetic field frequencies lower the punching effect regardless of the punching parameters used because of a domain wall's inertia [9,13]. However, electrical steel specimens punched with 35 µm CCL and worn CE seem to be stronger affected. While the frequency's impact on the field strength factor is limited to polarizations below 1.3 T, due to the stress-related domain wall mobility impairment, the specific iron loss factor is affected over the whole tested polarization spectrum.

3.2. Punching process analysis

When comparing the punch force over punch travel curves and the cutting surface parameters of the specimens punched with different parameter configuration in Figs. 6(a) and 7 to each other, a clear influence of the CCL and the CE wear state can be noticed. While small CCL maximize the cutting force and clean shear formation and minimize the rollover height, elevated CE wear changes the width of the punch force over punch travel curve and increases the rollover width and height as well as the clean shear and burr height.

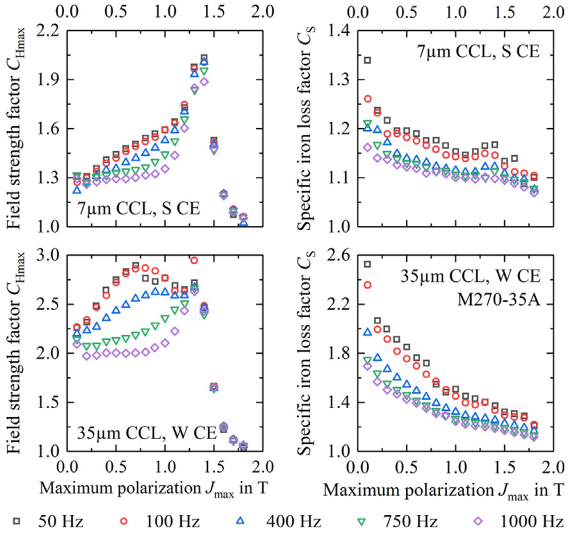

Fig. 5. Field strength and specific iron loss factor of M270-35A punched with two different parameter setups at different excitation frequencies.

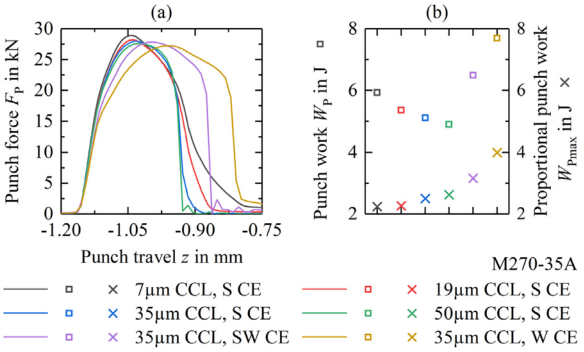

Fig. 6. (a), Punch force over punch travel curves as well as (b), punch work and proportional punch work when punching the electrical steel M270-35A with different parameters.

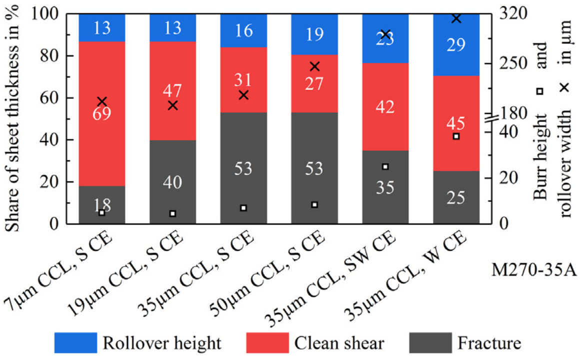

Fig. 7. Cutting surface parameters of the electrical steel M270-35A punched with different parameters.

Since the amount of material deformation and therefore the stress induction correlates with the punching work, it has been calculated according to (3). In addition a proportional cutting work from the start of the punching process till the force maximum according to (4) is calculated.

$$W_P = \int_{-1.2mm}^{-0.75mm} F_P(z)\,dz \tag{3}$$

$$W_{Pmax} = \int_{-1.2mm}^{z(Fmax)} F_P(z)\,dz \tag{4}$$

As punch work values in Fig. 6(b) indicate, the work gets minimal for high CCL and low CE wear. In comparison the proportional punch work is minimal for small CCL and sharp CE and gets bigger for high CCL and increasing tool wear.

Figs. 6 and 7 show that punching parameter variations change the amount of deformed material and thereby the amount of induced residual stress [8]. Matching these results with the magnetic properties in the following section helps identifying parameters allowing a predictive maintenance to be carried out.

3.3. Magneto-mechanical-parameter-correlation

To establish a predictive maintenance for punches and dies of magnetic core stamping tools a correlation in between punching-related magnetic property deterioration and in situ measurable parameters has to be found. Since the magnetic property degradation is getting bigger for increasing CCL and CE wear, correlating it with parameters that also increase at steady rate helps implementing such a predictive maintenance approach. Therefore, a single scalar value is easier to correlate than a parameter set like the punch force over tool punch travel curve.

When looking at the proportional punch work in Fig. 6(b) and the rollover height in Fig. 7 it can be seen that they also show a steady increase with rising CCL or CE wear while all the other values do not show this characteristic behavior. The burr height might also indicate a suitable measurement value but there is a danger of embossing it in multi-staged punching tools. Hence, sticking to an evaluation of the punching force over punch travel curve via the proportional punch work or the rollover height will deliver more reliable measurement values.

Plotting field strength and specific iron loss factor over rollover height or proportional punch work at an exemplarily maximum polarization of 1 T at 50 and 1000 Hz for the two investigated materials M270-35 A and NO30-16 in Figs. 8 and 9 visualizes a linear correlation between magnetic property degradation and in situ measureable parameters. This linear correlation for the first time opens the possibility for indirectly controlling magnetic property degradations due to punching by measuring punch force over punch travel curve or cutting surface parameters during magnetic core manufacturing. Therefore, by monitoring the proportional punch work or the rollover height an excessive impairment of the virgin material behavior can be limited.

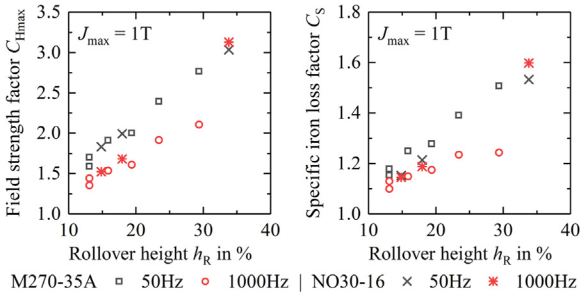

Fig. 8. Correlation of rollover height, field strength factor and specific iron loss factor for the electrical steels M270-35A and NO30-16.

4. Conclusion and outlook

This paper presents how in situ measurable parameters like a proportional punch work calculated from the punch force over punch travel curve or the rollover height, a cutting surface parameter, can be used to identify magnetic property degradations based on increasing CCL variations when changing or regrind punching tools or elevating CE wear when producing magnetic cores for a longer period of time. The linear correlation between punching-related proportional punch work or rollover height increase and field strength or specific iron loss growth establishes a basis on which excessive impairment of magnetic material behavior can be limited by a predictive maintenance approach.

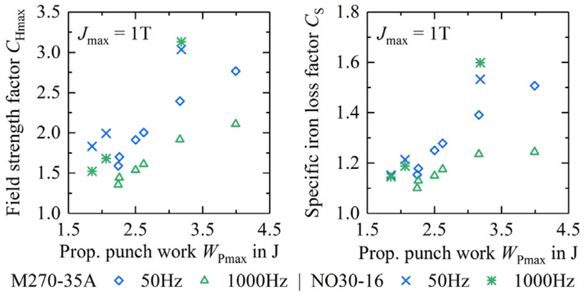

Fig. 9. Correlation of proportional punch work, field strength factor and specific iron loss factor for the electrical steels M270-35A and NO30-16.

Since the carbide tool material can last over multiple million punching strokes, regrinding of punch and die too late can result in magnetic cores with insufficient magnetic properties and thus to inefficient electrical machines. Therefore, in the near future a correlation of punch wear over tool life time with magnetic deteriorations and in situ measurable parameters is carried out. This helps identifying an optimum regrinding time in terms of economic and quality reasons. Considering a motor's area of application and the costs a customer is willing to pay for it, a product customized process window can thereby be determined.

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References

[1] Chikazumi S (2009) *Physics of Ferromagnetism*, Oxford University Press, USA. (first published February 27th 1997); ISBN 0199564817.

[2] Tekkaya AE, Allwood JM, Bariani PF, Bruschi S, Cao J, Gramlich S, Groche P, Hirt G, Ishikawa T, Löbbe C, Lueg-Althoff J, Merklein M, Misiolek WZ, Pietrzyk M, Shivpuri R, Yanagimoto J (2015) Metal Forming Beyond Shaping: Predicting and Setting Product Properties. *CIRP Annals* 64(2):629–653.

[3] Kurosaki Y, Mogi H, Fujii H, Kubota T, Shiozaki M (2008) Importance of Punching and Workability in Non-oriented Electrical Steel Sheets. *Journal of Magnetism and Magnetic Materials* 320(20):2474–2480.

[4] Schoppa A, Schneider J, Wuppermann C-D (2000) Influence of the Manufacturing Process on the Magnetic Properties of Non-oriented Electrical Steels. *Journal of Magnetism and Magnetic Materials* 215–216:74–78.

[5] Weiss HA, Steentjes S, Tröber P, Leuning N, Neuwirth T, Schulz M, Hameyer K, Golle R, Volk W (2019) Neutron Grating Interferometry Investigation of Punching-related Local Magnetic Property Deteriorations in Electrical Steels. *Journal of Magnetism and Magnetic Materials* 474:643–653.

[6] Schmidt KH (1975) Influence of Punching on the Magnetic Properties of Electric Steel with 1% Silicon. *Journal of Magnetism and Magnetic Materials* 2 (1–3):136–150.

[7] Belgrand T, Eple S (1998) Tell Us about Your Punch, We'll Tell You about Your Electrical Steel Magnetic Properties. *J Phys* IV(PR2). Pr2-611-614.

[8] Weiss HA, Leuning N, Steentjes S, Hameyer K, Andorfer T, Jenner S, Volk W (2017) Influence of Shear Cutting Parameters on the Electromagnetic Properties of Non-oriented Electrical Steel Sheets. *Journal of Magnetism and Magnetic Materials* 421:250–259.

[9] Weiss HA, Tröber P, Golle R, Steentjes S, Leuning N, Elfgen S, Hameyer K, Volk W (2018) Impact of Punching Parameter Variations on Magnetic Properties of Nongrain-oriented Electrical Steel. *IEEE Transactions on Industry Applications* 54(6).

[10] Beckley P (2002) *Electrical Steels for Rotating Machines*, IET, London.

[11] Neugebauer R, Kräusel V, Barthel T, Jesche F, Schönherr J (2013) Influence of a Defined Pre-load on the Stress State in the Precision Cutting Process. *CIRP Annals* 62(1):271–274.

[12] Shivpuri R, Singh S, Agarwal K, Liu C (2011) Energy Release Rate Based Approach for the Wear of Punches in Precision Blanking of High Strength Steel. *CIRP Annals* 60(1):307–310.

[13] Döring W (1948) Über die Trägheit der Wände zwischen Weißschen Bezirken. *Z Naturforschung 3a* 373–379. (On the inertia of walls between Weiss Domains).