Influence of the Manufacturing Process on the Magnetic Properties of Electrical Steel in E-Cores

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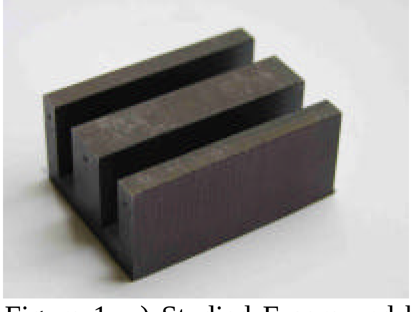
Abstract. The performance of an electromagnetic actuator depends on the design, the used type of electrical steels and the effects of the fabrication steps of the actuator on the magnetic properties. In the paper the voltage-current characteristic for E-cores, which have undergone different fabrication steps, are described. The aim of this study is to find a method for the calculation of the resulting B vs. H-characteristic for a ferromagnetic circuit. In this paper an E-core is studied. It can be noticed, that the deterioration effects by the fabrication steps give rise to a drop of the permeability of the magnetic core [1,3]. Two different measurement methods are used to obtain the U vs. I characteristic, respectively the B vs. H characteristic. In this context some considerable aspects of the standardised Epstein data are discussed since this Epstein material characteristic is the original basis for the electromagnetic design. The measured U vs. I characteristics are compared to the standard Epstein data as well as to the results obtained by a time harmonic finite element (FE) simulation applying the original Epstein data to the FE model.

Experimental Study

Fig. 1a shows the E-core used for the experiments. The cross section of two E-cores as they are used to measure the U vs. I characteristics is depicted in Fig. 1b. The dimensions of the E-core are indicated relative to the thickness L of the outer legs of the cores. The length of the E-core is 9L. Around the middle leg of each E-core, (Fig 1b) the coils C1 and C2 are located. The measuring samples (two E-cores in strong contact) form during all measurements a closed magnetic circuit. The measurements were realised under two different conditions: sinusoidal voltage in the primary coil or using a controller sinusoidal magnetic induction in the secondary coil (induced voltage). For the measurements using the controller-regulated set-up the same conditions apply as for measurements of the magnetic data of the electrical steel using an Epstein frame. All measurements were performed with the same two primary and secondary coils, C1 and C2 respectively.
For the first measurements an adjustable sinusoidal voltage U_{C1} was used as excitation of the primary coil C1. The induced voltage across the secondary coil C2 as well as the voltage U_{C1} across C1 and the current I_{C1} through C1 was captured for one period using an oscilloscope. (See Fig. 2a)
The second set of measurements was performed using the ‘measurement controller’ of an Epstein measurement set-up. (See Fig. 2b)



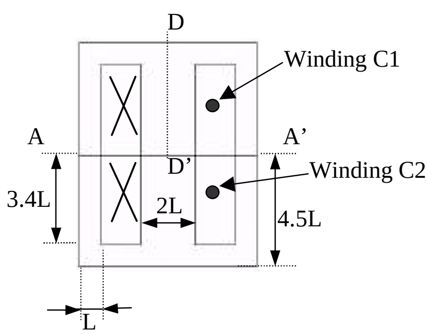


Figure 1: a) Studied E-core and b) cross sectional area of two E-cores, each containing a coil, forming a closed magnetic circuit (relative dimensions).

Table 1: Production States.

Production Steps	E-core/state number			
	1	**2**	**3**	**4**
Loosely packed parts	X	X	X	X
After packaging	X	X	X	X
Drilling of a hole in the middle along D-D’ axis (Fig 1b)		X		X
Polishing top, the plane through A-A’ perpendicular to the cross section			X	X
Polishing sides along the two outer legs			X	X
Annealing	X	X	X	X

The E-cores under investigation have undergone different production steps; see Table 1. They are all made using the high permeability grade 330-35AP from ThyssenKrupp Electrical Steel. For each measurement the same E-core out of production state 1 was used as a back iron, containing the secondary winding C2 (see Fig. 1b). The experiments showed that there is no significant difference between the different samples corresponding to the same production state. Therefore, from now on only the results from one sample per state will be depicted. For different induction levels, the actual values of U_{C1}, I_{C1} and U_{C2} are recorded for one period, with a sample rate of 128 samples a period. All measurements were performed for a frequency of 50 Hz.

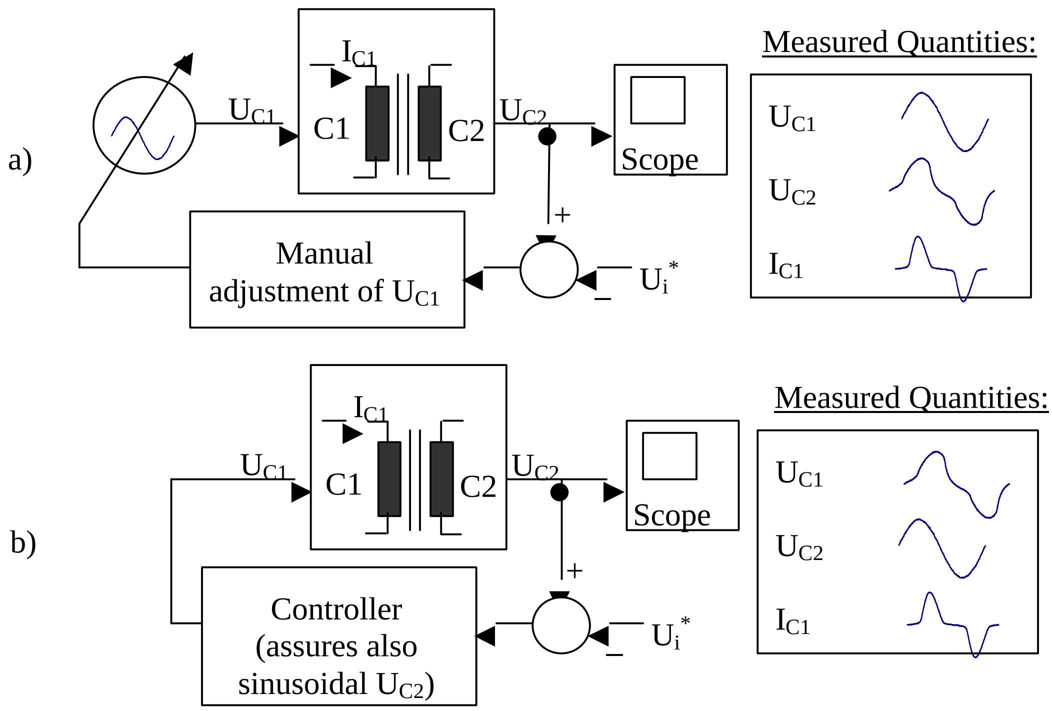


Figure 2: a) Principle of measurement for unregulated experiments and b) the principle of measurement for controlled experiments with sinusoidal magnetic induction as used also for measurements with an Epstein frame (Ui* is the voltage corresponding with the desired induction level).

Results. The results of the experiments are U vs. I characteristics corresponding to the four production states. In correspondence with Fig. 2, U is the measured induced voltage U_{C2} and I corresponds to the excitation current I_{C1} of the winding C_1. Figure 3 shows the U vs. I characteristic (peak values) for the unregulated measurements. On Figure 4 the results (peak values) for the experiments with controller are presented.

What concerns the influence of the production steps on the U vs. I characteristics, the same conclusions can be drawn for both measurement set-ups (regulated and not regulated). Although the differences between the states seem to be more pronounced for the unregulated set-up, it can be concluded that the effect of drilling a hole through the centre of the E-core has a significant influence. (Curves for state 2 and 4 in Figures 3 and 4.) It can be seen that polishing has a significant influence on the properties. (Curves 3 and 4 in Figures 3 and 4.)

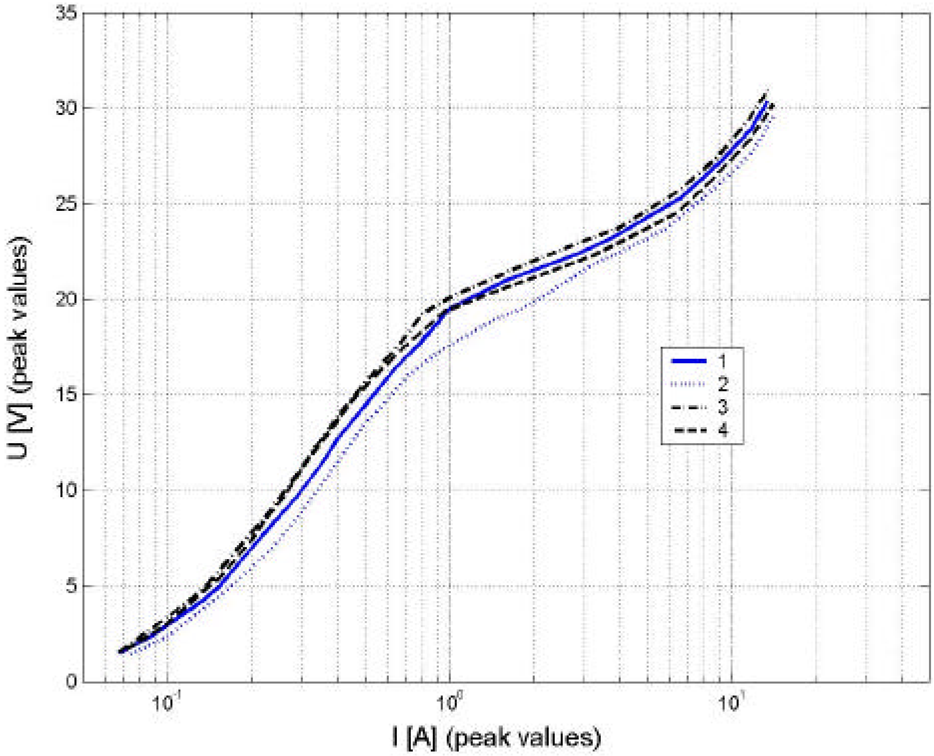


Figure 3: U vs. I characteristic of 6 production states for unregulated experiments (peak values).

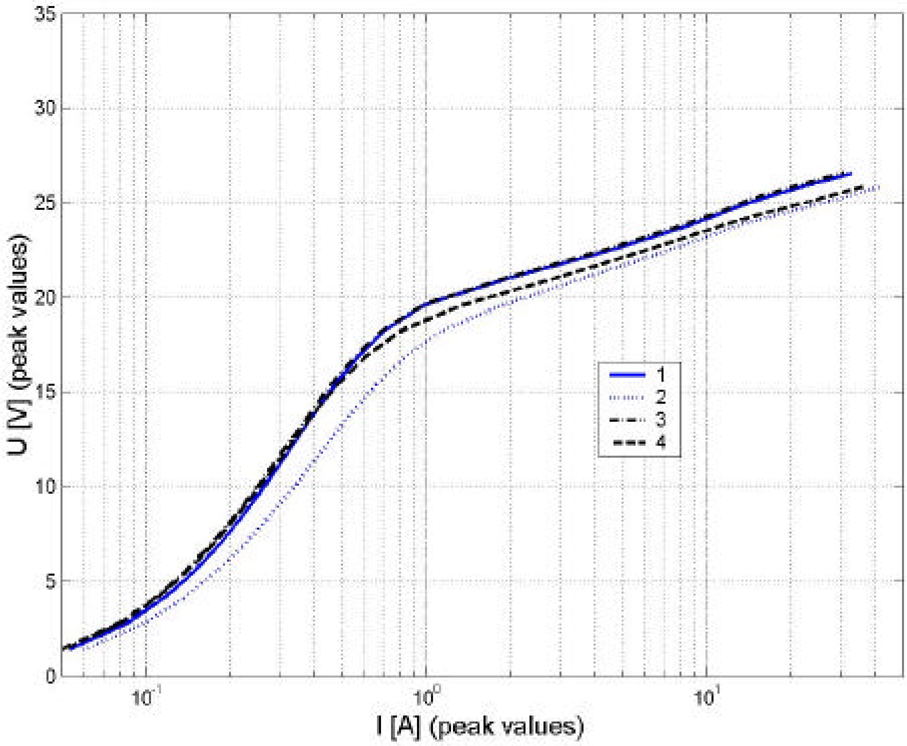


Figure 4: U vs. I characteristic of 6 production states for regulated experiments (peak values).

To evaluate the effects by the deterioration effects of the magnetic properties by the different fabrication steps or by using different types of electrical steels the resulting B vs. H characteristic of the E-core would be of interest. This B vs. H curve of the E-core (electromagnetic component) may be finally compared with the B vs. H characteristic of the delivered electrical steel, determined by using the Epstein frame.
To this purpose the measured B vs. H characteristic of the E-core should be converted to corresponding values for magnetic induction *B* and field strength *H*. Based on the law of Faraday-Lenz and on Ampères law one can find:

$$B = \frac{\hat{U}}{2pf \cdot A \cdot N} \quad . \tag{1}$$

$$H = \frac{N \cdot \hat{I}}{l} \quad . \tag{2}$$

With *l* the average length of the flux path, *N* the number of winding coils and *A* the cross section of this path. *A* is equal to $18L^2$ mm^2 and *l* is 20.6L mm.
Since the measurements using an Epstein frame are made under sinusoidal induced voltage, only the experimentally obtained U vs. I-curves for the E-core using the controller (regulated case) can be used.
Fig. 5 shows the BH-characteristics of the investigated cores in comparison to the B vs. H-curve of the electrical steel, measured by using the Epstein frame.

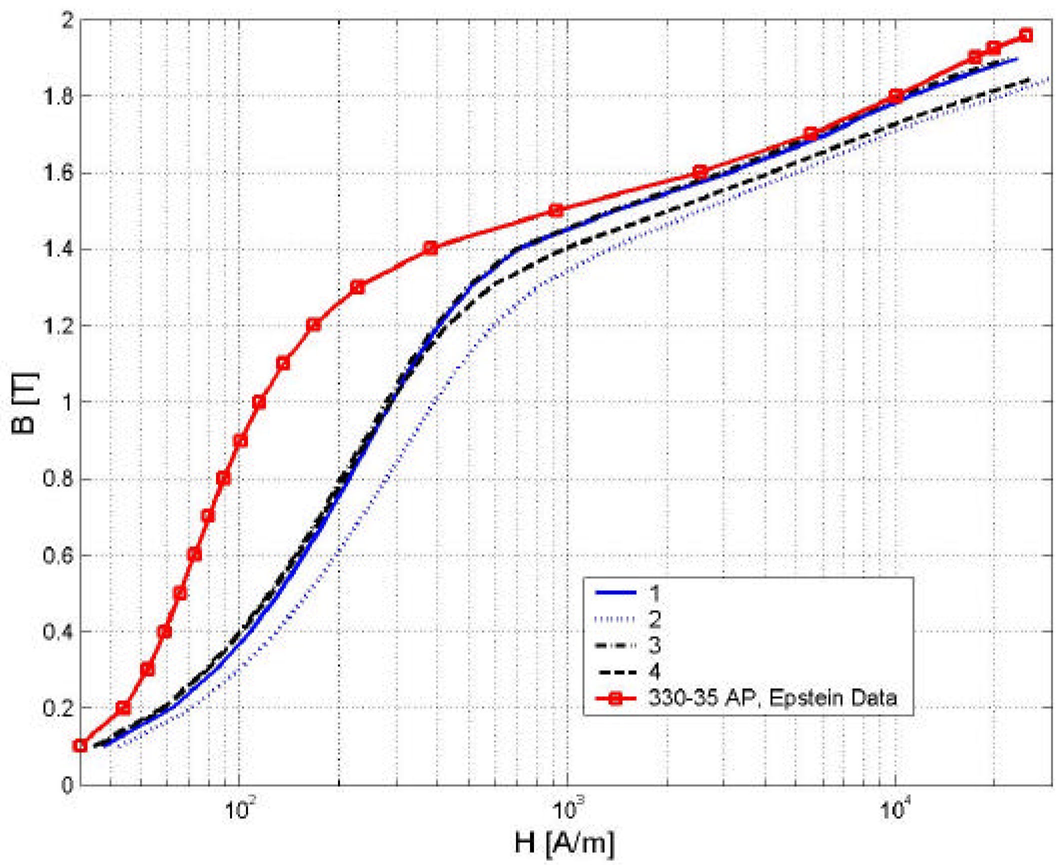


Figure 5: Calculated BH-characteristics for the controlled measurements compared to the BH-characteristic of the original material 330-35 AP (Epstein data).

Discussion.
The observed differences in the B vs. H-characteristics obtained from the measured U vs. I-characteristics of an electromagnetic component and from measurements using an Epstein frame, see Fig. 5, may in

general be caused by the deterioration effects due to the applied fabrication method and due to the design (original geometry) for the electromagnetic component. For the distinction between the fabrication process effects and design effects a finite element model may be useful.

The regarded core (closed magnetic circuit) is simulated using a time harmonic FE model. The magnetic data using the Epstein frame for the Power Core 330-35 AP electrical steel are used as material data for the solver. By imposing a current to the primary coil and calculating the induced voltage, any influence of the chosen geometry resulting in magnetic leakage flux is visible on the BH-characteristic and can be determined. The resulting BH-characteristic using the results of the FEM-calculations is obtained by applying equations 1 and 2. Figure 6 shows the results of the simulation of the original core (original geometry; deterioration effects by the fabrication process are not included) and of an altered geometry with increased leakage flux (changed geometry reflecting the deterioration effects by the fabrication methods).

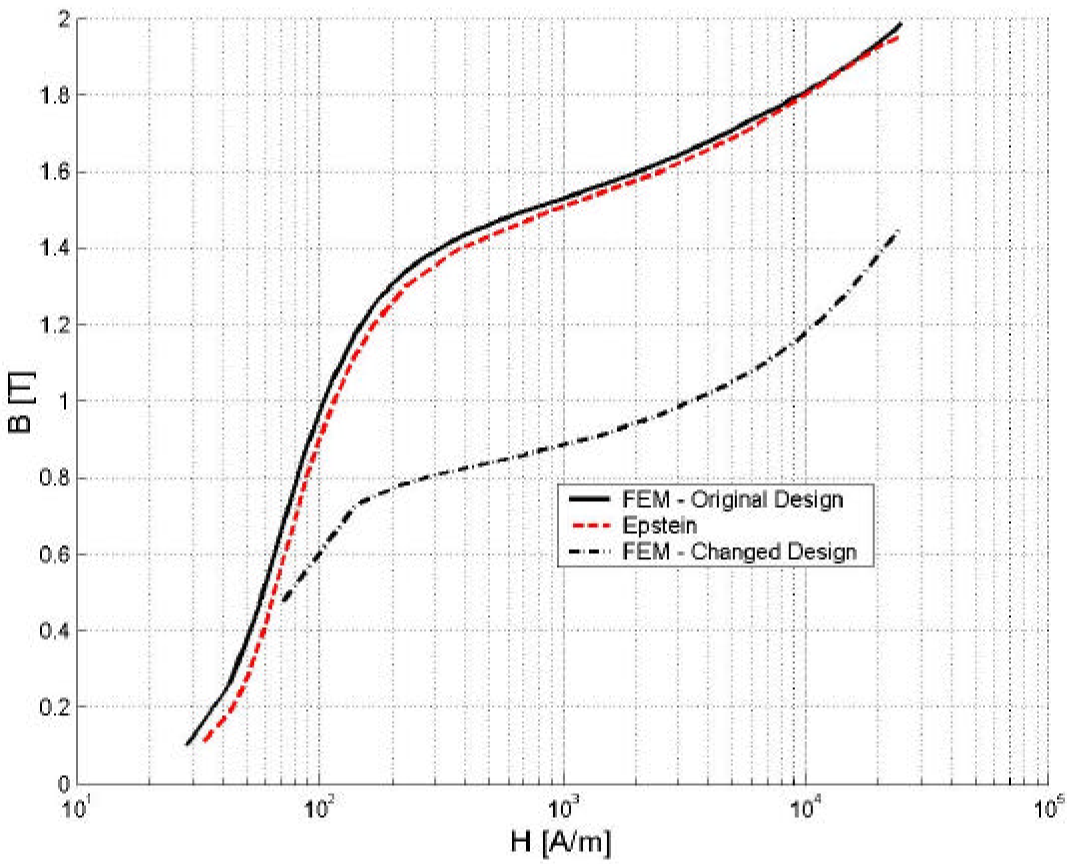


Figure 6: Comparison of BH-characteristics Epstein data and those obtained by FEM calculations.

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