High Saturation, High Strength Iron-Cobalt Alloy for Electrical Machines

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The power density of electrical machines can be vastly increased by the use of advanced soft magnetic materials with high saturation. The highest saturation values are obtained by using iron-cobalt alloys with a composition of 49% Co, 49% Fe and 2% V. In a recent study, an existing permanent magnet synchronous motor was improved by replacing the SiFe with iron-cobalt laminations. The FEM simulations indicated an increase in maximum torque of at least 25%. An actual prototype of this motor has been built and the results of the performance measurements are in good agreement with the calculations.

The iron-cobalt materials used for the prototype were the low-loss grade VACOFLUX® 50 for the stator and the high-strength material VACODUR® 50 for the rotor. It is shown that by using the newly developed alloy VACODUR® 49, both stator and rotor can be made from the same alloy, resulting in less material consumption.

While the stator can be annealed for optimum magnetic properties, it is possible to adjust the heat treatment of the rotor, so that yield strength requirements can be met. In order to achieve defined mechanical properties, the new alloy was designed to exhibit a linear relationship between annealing temperature and yield strength.

Introduction

The power density of electrical machines can be vastly increased by the use of advanced soft magnetic materials with high saturation. The highest saturation polarization of more than 2.3 T is obtained by using cobalt-iron alloys (CoFe) with a nominal composition of 49% Co, 49% Fe and 2% V. In a recent study, an existing 28 kW permanent magnet synchronous motor was improved by replacing the conventional silicon-iron (SiFe) with cobalt-iron laminations. The FEM simulations indicated an increase in maximum torque of at least 25% [Pieper et al, 2011].

Experimental

An actual prototype of this motor has been built to verify the calculations. The iron-cobalt materials used were the low-loss grade VACOFLUX® 50 for the stator and the high-strength material VACODUR® 50 for the rotor. The processing of the 0.35 mm thick laminations and the fabrication of the stack was done according to the VACSTACK® procedure in order to minimize the manufacturing losses and maintain the low loss level of the cobalt-iron materials [Volbers et al, 2010].

Figure 1 shows the actual measured mechanical power and torque in dependence of the rotational speed for both the motor made from SiFe and the one made from the CoFe material. For higher speeds the motor power will be limited to a constant value given by the inverter. The measurement results match very well with the FEM simulations as the predicted increase in maximum torque of +25% was confirmed.

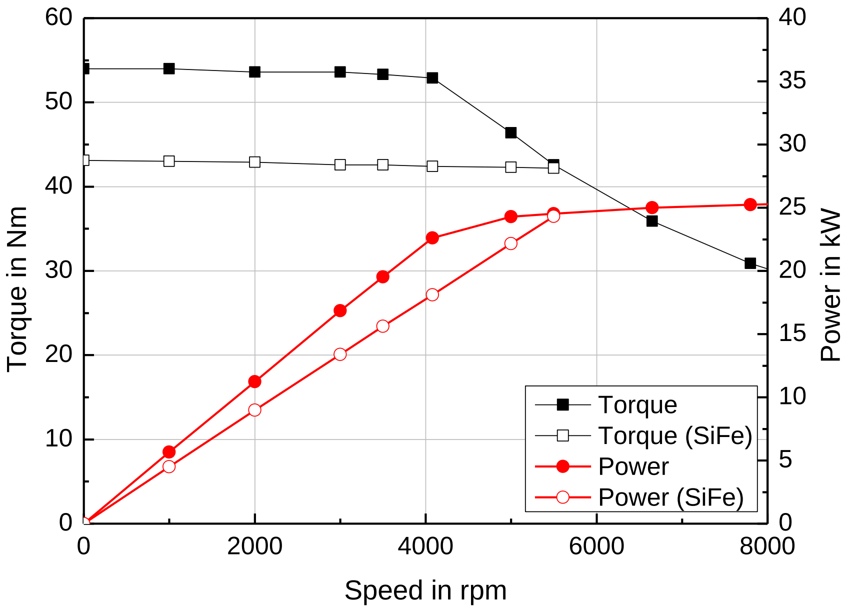

Figure 1: Measured torque and mechanical power vs. rotational speed for the actual prototype motor made from CoFe laminations (full symbols) and for the reference motor made from standard electrical steel (hollow symbols).

Material Considerations

The results show the technical advantage of using cobalt-iron instead of standard electrical steel. The drawback is that two different CoFe grades were required, which results in a high strip consumption. To overcome this limitation, the use of a new cobalt-iron material, VACODUR® 49, is suggested. By varying the final magnetic heat treatment, the material can be adjusted to exhibit similar magnetic and mechanical properties as either VACOFLUX® 50 or VACODUR® 50.

While the stator can be annealed for optimum magnetic properties, it is possible to adjust the heat treatment of the rotor, so that yield strength requirements can be met. Instead of using different materials it is then possible to stamp stator and rotor laminations from the same strip and simply adjust the heat treatment of the stator and rotor laminations.

Table 1 shows two proposed heat treatments to achieve a high DC induction and low core loss for the stator and high yield strength for the rotor. The magnetic saturation is determined by the composition, so that for higher field strengths both stator and rotor reach the same induction levels.

Parameter	***Unit***	***Stator***	***Rotor***
Heat Treatment		10h 880°C	3h 750°C
Coercivity Hc	A/m	30	106
DC Induction at 300 A/m	T	2.04	1.81
DC Induction at 800 A/m	T	2.20	2.08
DC Induction at 16 kA/m	T	2.30	2.30
Core Loss (1.5 T; 50 Hz)	W/kg	1.5	3.0
Core Loss (2.0 T; 400 Hz)	W/kg	60	77
Yield Strength $R_{p0.2}$	MPa	210	390

Table 1: Comparison of the typical magnetic and mechanical properties of VACODUR® 49 after different heat treatments.

The mechanical strength in this alloy is obtained by means of grain refinement: A moderate annealing temperature such as 750°C will lead to a fine grained microstructure which according to the Hall-Petch relation implies a high yield strength [Hall, 1951 and Petch, 1963]. High annealing temperatures such as 880°C cause additional grain growth and therefore lower the mechanical strength. The magnetic properties depend on the microstructure as well, i.e. small grains cause a high coercivity and larger grains a lower coercivity [Gerster et al, 2009].

From this, the following parabolic relationship between yield strength $R_{p0.2}$ and coercivity H_c can be derived [6],

$$H_c = H_0 + \frac{k'}{k^2}(R_{p0.2} - \sigma_0)^2, \qquad \{1\}$$

where H_0, k, k' and σ_0 are constants..

Figure 2 illustrates this mutual dependence for the new material VACODUR® 49: Any combination of yield strength and coercivity that corresponds to a point on the given curve can be obtained from the same batch of material by adjusting the heat treatment temperature in the range of 730°C to 880°C. Temperatures above 880°C should be avoided as this will lead to the formation of an austenitic phase.

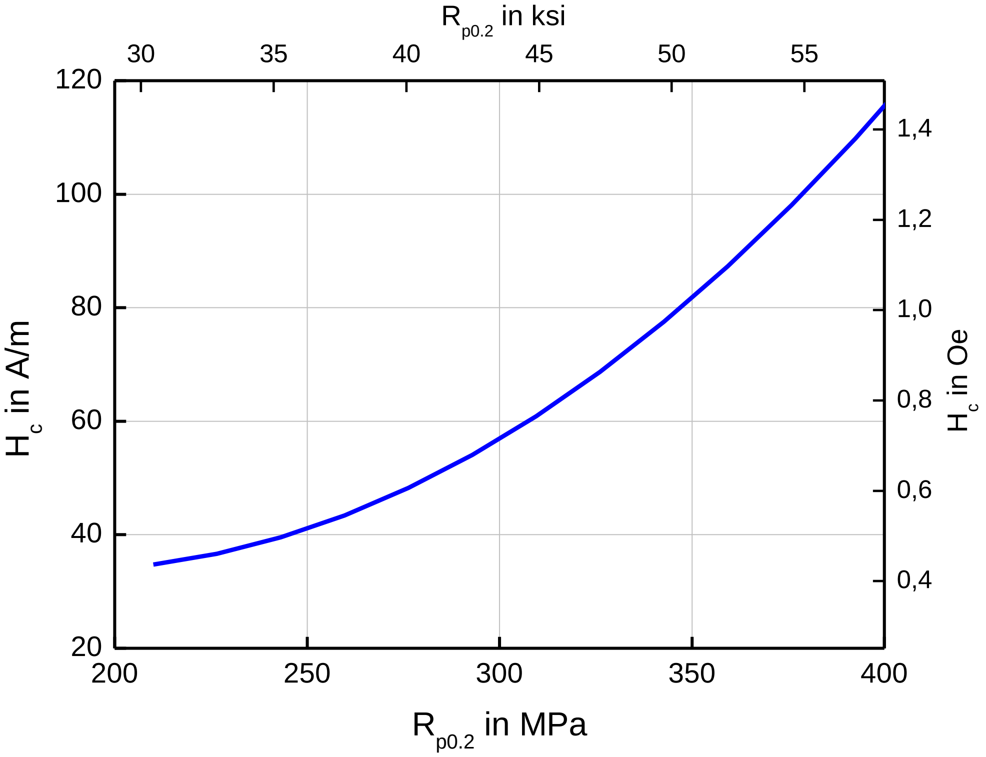

Figure 2: Possible combinations of coercivity H_c and yield strength $R_{p0.2}$ for VACODUR® 49.

In a production type furnace, the temperature of the final annealing is not always as well defined as under laboratory conditions and temperature gradients may occur. For a robust process it is therefore necessary that these differences in temperature will change the material properties in a predictable way. The new alloy was therefore designed to exhibit a linear relationship between annealing temperature and yield strength, as illustrated by figure 3.
If e.g. the temperature during the final magnetic annealing is (780 +/- 10)°C, then according to figure 3 the expected variation of the yield strength in this batch is approximately (351 +/- 13) MPa and according to figure 2 the coercivity will be around (82 +/- 8) A/m.

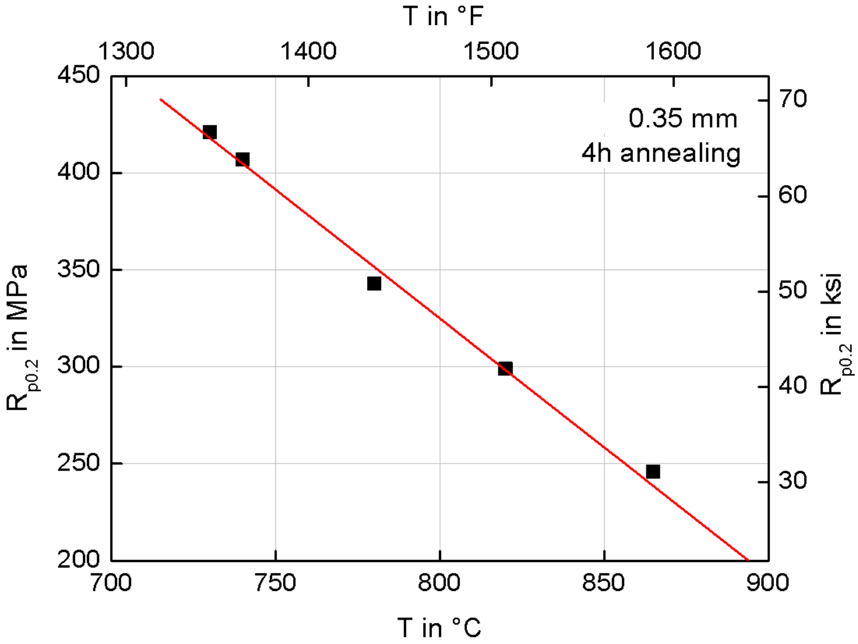

Figure 3: Dependence of the yield strength from the annealing temperature for 0.35 mm thick laminations made from VACODUR® 49. Annealing was performed in a dry hydrogen atmosphere with a constant hold time of 4h.

Summary

In conclusion measurements of the performance on a motor with cobalt-iron laminations confirm the increase in maximum torque of +25% in comparison to the formerly used standard electrical steel. In addition it was shown that by using the newly developed alloy VACODUR® 49, both stator and rotor can be made from the same cobalt-iron alloy, resulting in less material consumption and more flexibility regarding the magnetic and mechanical properties. The predictable change in yield strength during the final magnetic annealing allows a robust heat treatment process.

Acknowledgments

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