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MAGNETIC PROPERTIES OF AS-CAST IRON-COBALT ALLOYS

MAGNETNE LASTNOSTI LITIH ŽELEZO-KOBALTOVIH ZLITIN

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The structural and magnetic properties of iron-cobalt alloys (FeCoV) were compared to those of electrical steel alloys. The latter are widely used for the ferromagnetic cores of electric motors. However, the as-cast and rolled FeCoV alloys, which were analysed, showed enhanced magnetic properties compared to electrical steel alloys. Moreover, since they can be cast directly into the final shape of the rotor's main structure (excluding the pole shoes, which must be laminated) for a wound-rotor synchronous electric motor, the production becomes more cost-effective and energy-efficient. In addition, the performance of the electric motor is improved in terms of mechanical output power and energy efficiency.

Keywords: iron-cobalt alloys, ferromagnetic materials, electromagnetic energy conversion

Strukturne in magnetne lastnosti železo-kobaltove zlitine (FeCoV) smo primerjali z zlitino elektro pločevine. Slednja se pogosto uporablja za feromagnetna jedra v elektromotorjih. Vendar pa so ulite in valjane zlitine FeCoV, ki smo jih analizirali, pokazale izboljšane magnetne lastnosti v primerjavi z zlitinami elektro pločevine. Poleg tega jih je mogoče ulivati neposredno v končno obliko in s tem formirati glavni del rotorja (razen polovih čevljev, ki morajo biti laminirani) sinhronskega elektromotorja z navitim rotorjem, zato je proizvodnja cenejša, porabljena energija pa manjša. Mehanska moč na gredi elektromotorja ter energijski izkoristek motorja se prav tako povečata.

Ključne besede: železo-kobaltove zlitine, feromagnetni materiali, elektromagnetna pretvorba energije

1 INTRODUCTION

Soft-magnetic cores of electromagnetic energy converters, such as electric motors, transformers, and actuators, are commonly built from electrical steel alloys. These alloys achieve levels of saturation magnetization at approximately 1.8 T,[1] allowing compact designs of magnetic circuits. On the other hand, iron-cobalt alloys (FeCoV) have superior magnetic properties compared to electrical steel, opening a new path for electromagnetic structures with ultra-high compactness. The saturation magnetization of binary iron-cobalt alloys reaches 2.4 T, which is an approximately 30-% increase from electrical-steel saturation levels, and consequently a significant reduction in a device's volume.[2–7] However, a binary iron-cobalt alloy is extremely brittle and in order to avoid this as well as improve other mechanical properties (high strength and creep resistance[8]) and electrical properties (electrical resistivity[8]), other alloying elements must be added, e.g., V, Si, Al, Cr, Mn, etc.[8,9] Adding different amounts of these elements will unavoidably decrease the initial saturation magnetization of the binary iron-cobalt alloy, but the decrease can be mitigated with proper heat treatment between 600 °C and 900 °C. Heat treatment also improves mechanical properties by increasing strength and ductility, and enhances some magnetic properties by decreasing coercivity and core losses.[8] The temperature of the heat treatment can enhance either mechanical or magnetic properties, e.g., annealing at 600 °C shows the best creep resistance,[8] while annealing at 800 °C provides a good balance between saturation magnetization and coercivity (2.019 T and 194 A/m, respectively).[9] FeCoV alloys have shown the potential for usage in internal combustion engines as high-temperature actuators with high dynamic performance,[9] in electric vehicles as high-efficiency traction motors,[10–13] and particularly in aerospace applications, where they can be used in compact and low-weight generators and actuators.[14–21] What these applications have in common is their ability to justify the higher initial cost of components, arising from the high content of the expensive material (cobalt), due to the energy savings during their lifetime.

The focus of this study was on the magnetic properties of the as-cast ferromagnetic materials for high-performance electric motors, e.g., for the automotive industry, intended for easier and energy-saving production. FeCoV alloys were used for magnetic cores to enhance the motor mechanical performance. Alternative production methods such as casting, additive manufacturing (3D printing)[22–24] and powder metallurgy[25] were not used in this study due to the additional step required for powder production. Moreover, in order to maintain the intrinsic material properties, all rough mechanical reshaping, such as stamping, causing material deterioration[26,27] had to be avoided. Thus, in the study, only directly as-cast

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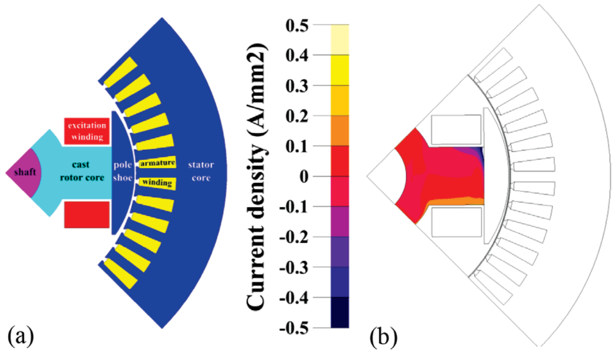

Figure 1: a) WRSM design (one magnetic pole); b) current density of eddy currents in the cast part of the rotor

magnetic materials and additionally rolled FeCoV alloy were considered. Such a production procedure could be considered for a wound-rotor synchronous motor (WRSM). The WRSM has a DC magnetic field in the rotor, which rotates synchronously with the rotating magnetic field (AC) on the stator. Due to the time-invariable magnetic field there is no electromagnetic induction that would cause eddy-current losses in the rotor. Therefore, the internal part of the rotor (shown in turquoise in **Figure 1**) could be die-cast as a single component, while the pole shoes (shown in blue in **Figure 1**) had to remain laminated due to the presence of the stator slots. Namely, the latter causes time-varying higher harmonic components in the magnetic field.

For the purposes of magnetic comparison of the materials, a widely used ferromagnetic material, i.e., electrical steel, was first produced. Its acquired properties served as the internal benchmark. Then, a custom initial FeCoV alloy with 49 % Fe and Co, and 2 % V was produced. Vanadium was added for hardening[28]. Additionally, the influence of rolling on the magnetic properties of FeCoV was analysed by measuring these properties.

2 EXPERIMENTAL PART

The materials were made from pure elements including electrolytic Fe, electrolytic Co, pure V, metallurgically pure Si, and primary Al. 10-kg charges were melted in a vacuum induction melting furnace with an alumina crucible. The metals were cast into 60 × 60 mm ingots, which were roughly 400 mm long. The as-cast electrical steel (Fe-Si-Al) served as the introductory sample. Then a part of the as-cast Fe-Co-V ingot was cut and rolled at 1200 °C to a 20-mm thickness. Metallographic samples were ground and polished, followed by 5 % Nital etching. Optical micrographs were taken with a Nikon Microphot FXA light optical microscope. The chemical compositions of the alloys were analysed with LECO CS and ICP-OES. They are given in **Table 1**.

Three samples in the form of a rod were produced: as-cast electrical steel, as-cast FeCoV and rolled FeCoV. They were machined (ground across whole length) to a diameter of 10.005 ± 0.001 mm in order to accurately determine their cross-sectional areas. Precise information regarding the cross-section was needed because the magnetic flux density *B* for the samples was calculated from the measured magnetic flux. Using the MagnetPhysik Remagraph, the relation between the magnetic field strength *H* (**Figure 2a**) and magnetic flux density *B* (**Figure 2b**) was obtained as a quasi-static DC hysteresis loop, in accordance with the IEC 60404-4 standard.[29,30] Each sample was demagnetized prior to each B-H mea-

Table 1: Chemical compositions of the electrical steel and FeCoV alloy (*w*/%)

	Al	Co	Si	V	C	Fe
Electrical steel	0.43	/	2.40	/	0.004	Bal.
As-cast/rolled FeCoV	/	48.95	/	1.99	0.002	Bal.

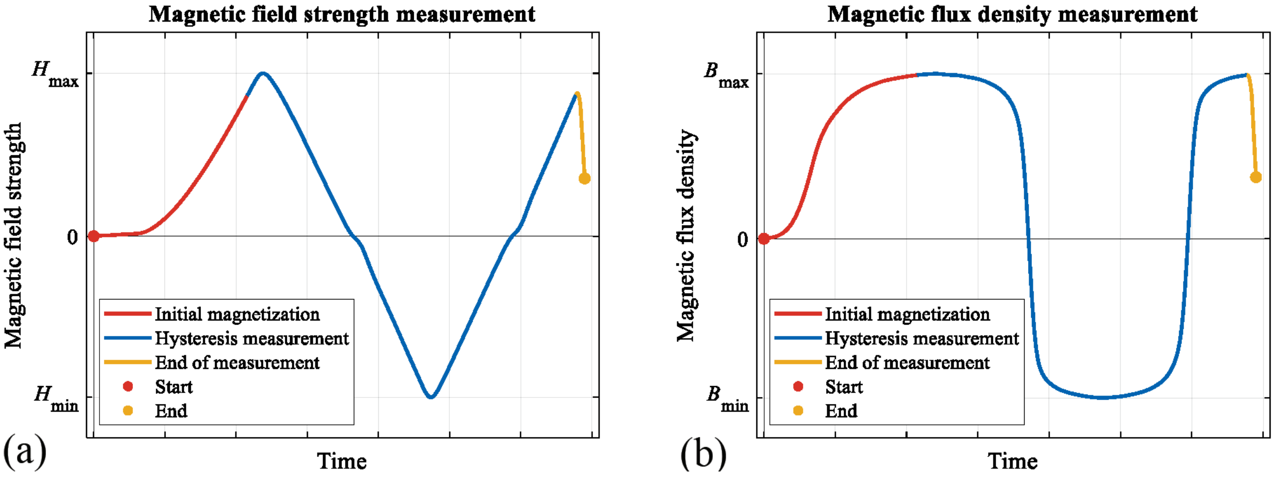

Figure 2: Temporal measurement of: a) magnetic field strength *H*; b) magnetic flux density *B*

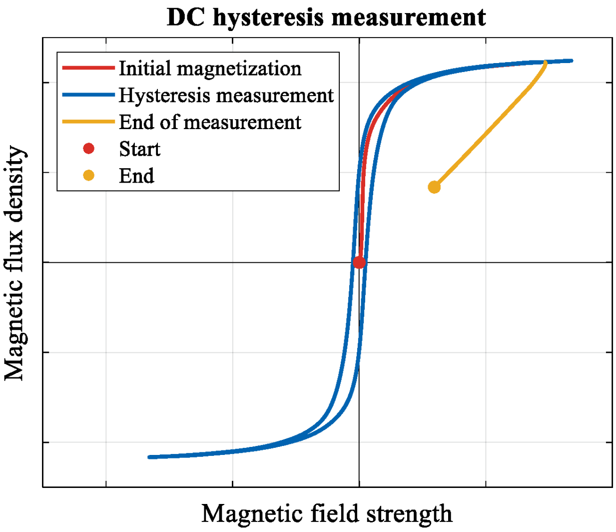

Figure 3: Complete measurement of *B-H* hysteresis loop with the DC method

surement. Then, the DC hysteresis measurement was performed on the samples by varying the current excitation in the standardized yoke, changing the magnetic field strength from –5000 A/m to +5000 A/m. Such an amplitude of the magnetic field strength was sufficient to reach the saturation levels for all three samples. Therefore, it represents the measurement of one cycle by the Remagraph RE3, forming the hysteresis loop (**Figure 3**).

3 RESULTS

The microstructure of electrical steel consisted of 100 % ferrite (a body centred cubic (BCC) crystal lattice); the average grain size was larger than 1 mm, as seen in **Figure 4**; and there was no preferential orientation of the grains due to the absence of deformation, as it was in the as-cast state.

The FeCoV alloy has a BCC crystal lattice at room temperature. As the solidification process can be a bit more complex, there are still remains of the dendritic structure, as seen in **Figure 5**, resulting in a more uneven grain size ranging from a couple of mm to less than 100 µm.

The rolled FeCoV alloy shows a significant grain-size reduction, but the grains are elongated, measuring a few 100 µm in length and several 10 µm in width, as seen in **Figure 6**.

The hysteresis loops for the as-cast electrical steel, as-cast FeCoV and rolled FeCoV are shown in **Figures 7** and **8**. For comparison, each of the graphs also includes

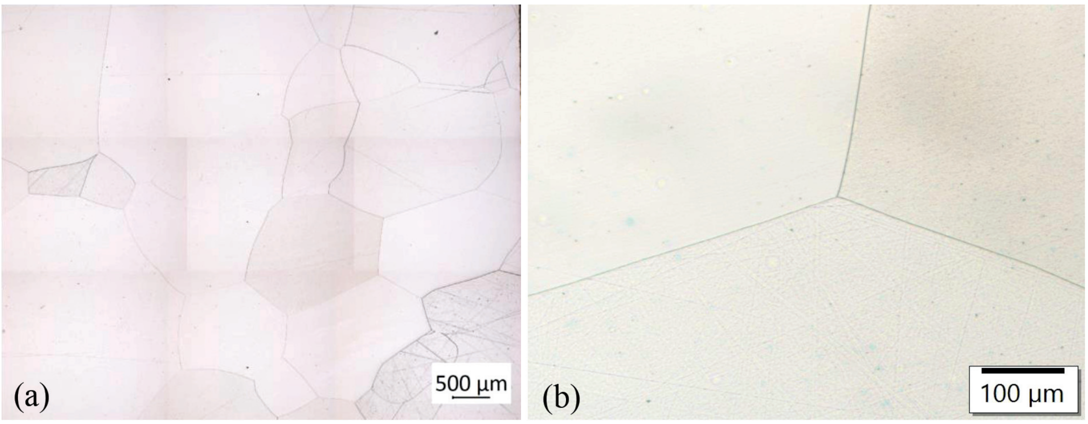

Figure 4: Microstructure of the as-cast electrical steel: a) at a lower and b) at a higher magnification

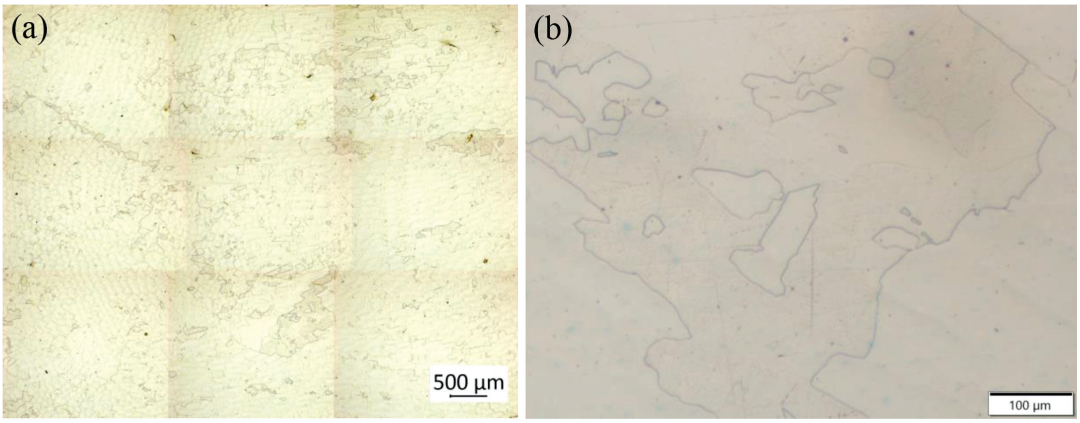

Figure 5: Microstructure of the as-cast FeCoV alloy: a) at a lower and b) at a higher magnification

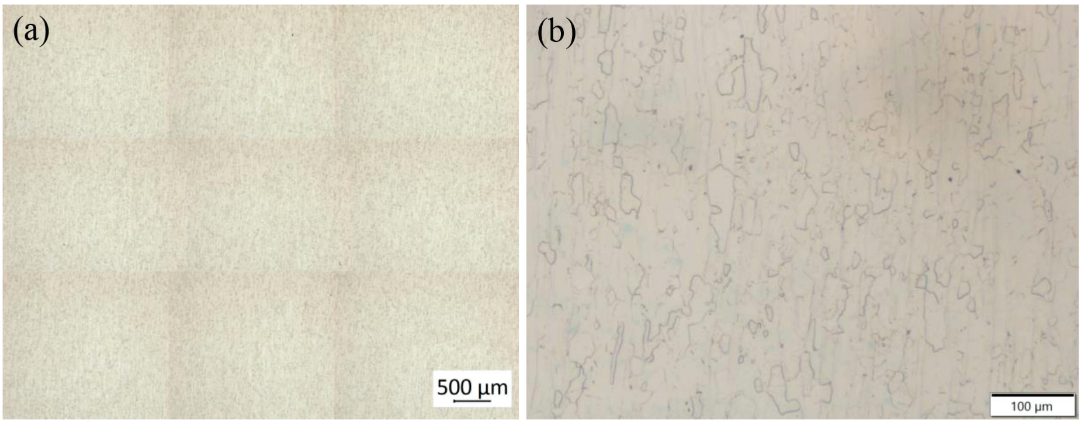

Figure 6: Microstructure of the rolled FeCoV alloy: a) at a lower and b) at a higher magnification

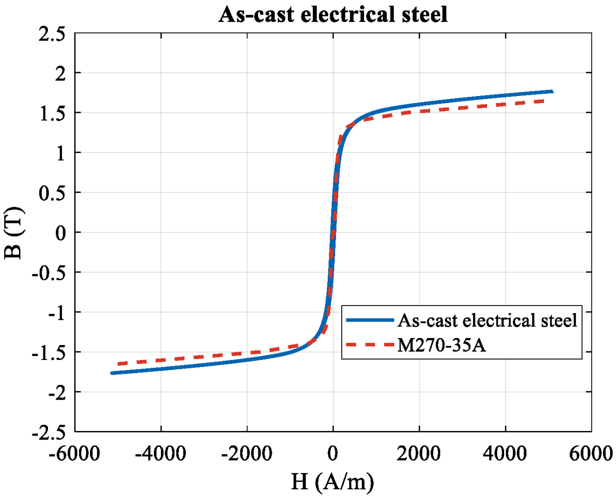

Figure 7: Hysteresis loop of the electrical steel alloy

the B-H curve of a commonly used electrical steel (i.e., Cogent M270-35A, from a particular datasheet[31]). The area of the hysteresis loop of the as-cast electrical steel (**Figure 7**) is small, resulting in a very narrow hysteresis loop, hardly visible in the graph. The maximum values of magnetic flux density reach approximately B = 1.76 T, which is anticipated for this ferromagnetic material. Both FeCoV samples show enhanced performance in terms of magnetic flux density compared to the as-cast electrical steel. The measured values exceed B = 2.2 T (see **Table 2**). However, the areas of the hysteresis loops are visibly larger. The hysteresis loop of the as-cast FeCoV is somewhat smaller than that of the rolled FeCoV (**Figure 8**).

Table 2: Comparison of magnetic properties of the samples

	B at H = 2000 A/m	B at H = 5000 A/m
As-cast electrical steel	1.603 T	1.762 T
As-cast FeCoV	2.076 T	2.230 T
Rolled FeCoV	2.035 T	2.212 T

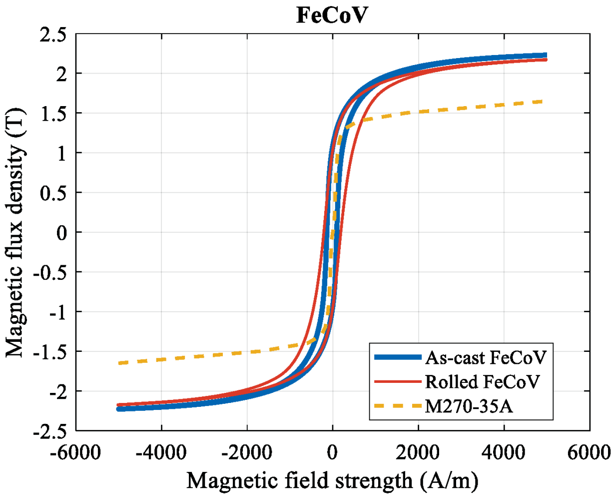

Figure 8: Hysteresis loops of the FeCoV alloys

4 DISCUSSION

Both FeCoV samples showed higher saturation magnetic flux densities compared to electrical steel. The as-cast FeCoV sample has a smaller area of the hysteresis loop and slightly better magnetic performance than the rolled FeCoV (+2 % at H = 2000 A/m and +0.8 % at H = 5000 A/m). However, since the magnetic field in the rotor of a synchronous motor is constant (DC), the hysteresis loop area has a negligible influence on the motor performance. Moreover, it might be even desired in some cases to have a larger hysteresis loop in order to maintain magnetization, when the magnetization current is zero (remanent magnetic flux density) and even more when there is an opposing magnetic field, excited by the stator winding. The methods for extending the area of hysteresis loops for a WRSM with as-cast rotor structures will be the subject of the future investigations.

5 CONCLUSIONS

The goal of the study was to investigate the magnetic properties of the as-cast FeCoV material. With the study, we wished to improve the mechanical performance of the wound-rotor synchronous motor (WRSM) as well as reduce the costs and energy consumption during the production of WRSM rotors. The rotor generates a DC magnetic field and can be built from a massive part, i.e., there is no need for laminations. It was shown that the as-cast FeCoV alloy has excellent magnetic properties, compared to the electrical steel alloy. Consequently, the main part of the rotor can be made thinner, leading to a lower mass and higher energy efficiency during the motor operation. Moreover, the as-cast FeCoV alloy also has slightly better properties than the rolled FeCoV. This is an important fact as the main magnetic part of the rotor can then be directly cast into the final shape without the need for rolling and further excessive machining of the rotor. Thus, certain steps in the production process can be omitted, saving the time and energy, and lastly also the costs.

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