Magnetic properties of 42CrMo4 steel

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Abstract. Low alloyed high-grade chrome-molybdenum ferritic steel was investigated from the point of views of magnetic properties in dependence on heat and mechanical treatment. This steel can be used as components of magnetic circuits or some parts in electrical equipment. The basic information on structure and phase composition was obtained by optical and scanning electron microscopy, X-ray Powder Diffraction and Mössbauer Spectroscopy. The temperature stability of the material was proved by measurements of temperature dependences of magnetic moment. The magnetic parameters were obtained by measuring of magnetic hysteresis loops in dependence on saturation field and their frequencies. The results are discussed from the point of view of possible applications as a magnetic material in the very extremely environment, where high mechanical stresses and elevated temperatures can occur.

1 Introduction
The knowledge of magnetic properties of steel, which is intended for electrical machine, is very important because it can be applied as part of magnetic circuit and these parameters play important role. It is required the knowledge of parameters such as saturation magnetization, coercivity, magnetic losses, permeability and electrical resistivity in dependence on temperature and heat&mechanical treatment history. The content of datasheets is seldom for magnetic properties of construction low alloyed steels [1-3]. The aim of this study is to describe magnetic behavior of 42CrMo4 steel. Possible applications of this steel can be as parts of magnetic circuits or some parts in electrical equipment [4, 5].

2 Experimental
The samples of the 42CrMo4 steel were obtained from a rod and cut to smaller cylinders and toroids. The rod was heat treated and soft annealed. Chemical composition from producer was confirmed by Glow discharge optical emission spectrometry (GDOES) and the same elements were found by scanning electron microscope Tescan LYRA with EDX detector. The sample for microscopy was cut from cylinder (diameter 55 mm and thickness 4 mm) using spark erosion cutting. Surface of sample was ground on SiC paper to 2500 grid and polish by colloidal silica and it was etched first in Vilella-bain and consequently in 2% Nital for better resolution. The chemical composition according to material description and identified by GDOES was following:
Samples for magnetic measurement were made from cylinder with diameter 60 mm by lathe and no additional adjustments were done. The aspect ratio of these samples is different to verify measured parameters on different sized toroid. The ideal ratio with homogenous field is 1.1 and border aspect ratio is 1.25. If the ratio is higher, the magnetic flux is not spread homogenous in entire cross section [6].

Structure and phase composition was investigated using optical microscopy (OM), scanning electron microscopy (SEM), X-ray powder diffraction (XRD) and \(^{57}\)Fe Mössbauer spectroscopy (MS). The surfaces of the samples were examined by optical microscope Neophot 32 by Carl Zeiss Jena and scanning electron microscope Tescan LYRA 3 XMU FEG/SEMxFIB equipped with X-Max80 EDX detector for X-ray microanalysis and EBSD detector Nordlys by Oxford Instruments with Aztec control system. The X-ray powder patterns were collected on X’Pert diffractometer and CoKα radiation with qualitative analysis by HighScore® software and the JCPDS PDF-4 database. For a quantitative analysis HighScore plus® with Rietveld structural models based on the ICSD database was applied. Chemical analysis of the material was done by Glow discharge optical emission spectrometry using GD-Profiler 2 instrument with the Quantum™ XP software (Horiba Jobin Yvon, France) operating in radio frequency at 13.56 MHz. \(^{57}\)Fe MS spectra were measured at room temperature in scattering geometry ~ 80 MGy. \(^{57}\)Co(Rh) radioactive source and calibrated against \(\alpha\)-Fe as the standard. The values of the isomer shift are related to \(\alpha\)-Fe at room temperature. The computer processing of the spectra yielded the values of the relative spectrum area I and values of the hyperfine parameters including isomer shift \(\delta\), quadrupole splitting \(\Delta\), and hyperfine induction \(B_{hf}\). Changes in magnetic properties by high temperature including isomer shift \(\delta\), quadrupole splitting \(\Delta\), and hyperfine induction \(B_{hf}\). Changes in magnetic properties by high temperature were investigated by temperature dependence of magnetic moment. The temperature dependence of the magnetic moment was measured under vacuum (~ 10\(^{-2}\) Pa) using vibrating sample magnetometer in an external magnetic field of 5 mT and in a temperature range of 25 – 800 °C with a sweep of 4 °C·min\(^{-1}\) in vacuum. The dependence of magnetic moment on external field (hysteresis loop) was measured before and after annealing at room temperature in external fields ± 1 T. The magnetic parameters were acquired by equipment Remagraph – Remacom C-710 (Magnet-Physik Dr. Steingroever GmbH). It is measuring the magnetic flux through the coil and it is based on the principle of Faraday law of

| Table 1. Chemical composition in wt. %. |
|----------------------------------------|
| **Element** | **Datasheet** | **Result** |
| C          | 0.38 – 0.45  | 0.42       |
| Si         | max. 0.40    | 0.24       |
| Mn         | 0.6 – 0.9    | 0.83       |
| P          | max. 0.025   | 0.010      |
| S          | max. 0.035   | 0.000      |
| Cr         | 0.90 – 1.20  | 1.12       |
| Mo         | 0.15 – 0.30  | 0.19       |

| Table 2. Parameters of toroid samples |
|---------------------------------------|
| **Dimensions of the sample**          |
| **Outer diameter**                    | 54.95 | 44.32 | 44.37 | 54.97 | 54.97 | 54.92 | 54.92 | 54.92 |
| **Inner diameter**                    | 47.3  | 40.4  | 38.07 | 47.42 | 45.02 | 39.95 | 32.95 | 24.96 |
| **Thickness**                         | 1     | 2     | 3.07  | 3.8   | 5     | 7.52  | 10.96 | 14.92 |
| **Mass**                              | 4.6   | 3.94  | 9.44  | 17.67 | 30.12 | 64.94 | 129.54 | 218.74 |
| **Primary windings**                  | 109   | 97    | 95    | 104   | 110   | 92    | 126   | 97    |
| **Secondary windings**                | 20    | 40    | 20    | 40    | 20    | 40    | 40    | 40    |
| **Ratio**                             | 1.16  | 1.10  | 1.17  | 1.16  | 1.22  | 1.37  | 1.67  | 2.20  |
electromagnetic induction. Saturation magnetization and hysteresis losses were measured on toroid shaped samples. Part equipment Remacomp was used for the measurement with frequency and Remagraph without frequency. The magnetic properties were measured in frequency range 0 – 2000 Hz at room temperature.

3 Results and discussion
Information on the structure and phase composition were obtained using OM, SEM (Figure 1, 2) and XRD. The ferrite (matrix) structure parameters were unambiguously recognized from the XRD data (Figure 3). The presence of carbide Cr$_{23}$C$_6$ and (Fe, Mn)$_3$C in the steel was also confirmed but intensities of their diffraction peaks are close to the detection limits. Content of these elements is about 3.6 wt.% (Fe, Mn), and 1.5 wt.% Cr$_{23}$C$_6$.

![Figure 1. Scanning electron microscopy of the 42CrMo4 steel sample 2000 magnification.](image1)

![Figure 2. Scanning electron microscopy of the 42CrMo4 steel sample 10 000 magnification.](image2)

The Mössbauer spectrum of the steel sample is shown in Figure 4. The crosses denote experimental points and the line the fitted function [7]. Above the spectrum three main fitted components are drawn.

![Figure 3. X-ray pattern of 42CrMo4 steel (□ferrite, ■ (Fe, Mn)$_3$C, and ◆ Cr$_{23}$C$_6$) obtain at room temperature.](image3)

![Figure 4. Room temperature temperature Mössbauer spectrum of the 42CrMo4 steel sample.](image4)

The experimental data were fitted by three sextet with mean hyperfine induction $<B_{hf}> = 32.7 \pm 0.1$ T and relative content c = 0.94±0.01 which represent α phase. The sextet with hyperfine induction $B_{hf} =$
21.0±0.1 T, δ = 0.114±0.005 mm·s⁻¹, QS = -0.374±0.010 mm·s⁻¹ and c = 0.02±0.01 represents cementite Fe₃C. The analyzed doublet (δ = 0.160±0.007 mm·s⁻¹, Δ = 0.427±0.010 mm·s⁻¹ and c = 0.04±0.01) can be ascribed to Cr₂₃C₆ carbide [8, 9].

The temperature dependence of magnetic moment of the 42CrMo4 sample is drawn in Figure 5. From this dependence, we can observe magnetic transformations (Curie temperatures) at ~180 °C of cementite and at ~ 775 °C of ferrite matrix [10]. The hysteresis loops are given in Figure 6. They show that the samples remained stable after the vacuum annealing during the measurement of the above mentioned temperature dependence of the magnetic moment up to 800 °C in vacuum. From the saturation state, we can derive saturation magnetization which is 191.0 ± 0.4 emu·g⁻¹, i.e. 191 A·m²·kg⁻¹ or 2.40·10⁻³ Wb·m·kg⁻¹.

**Figure 5.** Temperature dependence of magnetic moment of the 42CrMo4 steel sample measured in vacuum. The detailed insert shows the temperature hysteresis of α→γ→α magnetic phase transformation.

**Figure 6.** DC hysteresis loops of the 42CrMo4 steel sample before and after annealing.

The results of magnetic measurements on toroid shaped samples are shown in Figures 7. – 11. The basic comparisons are made among hysteresis curves measured without frequency because there are minimal eddy currents. In Figure 7, there is comparison among samples with the same ratio between outer and inner diameter but there are different thicknesses. Sample 1 is too thin and cross-section is not square. Hysteresis curve of sample 1 has the highest slope in contrast with sample 4 which has only one difference in the setting data, thickness. Sample 3 has smaller dimensions like sample 4 but the ratio is the same and slope of hysteresis curve is between sample 1 and 4.

Any significant differences on BH curves are not seen between the same outer diameter but slightly different ratio 1.10 and 1.17. The biggest differences may be expected between sample 4 and 7 but it is not. Sample 4 has the higher magnetic field strength. Distribution of magnetic flux through the cross-section is uneven but it has not significant influence on the shape of BH curve.
Initial magnetization curves of all samples can be seen on Figure 8. The biggest differences are between samples with cross-section which is not square or with different outer diameter. Differences between samples can be seen better on Figure 9., where is shown permeability of each sample. The worst permeability has sample 1 than sample 2 and 3 and rest of samples have similar permeability except for sample 8. This sample has the biggest cross-section and the worst ratio of diameters but permeability is worse than rest of the slightly smaller samples. Measurement errors can occur due to difficulties to put on enough primary winding on inner diameter which results in an uneven distribution of the magnetic flux through the cross-section. It was done measurement with frequencies besides quasistatic measurements and values of total magnetic losses were investigated. Results of these measurements can be seen on Figures 10. and 11. Samples with bigger volume have higher total magnetic losses and they are increasing exponentially as expected. It was not possible to measure Samples 7 and 8 on higher frequencies because of smaller number of windings which can be possible to put on these toroid samples and limitation of measuring device.
4 Conclusions

Obtained results show from XRD and Mössbauer spectroscopy that the samples consist of ferrite and (Fe, Mn)$_3$C and Cr$_{23}$C$_6$ carbides. The measurements of temperature dependences of magnetic moments confirm phase stability up to Curie temperature of ferrite (~775 °C). The saturation magnetization at room temperature is $191.0 \pm 0.4$ emu·g$^{-1}$, i.e. $191 \text{ A·m}^2\text{·kg}^{-1}$ or $2.40 \times 10^{-3}$ Wb·m·kg$^{-1}$ which corresponds with hyperfine induction $B_{hf} = 32.7 \pm 0.1$ T derived from the ferrite component in Mössbauer spectrum. Magnetic parameters were measured on toroid samples which were made from solid material of 42CrMo4 steel. It can differ in addition on dimensions of these samples. Bigger samples give better permeability but it is difficult to measure them in higher frequencies. Too small samples have disadvantage of difficult demagnetization before quasistatic measurements. The AC measurements show that the total magnetic losses are dependent on frequency and excitation exponentially. For example, the power losses were 34.86 W·kg$^{-1}$ in sample 4 at 50 Hz. The knowledge of the size of total magnetic losses is important at higher frequencies than 50 Hz in magnetic circuits. The temperature of the steel parts is increasing because of these losses and therefore it is appropriate to calculate their size. DC permeability reaches the maximum ~ 611 at magnetic field strength ~ 1279 A·m$^{-1}$. The obtained data on phase composition and magnetic behavior indicates, that the 42CrMo4 steel has good potential for applications in magnetic circuits where good mechanical properties together with soft magnetic properties are requested.

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