

## MAGNETIC AND TRANSPORT PROPERTIES OF 41CrMo4 STEEL

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### Abstract

Steel, which was designated to process as high-grade and hardening of surface was investigated from the point of views of magnetic and transport properties. The aim of this study is to describe the magnetic behavior, electrical resistivity and thermal conductivity of this material in case that it is applied for the components of magnetic circuits or some parts in an 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 and electrical resistivity. The magnetic parameters were obtained by measuring of magnetic hysteresis loops in dependence on saturation fields and their frequencies. The parameters are discussed from the point of view of possible applications as a magnetic material, which can be stressed by enormous mechanical forces.

**Keywords:** 41CrMo4 steel, magnetic properties, electrical resistivity

### 1. INTRODUCTION

Several construction steels may be applied as parts of magnetic circuits, where parameters of their magnetic and transport properties play an important role. For many applications knowledge of parameters for direct (DC) and alternating (AC) magnetic fields as saturation magnetization, coercivity, magnetic losses, susceptibility and electrical resistivity in dependence on temperature and heat&mechanical treatment history are requested. In literature some data on magnetic properties of construction low alloyed steels are seldom [1-3]. The aim of this study is to describe magnetic behaviour and electrical resistivity of 41CrMo4 steel in case that it is applied as a soft magnetic material for the components of magnetic circuits or some parts in an electrical equipment.

### 2. EXPERIMENTAL

The samples of the 41CrMo4 steel were obtained from a commercial rod. The chemical composition according to material description was following (**Table 1**):

**Table 1** Chemical composition in wt. %

C	Si	Mn	P	S	Cr	Mo
0.36 - 0.44	0.15 - 0.40	0.50 - 0.80	Max. 0.025	Max. 0.035	0.90 - 1.20	0.15 - 0.30

Structure and phase composition was studied using optical microscopy (OM), scanning electron microscopy (SEM), measurements of X-ray powder diffraction (XRD) and <sup>57</sup>Fe Mössbauer spectroscopy (MS). XRD was measured by means SmartLab (Rigaku) automatic diffractometer in conventional Bragg-Brenato geometry, and with CuK $\alpha_{1,2}$  radiation,  $\beta$ -filter in diffracted path and linear positional sensitive detector D-TEX. The negative effect of fluorescence caused by Cu characteristic radiation on Fe-rich sample was reduced by ability of

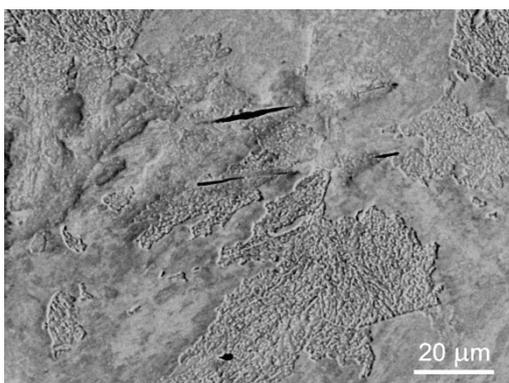
detector decreased the detection of low energetic photons during the measurements. For the qualitative and quantitative analysis HighScore Plus program (PANAnalytical) equipped by JCPDS PDF-4 database was used. <sup>57</sup>Fe MS spectra were measured at room temperature in transmission geometry ~ 10 mCi <sup>57</sup>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 behaviour by high temperature were investigated by temperature dependence of magnetic moment and electrical resistivity. The temperature dependence of the magnetic moment was measured under vacuum ( $\sim 10^{-2}$  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 in vacuum. The dependence of magnetic moment on external field (hysteresis loop) were measured before and after annealing at room temperature in external fields  $\pm 1$  T. Electrical resistivity were measured by four point method on thin strip in vacuum furnace using Keithley 2000 multi-meter.

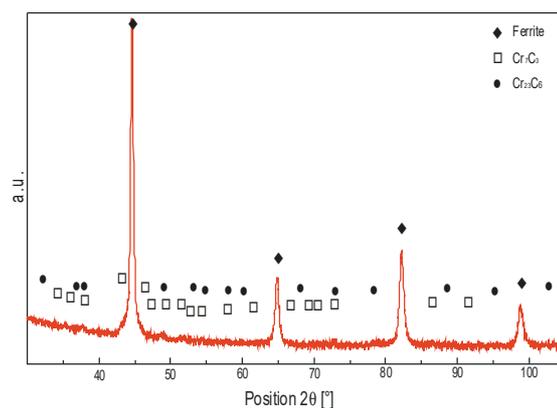
For AC measurements and quasistatic measurements of saturation magnetization and hysteresis losses equipment Remagraph - Remacomp C - 710 (Magnet-Physik Dr.Steingroever GmbH) was used with the ring core samples. This device is measuring the magnetic flux through the coil and it is based on the principle of Faraday law of electromagnetic induction. Outer diameter of this sample was 44.4 mm, inner diameter was 38.1 mm, height of this sample was 3 mm, weight was 9.07 g. Number of turns of primary winding was 101 and secondary winding had 20 turns. The properties were measured in frequency range 0 - 3000 Hz at room temperature. For the measurement without frequency was used part Remagraph and Remacomp was used for the other measurements (frequency range, which can this device use is approximately 10 Hz to 10 kHz).

## 2.1. RESULTS AND DISCUSSION

Information on the structure and phase composition was obtained using OM, SEM (**Fig. 1**) and XRD. From the XRD data (**Fig. 2**) the ferrite (matrix) structure parameters were unambiguously recognized. The presence of carbides Cr<sub>7</sub>C<sub>3</sub> and Cr<sub>23</sub>C<sub>6</sub> in the steel was also confirmed but intensities of their diffraction peaks are close the detection limits. Their content is about 0.4 wt. % Cr<sub>7</sub>C<sub>3</sub> and 0.2 wt.% Cr<sub>23</sub>C<sub>6</sub>.

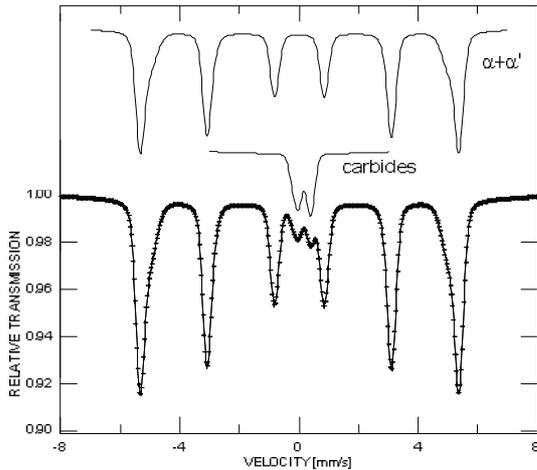


**Fig. 1** Scanning electron microscopy of the of 41CrMo4 steel sample

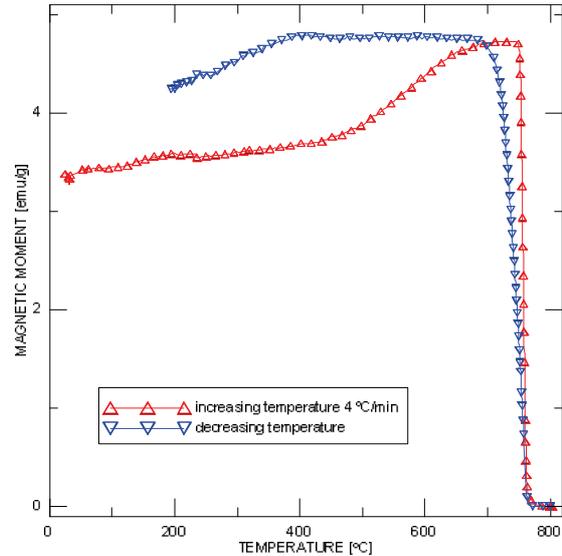


**Fig. 2** X-ray pattern of 41CrMo4 steel. (♦ferrite, □ Cr<sub>7</sub>C<sub>3</sub>, and • Cr<sub>23</sub>C<sub>6</sub>)

The Mössbauer spectrum of the steel sample is shown in **Fig. 3**. The experimental data were fitted by three sextet with mean hyperfine induction  $B_{hf} = 32.9 \pm 0.1$  T and two doublets. The sextets represent  $\alpha + \alpha'$  phases, the doublets can be ascribed to Cr<sub>7</sub>C<sub>3</sub> and Cr<sub>23</sub>C<sub>6</sub> type of carbides with agreement to parameters published in [4].

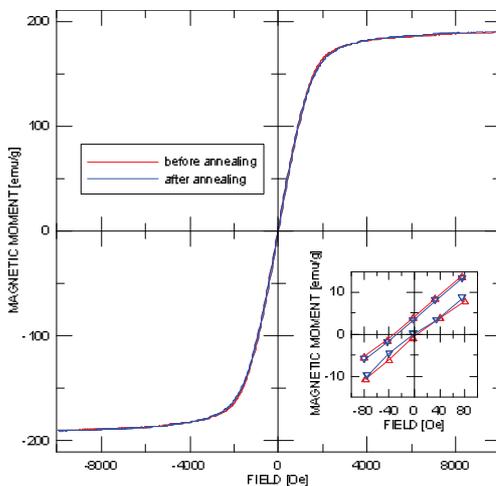


**Fig. 3** Room temperature Mössbauer spectrum of the 41CrMo4 steel sample. The crosses denote experimental points and the line the fitted function. Above the spectrum two main fitted components are drawn

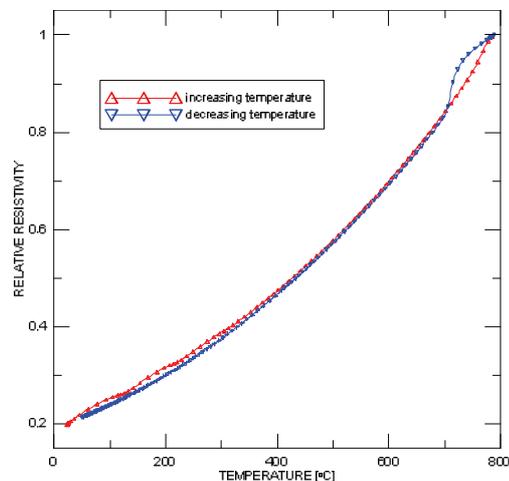


**Fig. 4** Temperature dependence of magnetic moment of the 41CrMo4 steel sample measured in vacuum

The temperature dependence of magnetic moment of the 41CrMo4 sample is drawn in **Fig. 4**. From this dependence we can observe magnetic transformation at approx. 775 °C which corresponds to Curie temperature of the ferrite matrix [5]. The hysteresis loops are given in **Fig. 5**. 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  $190.0 \pm 0.2$  emu/g., i.e.  $190 \text{ A}\cdot\text{m}^2\cdot\text{kg}^{-1}$  or  $2.39\cdot 10^{-3} \text{ Wb}\cdot\text{m}\cdot\text{kg}^{-1}$ . The temperature dependence of electrical resistivity is drawn in **Fig. 6**. The slight deviation from a smooth increase with temperature increase may be observed in two temperature regions: (i) The processes of recovery (defect annihilation) in the region up to approx. 200 °C and (ii) in region of Curie temperature at approx. 770 °C. The resistivity of the steel at room temperature is  $12\cdot 10^{-8} \text{ Ohm}\cdot\text{m}$ . In agreement with the temperature dependence of magnetic moment formation of an amount of austenite causes increase in resistivity by temperature decrease in range 770 - 705 °C.

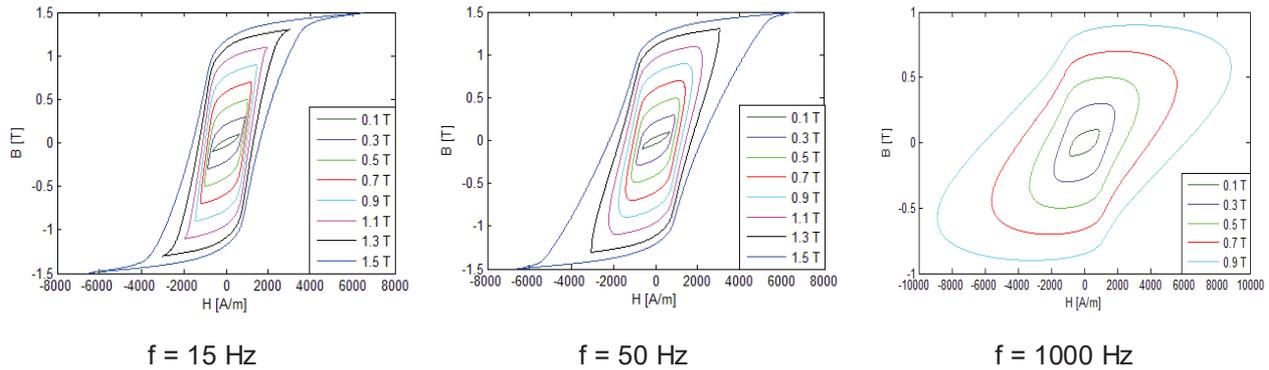


**Fig. 5** DC hysteresis loops of the 41CrMo4 steel sample before and after annealing

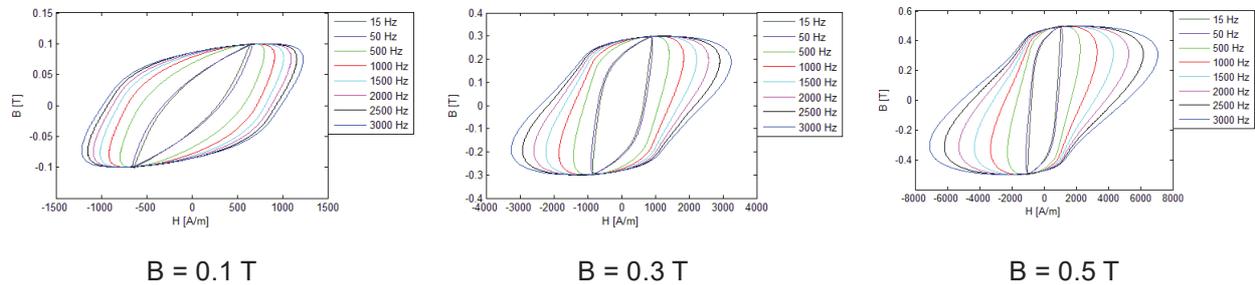


**Fig. 6** Temperature dependence of resistivity of the 41CrMo4 steel

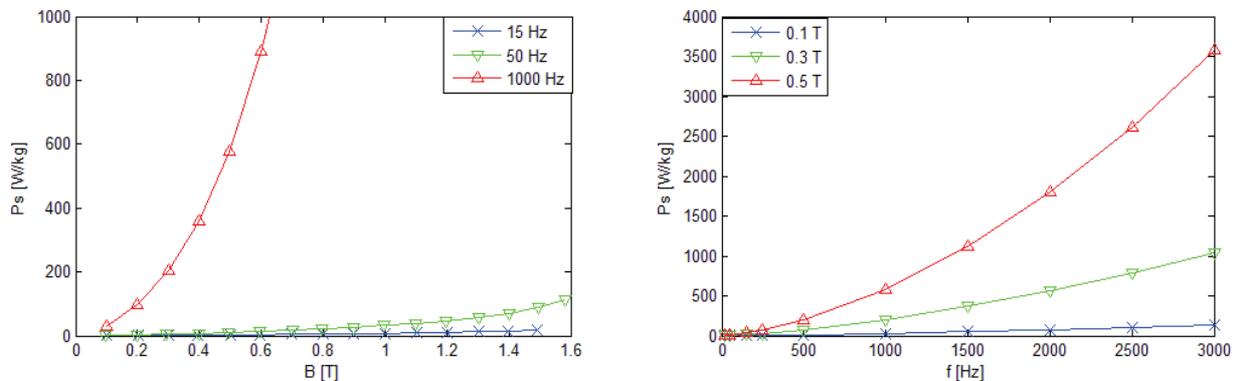
The examples of the results obtained by AC magnetic measurements are shown in **Figs. 7-9**. The shapes of hysteresis curves (**Figs. 7 and 8**) are changing with increasing excitation, where measured material is reaching saturation. With the increasing frequency the shapes of hysteresis curves become elliptic form and the areas of these curves (eddy current losses) are increasing. As expected, power losses  $P_s$  are dependent on excitation (hysteresis losses) and frequency of excitation (eddy current losses) so that the value of  $P_s$  is increasing with frequency and magnetic flux density too (**Fig. 9**). It should be noted, that the measurements at high frequencies were very fast and so the sample was not warm up too much despite the fact that value of total losses were high.



**Fig. 7** Hysteresis curves with increasing excitations and frequencies



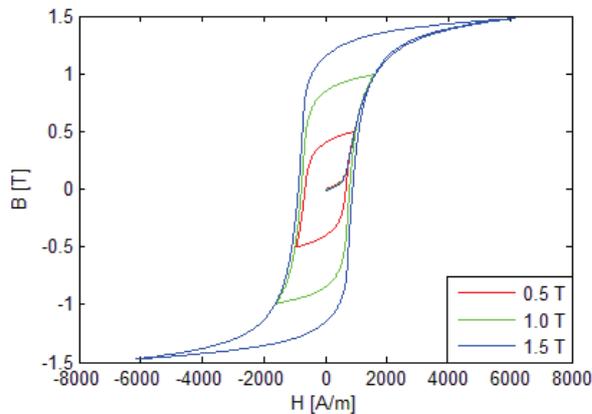
**Fig. 8** Hysteresis curves with increasing frequencies and saturations



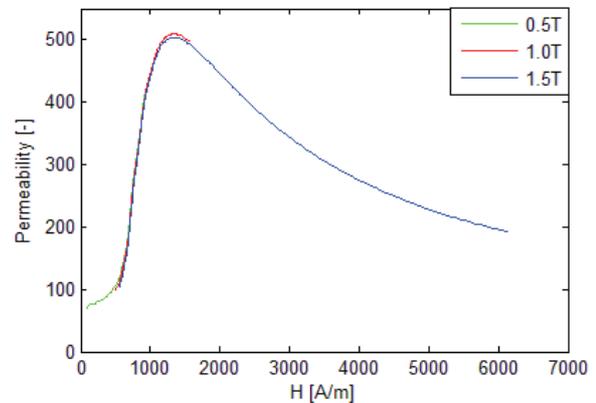
**Fig. 9** Hysteresis losses in dependence on excitation and frequency

DC measurement of hysteresis curves can be seen on **Fig. 10**. These curves are much narrower, than previous hysteresis curves at different frequencies, because only hysteresis losses are there and eddy

current losses do not appear almost at all. The changes of DC permeability can be seen on **Fig. 11**. It reaches the maximum ~500 at magnetic field strength ~1360 A/m.



**Fig. 10** Hysteresis curves with increasing saturations at zero frequency



**Fig. 11** Curves of permeability with increasing saturations at zero frequency

### 3. CONCLUSIONS

We have measured magnetic parameters and electrical resistivity of 41CrMo4 steel. XRD and Mössbauer spectroscopy show, that the samples consist of ferrite and Cr7C3 and Cr23C6 type of carbides. The measurements of temperature dependences of magnetic moments and electrical resistivity confirm phase stability up to Curie temperature of ferrite (~770 °C). The room temperature resistivity was  $12 \cdot 10^{-8}$  Ohm·m. The saturation magnetization at room temperature is  $190.0 \pm 0.2$  emu·g<sup>-1</sup>, i.e.  $190$  A·m<sup>2</sup>·kg<sup>-1</sup> or  $2.39 \cdot 10^{-3}$  Wb·m·kg<sup>-1</sup> which corresponds with hyperfine induction  $B_{hf} = 32.9 \pm 0.1$  T derived from the ferrite component in Mössbauer spectrum. The AC measurements show that the power losses are strongly dependent on frequency and excitations. For frequency 50 Hz and excitation 1.5 T the power losses reach ~100 W·kg<sup>-1</sup>. It is very important to know power losses in the magnetic circuits for the frequencies above 50 Hz. The temperature of the steel parts is increasing because of these losses so their value should be calculated. DC permeability reaches the maximum ~500 at magnetic field strength ~1360 A/m.

### ACKNOWLEDGEMENTS

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