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MAGNETIC CHARACTERISATION OF PHASE TRANSFORMATIONS IN TRIP STEELS

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In the present work the microstructure and the strain induced phase transformation of TRIP steel were studied. Sheet samples were elongated in a tensile testing machine. The number of samples was eighteen; the applied deformation was up to 28%. The magnetization curves were measured by a single sheet tester-type magnetic property analyzer. The series of symmetrical minor hysteresis loops and the saturation loop were measured.

Our novel data evaluation technique was applied for data evaluation of the magnetic measurements. This method is based on the multiphase-hyperbolic model of magnetization and it is called model based data evaluation (MBDE) technique. The MBDE method allows us to separate the magnetic contribution of different magnetic phases of the tested alloy. The magnetic contribution of ferrite, bainite and martensite phases were determined. Not only their relative phase ratios can be determined by this unique phase decomposition method but the magnetization curves of the individual contributory phases, can be calculated as well.

The application of model based data evaluation technique (MBDA) seems to be a promising and sophisticated data evaluation tool in magnetic measurements.

Keywords: hysteresis, modelling, magnetic measurements, phase separation, mlticomponent-hyperbolic model, TRIP steel

1 INTRODUCTION

Formable high strength steel sheets for the automotive industry have been developed in response to the conflicting demands for safety and weight reduction. This required steel sheets with extremely large ductility maintaining desired strength about 980 MPa. Transformation induced plasticity (TRIP) steels with an excellent combination of elongation over 30% and high tensile strength of 980MPa presented an answer for such demands [1]. The remarkable strength to ductility balance of TRIP steels results from the strain-induced transformation of retained austenite to martensite during plastic deformation. The retention of austenite is obtained by the combination of appropriate chemical composition and thermo-mechanical processing (TMP) of steel. The typical microstructure of TRIP steels consists of 50 vol % ferrite, 35 vol % bainite and 15 vol % metastable retained austenite [2]. This steel offers large dynamic energy absorption and thus leads to improved crash worthiness for better passenger safety in the car industry. These excellent mechanical properties mainly arise from strain-induced transformation of retained austenite to martensite, accompanied by a volume expansion resulting in plastic deformation and the work hardening of surrounding ferritic phases [3]. Therefore the so called TRIP effect in these steels arises from a martensitic transformation of the metastable retained austenite phase induced by external stress. The paramagnetic austenite phase (γ-Fe) transforms to ferromagnetic martensite phase while the mechanical and magnetic properties of the surrounding ferrite phase changes. The carbon concentration in the austenite grains and the grain size of the retained austenite play a crucial role in the TRIP properties as they significantly affect the mechanical stability of the retained austenite.

2 THEORY

The predecessor of the hyperbolic model was the $T(x)$ model which was published by Takacs [4]. This model presents a phenomenological mathematical description of magnetic, sigmoid shaped hysteresis loops and normal magnetization curves in closed mathematical form. The $T(x)$ model was developed and it was called hyperbolic model. In its new form it is able to describe the saturation effect and it has better fitting accuracy.

In this work a more sophisticated version of the hyperbolic model is presented. The model is extended to alloys which contain two or more magnetic phases. This new version of the model is called multiphase-hyperbolic model (MHM). Therefore the multiphase-hyperbolic model can be applied for alloys which contain one magnetic (*ie* ferro-, or ferrimagnetic) phases. The model, described here, enables us to decompose a measured compound magnetization curve and to separate the elementary magnetization curves in multiphase alloys.

It is known that the thermodynamically equilibrium state of a magnetic material can be characterized by its anhysteretic magnetization curve [5]. In the MHM model the anhysteretic magnetization curve is constructed as a linear combination of "tanh" functions (1). According to the main idea of the model the ascending and descending arms of each hysteresis loops can be constructed by shifting the anhysteretic curve, described by (1), horizontally by α_i and at the same time vertically by β in a symmetrical way, see (2) to (5). Considering that the ascending and descending legs of each hysteresis loop must intercept at their maxima, the value of β can be calculated (6).

The analytical approach described here was based on the initial assumption that, when an alloy contains two or

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more magnetic metallurgical phases they are not interacting magnetically therefore their magnetization curves can be linearly superimposed. From this, it has followed, that in a simple case the hysteresis loop of an alloy can be composed by linear superposition of the sigmoid type loops of the individual components, by using Maxwell superposition principle. This model facilitates the linear superposition of the individual sigmoid loops and indeed provides the way to separate the simple phases and/or the different parallel magnetic processes acting in an alloy during magnetization.

In an alloy the contribution of the individual magnetic phases to the combined hysteresis loop can be described by the following mathematical equations.

$$M = \sum_{i=1}^{N} \left[A_i \tanh\left(N_i H\right) \right] \tag{1}$$

$$M_+ = \sum_{i=1}^{N} \left(A_i f_+ \right) + \beta \tag{2}$$

$$M_- = \sum_{i=1}^{N} \left(A_i f_- \right) - \beta \tag{3}$$

$$f_+ = \tanh\left[N_i \left(H - \alpha_i \right) \right] \tag{4}$$

$$f_- = \tanh\left[N_i \left(H + \alpha_i \right) \right] \tag{5}$$

$$\beta = \frac{1}{2} \sum_{k=1}^{N} A_i \left(f_- - f_+ \right) \qquad for \;\; H = H_m \tag{6}$$

$$R_i = \frac{A_i}{\sum_{i=1}^{N} A_i} 100\% \tag{7}$$

The model is characterised by practical parameters used in magnetism. Here M_+ and M_- are the normalized ascending and descending arms of the $M(H)$ magnetic hysteresis loop respectively, H is the magnetic field of excitation, M is the magnetization, α_i is the coercivity of the i-th magnetic phase. A_i is the amplitude of the components present, N_i is the scaling factor and β is the integration constant, while H_m represents the maximum field excitation. The index i refers to the individual components of the magnetic circuit and N is the number of total magnetic components involved. In the present application of the model N equals 4. Components #1, #2, #3 represent the three magnetic phases of the measured sample and #4 represents the reversible component of the magnetization process [6]. The magnetic micro constituents (phases) of the tested TRIP alloy are the ferrite, bainite and the strain induced martensite. The reversible component has zero coercivity therefore $\alpha_3 = 0$. Physically the reversible magnetization component expresses the elastic behaviour of domain walls during the magnetization process as well as the possible paramagnetic contribution.

The relative contribution of the i-th magnetic phase to the magnetization process is expressed by R_i. If the alloy contains only magnetic (*ie* ferro- or ferrimagnetic) phases the value of R_i expresses the relative phase ratio of the i-th magnetic phase of the alloy.

The loci of the crossover points of the up-going and down-going parts of the minor loops and the saturation hysteresis loop are referred as normal magnetization curve [8, 9]. From the (1) to (6) the mathematical function of the normalized normal magnetization curve can be calculated. The form of the obtained normal magnetization curve contains three irreversible parts and a part corresponds to the reversible magnetization (8).

$$\begin{aligned} \frac{M(H)}{M_0} &= M_{irrev1} + M_{irrev2} + M_{irrev3} + M_{rev} \\ \frac{M(H)}{M_0} &= M_{ferrite} + M_{bainite} + M_{martensite} + M_{rev} \end{aligned} \tag{8}$$

Where M_0 is value of the saturation magnetization.

In this work the minor hysteresis loops and the normal magnetization curve were measured by alternating current measurement. The theoretical normal magnetization curve (8) was fitted to the measured normal magnetization curves and the model parameters were determined.

3 TESTED SAMPLES

The tested samples were cut out from a cold rolled sheet of TRIP 700 type steel produced by the Thyssen-Krupp Company. The nominal chemical composition of the tested material is summarized in Table 1.

Table 1. The nominal chemical composition of the tested steel.

C	Mn	Si	Al	P	S	Fe
0.28	1.41	0.28	1.04	0.016	0.001	Rest

Their sizes were 150×20 mm the thickness was 1.18 mm. The longitudinal direction of the samples was corresponding to the rolling direction of the sheet material. Therefore the samples were magnetized according to their rolling direction.

Table 2. Typical mechanical properties of the TRIP 700 steel.

Upper yield strength	Fracture strength	Fracture strain
539 MPa	751 MPa	28 %

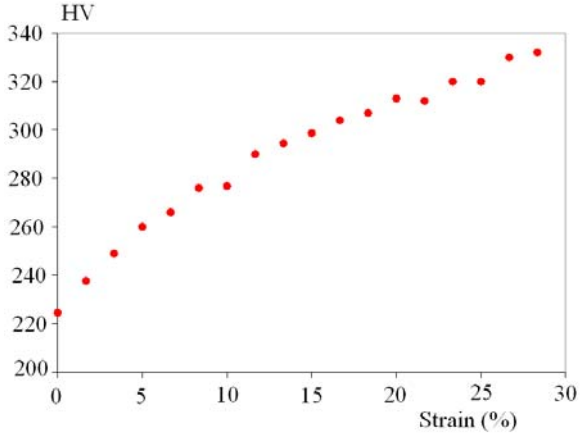

Fig. 1. The measured Vickers hardness values of the elongated samples.

The most important mechanical properties of the tested TRIP 700 steel are summarized in Table 2.

The samples were elongated at room temperature in a tensile testing machine. The applied strain values were 0, 1.67, 3.33, 5.00, 6.67, 8.33, 10.00, 11.67, 13.33, 15.00, 16.67, 18.33, 20.00, 21.67, 23.33, 25.00, 26.67, 28.33 %.

The Vickers hardness values of the elongated samples were measured by applying 2000 grams of load. The significant increase of hardness can be seen in Fig. 1.

4 MAGNETIC MEASURING ARANGEMENT

A single sheet tester type magnetic analyzer was used for measuring the symmetrical minor magnetic hysteresis curves. The applied measuring yoke contains two symmetrical U-shaped laminated FeSi iron cores to close the magnetic circuit. The excitation current was sinusoidal produced by a digital function generator and a power amplifier, used in voltage regulated, current generator mode. The driving coil and the pick-up coil were around the middle part of the specimen. The permeameter was under the control of a computer in which a 16 bit input-output data acquisition card accomplished the measurements. The applied maximum excitation field strength was 2100 A/m. In case of each samples 200 minor hysteresis loops were measured.

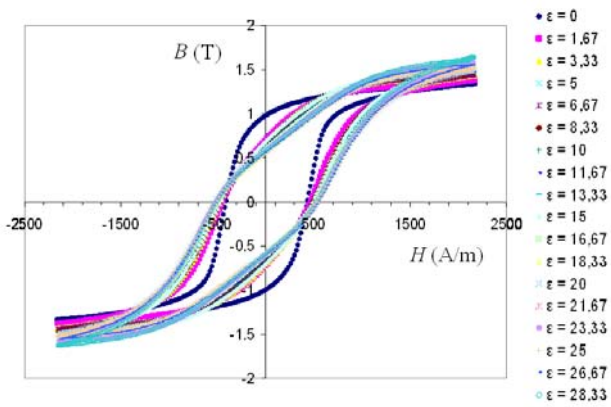

Fig. 2. A set of measured hysteresis loops of the plastic deformed sample series.

Each minor hysteresis loops were recorded by measuring 500 points of them. The excitation magnetic field was increased in steps and there was 5 seconds delay between the steps and the data acquisition to ensure the sample perfect magnetic accommodation, free of the effect of magnetic transients. All the magnetic measurements were carried out by using sinusoidal excitation at a frequency of 5 Hz.

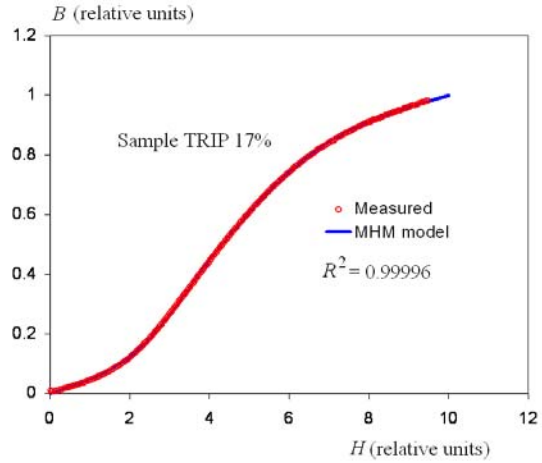

Fig. 3. The points of the measured normal magnetization curve and the fitted normal curve of the MHM model.

Because of the relatively low excitation frequency and small thickness of the samples, the completed magnetic measurements could be regarded as pseudo-static and the effect of eddy-current on the magnetization curves were negligibly small, well within the measuring error. The permeameter allowed us to derive all the practical magnetic parameters such as coercivity, remanence directly from the measured hysteresis loops. A set of the measured hysteresis loops can be seen in Fig. 2.

5 PHASE DECOMPOSITION AND RESULTS

The normal magnetization curve (8) of the multiphase-hyperbolic model was fitted to the measured normal curves. The fitting parameters were determined by our special two step iteration technique based on the Levenberg-Marquardt method. Although the shapes of the measured normal curves are quite complex the fitted normal curves are perfectly fit to the experimental points from zero field to the near saturation range. The calculated deterministic coefficients were always better than 0.995 in all tested cases. As an example, Fig. 3 depicts the measured and fitted combined normal magnetization curves of the experimental sample TRIP 17%. From the calculated fitting parameters of the MHM model the individual magnetization curves and the relative phase ratio of the constituent magnetic phases were determined. Therefore the hysteresis loops and the

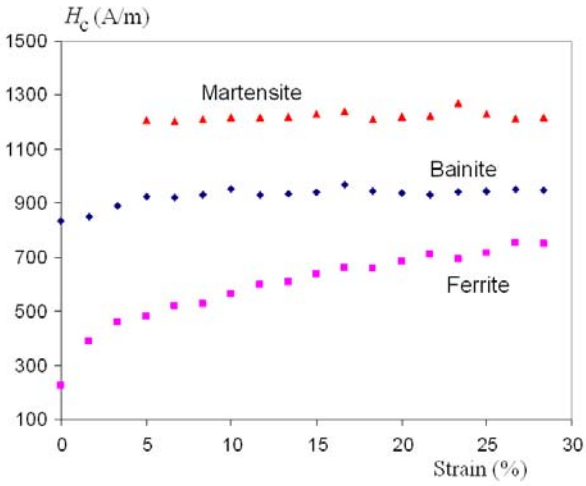

Fig. 4. The determined coercivity values of the constituent magnetic phases.

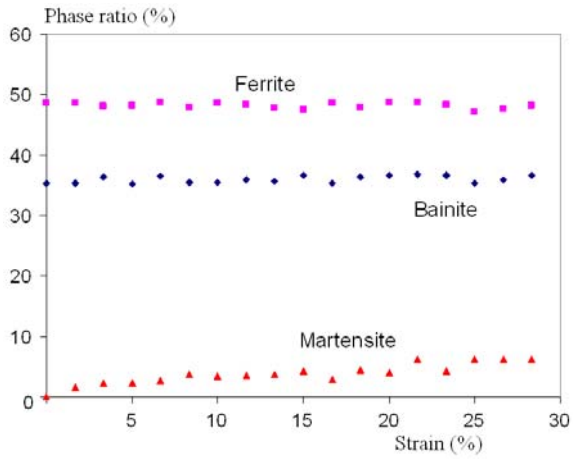

Fig. 5. The determined phase ratio values of the constituent phases.

normal magnetization curves of the ferrite, bainite and martensite phases were determined. The calculated values of coercivity and the relative phase ratios are plotted in Fig. 4 and Fig. 5, respectively. The phase ratio values calculated by MBDE technique are in good agreement with the results of our electron beam scattering diffraction (EBSD) measurements.

The applied MBDE analysis helped us to understand better the metallurgical sub processes of the strain induced phase transformation of TRIP steel.

It can be concluded that the relative amount of ferrite and bainite phases do not change during the plastic deformation process. But the amount of martensite phase monotonically increases due to plastic deformation. Consequently the ferrite → martensite phase transformation is continuous during the deformation process up to 28% strain.

The coercivity of bainite and martensite phases does not affected by the plastic deformation. But the coercivity (and hardness) of the ferrite phase significantly and continuously increases due to plastic deformation. Therefore the significant work hardening of the TRIP steel is caused by both the increasing amount of strain induced martensite phase and the hardening of ferrite phase. It can be supposed that the hardening of ferrite phase is caused by the specific volume increase of the surrounding martensite grains during the austenite → martensite phase transformation.

6 CONCLUSIONS

In this work a novel data evaluation technique was introduced to separate the magnetic contribution of the magnetically different phases of TRIP alloy.

This procedure is based on the multiphase hyperbolic model and it is called model based data evaluation (MBDE) technique. The magnetically different micro constituents (phases) of TRIP steel were decomposed. The individual magnetization curves of ferrite, bainite and martensite were determined by MBDA.

The MBDE technique was applied for studying the plastic strain induced phase transformations in TRIP steels. It was proved that the magnetically different phases (or micro constituents) of the TRIP steel (i.e. ferrite, bainite, martensite) can be separated and their individual magnetization curves can be determined.

The application of model based data evaluation technique (MBDA) seems to be a promising tool in data evaluation of magnetic measurements.

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