E-Journal of Advanced Maintenance Vol. 11 No. 3 (2019) 118-123
Japan Society of Maintenology

Investigating the performances of parameters of magnetic hysteretic loop on characterizing the residual plastic strain in low carbon steel

Xiaodong ZHANG, Bin WU , Xiucheng LIU* and Cunfu HE

College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing 100124, China

ABSTRACT

The residual plastic strain in ferromagnetic structural components will affect the structural integrity, the mechanical properties of materials and even the service life. Therefore, accurately characterizing the degree of residual plastic strain is important to predict the service life time of components. The plastic deformation changes the dislocation density and the magnetic hysteretic properties of ferromagnetic materials. The variation in the shape of magnetic hysteresis curves will be suitable indicators for nondestructive evaluation of the residual plastic deformation in ferromagnetic steels. The core issue is to find stable magnetic parameters a that are sensitive to the changes of the residual plastic strain. In this study, the performances of the magnetic parameters (including coercive force H_c, maximum magnetic flux density B_{max}, hysteresis loss W_L and the harmonic amplitudes of magnetic flux density b_1, b_3) to the residual plastic strain in low carbon steel were investigated by experiments. Especially, the influences of excitation frequency on the performances of magnetic parameters in characterizing the residual plastic strain were analyzed. The results show that both the parameters of B_{max} and b_1 demonstrate linear dependency on the residual plastic strain ε_p even the frequency of the applied magnetic field changes. Therefore, the parameters of B_{max} and b_1 are preferred parameters to characterize the residual plastic strain in the tested low carbon steel.

KEYWORDS

Magnetic hysteretic loop, residual plastic strain, low carbon steel, magnetizing frequency

1. Introduction

Plastic deformation occurred in ferromagnetic materials results in residual plastic strains, which may lead to the generation of micro-cracks and change the mechanical properties of the materials [1]. Accurately characterizing the degree of residual plastic strain is helpful for material evaluation. The application of the magnetic technique is capable of evaluating the residual strain in a quick and nondestructive way.

The plastic deformation changes both the dislocation density and residual stress inside the ferromagnetic materials, affecting the pining effect applied to the domain-wall while the materials is subjected to an external magnetic field. The change of microstructures and the residual stress affects the macroscopic hysteretic magnetic properties of ferromagnetic materials [2, 3]. The influences of plastic deformation on the magnetic properties and magnetic parameters has been studied in Ref. [4, 5]. To explain the magnetic behavior induced by plastic deformation, J-A model was extended to incorporate the effect of plastic deformation by introducing the dislocation density into the effective field of the model [6-8]. Therefore, the magnetic method, major hysteresis loop measurement, can be applied on the characterization of the residual plastic strain of magnetic material [9]. In order to measure the major magnetic hysteresis loop, the magnetic measurements should be static and the effect of eddy current on the magnetization curves can be negligibly. However, in the actual detection, the exciting frequency is low frequency, such as 5Hz and 10Hz, which can be regarded as pseudo-static. And the effect of different low exciting frequencies on the parameters extracted from the hysteresis loop should be investigated.

In this study, the residual plastic strain is induced in dog bone specimens of low carbon steel by stretching the specimen to its plastic stage and then unloading to free state. The magnetic hysteretic curves of the specimens are measured. Multiple parameters extracted from the measured hysteretic

*Corresponding author, E-mail: xiuchliu@bjut.edu.cn

curves are used to characterize the residual plastic strain. Linear curve fitting operation is applied to the measured data to help find suitable magnetic parameters for nondestructive evaluation of residual plastic strain. Meanwhile, the influences of excitation frequency on the reliability of magnetic parameters in characterizing the residual plastic strain were analyzed. Under different excitation frequencies, the sensitivity of the investigated magnetic parameters to the residual plastic strain is analyzed. Finally, the suitable magnetic parameters for residual plastic deformation evaluation are selected by conducting comparison studies.

2. Experiment

2.1. Specimen preparation

The chemical composition of the tested low carbon steel is given in Table. 1. The specimens are machined from the same carbon steel plate along the rolling direction, and the sizes of the dog bone specimens are shown in Fig.1. The sizes of the middle part of the specimen is selected as about 120mm(length)×30mm(width)×3mm(thickness), according to the Chinese Standard GB/T 228-2002. Then the specimens were alternatively uniaxially tensioned to plastic deformation stages with different applied tensile stress holding 60s and then unloaded from different stress levels. The stress rate is 20MPa/s. The residual strain at the center of specimen is measured by micrometer, namely the change of calibration length before and after tensile test. As a results, the residual plastic strains of each specimen is different from the rest specimens. The measured residual plastic strains for all the tested specimen are given in Table 2. No.1 specimen is non-deformed to act as a reference.

Table 1 Chemical composition of low carbon steel

Specimens	C	Si	Mn	P	Cu	Cr	S
wt (%)	0.041	0.017	0.11	0.012	0.012	0.014	0.0082

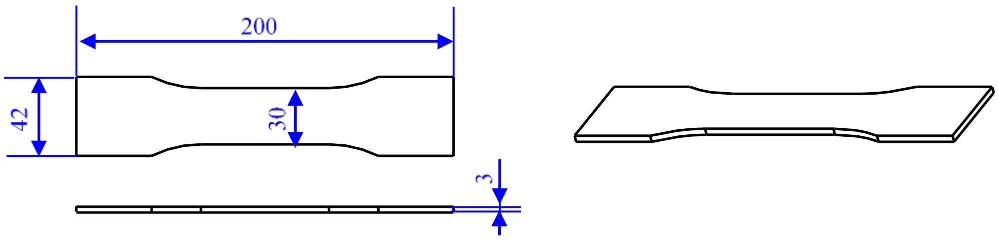


Fig1. The dimensions of the specimen (non-deformed)

Table 2 Residual plastic strain of the specimens

Specimens	1	2	3	4	5	6	7	8	9
ε_p (%)	0.00	0.80	1.11	1.59	1.91	2.23	2.72	3.24	3.69
Specimens	10	11	12	13	14	15	16	17	18
ε_p (%)	3.99	4.88	5.56	6.21	6.58	9.10	9.19	10.70	13.29

2.2. Experiments and results

The experimental system as shown in the Fig.2 consists of a signal excitation and acquisition system, the bipolar power supply, a U-shaped ferrite yoke, a hall sensor and the induction coil. In the experiments, the signal generator output a sinusoidal wave with the frequency of 2, 6, 10, 14, 18 Hz respectively. The output signal is amplified by a bipolar power supply and then fed into the excitation coil wound on the yoke to provide magnetic field for samples magnetization. A Hall sensor was placed above the specimen to obtain the surface magnetic field intensity and the induction coil was wound directly around the sample to measure the change of the magnetic flux.

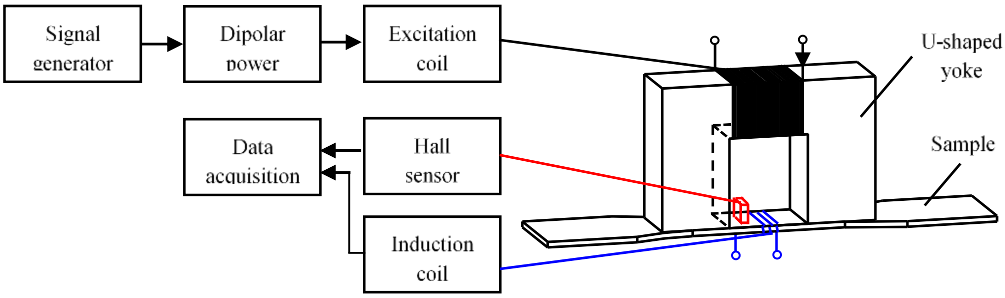
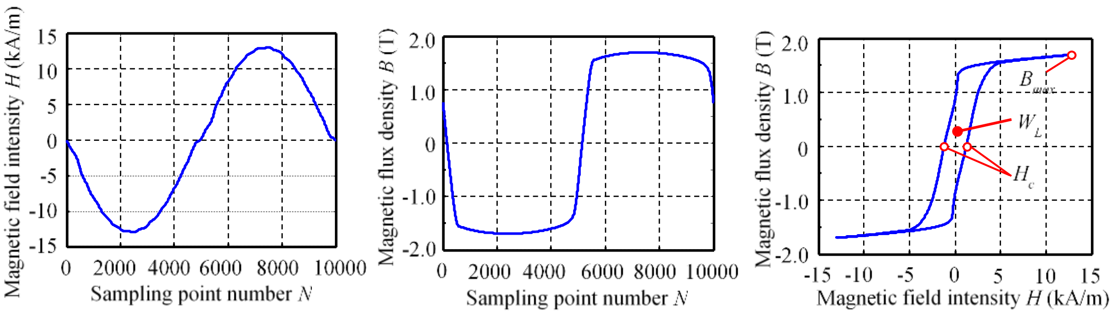


Fig.2 The Schematic diagram of experimental system

The hysteresis loops of the dog bone samples were measured at room temperature and the specimens were preliminarily demagnetized via demagnetizer TC-2 before measuring the magnetic hysteretic curves in order to eliminate the disturbance of different initial remanence introduced by manufacturing process.

The typical output signals of Hall sensor and pick-up coil and the obtained hysteresis loop are plotted in Fig.3. The variation in the shape of magnetic hysteresis loop may be suitable indicators for nondestructive evaluation of the residual plastic strain. Several parameters are extracted or estimated from the measured results to characterize the residual plastic strain of the samples. The investigated parameters includes the coercive force H_c, hysteresis loss W_L, maximum magnetic flux density B_{max}, the first and third harmonic amplitudes of measured surface magnetic field b_1, b_3 and the ratio of third to first harmonic amplitude b_3/b_1 .



(a) The signal of magnetic field intensity (b) The signal of magnetic flux density (c) The hysteresis loop

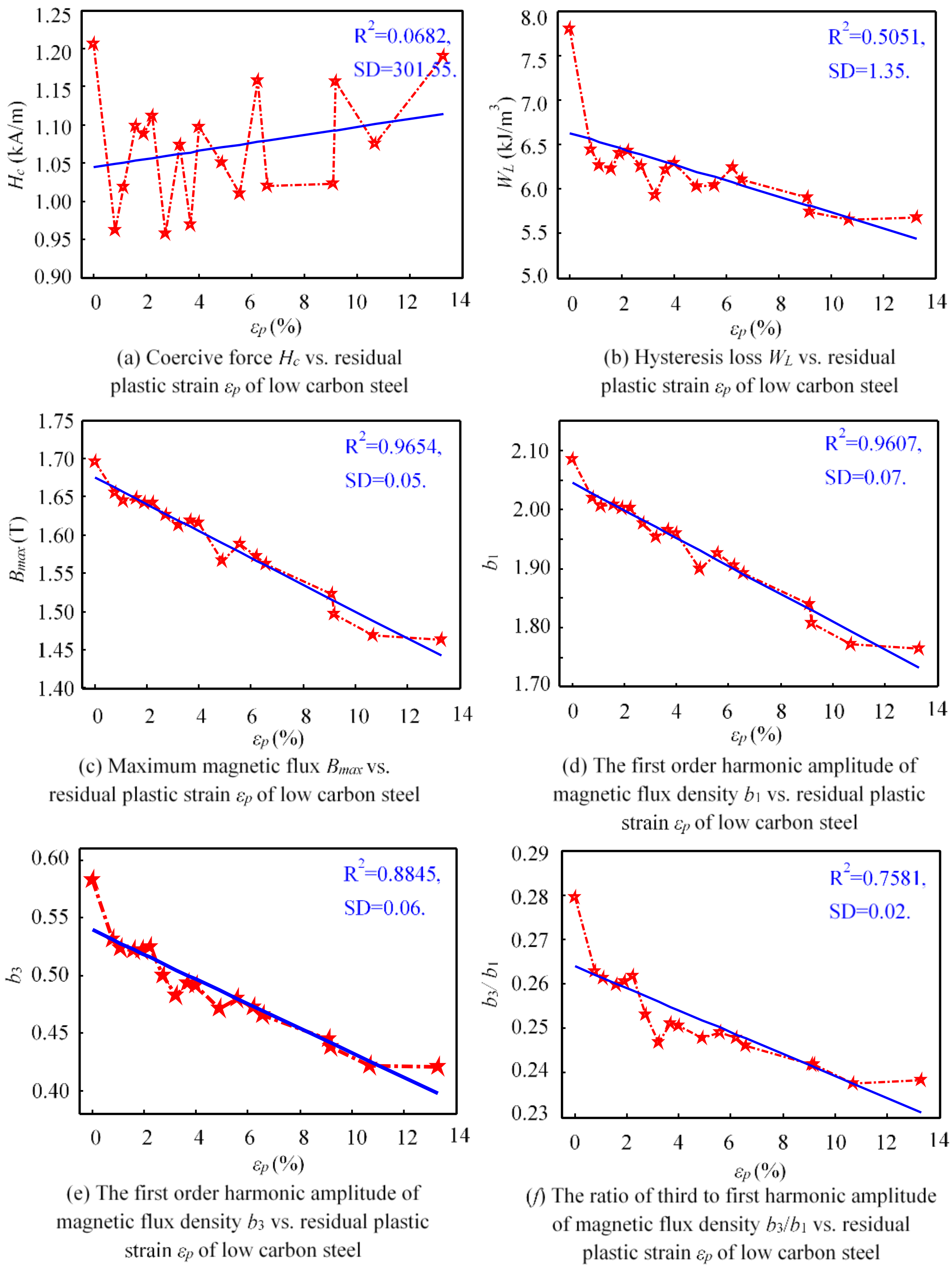
Fig.3 The typical magnetic signals measured

The results obtained under the condition with an excitation frequency of 2 Hz are taken as examples to investigated the sensitivity of the magnetic parameters on the characterizing the residual strain. Simple linear regression fitting operation is applied to the measured data of magnetic parameters and the residual strain. The analysis results are shown in Fig.4.

Both the parameters of B_{max} and b_1 demonstrate linear dependency on the residual plastic strain ε_p, whose regression coefficients R^2 are 0.9654 and 0.9607, respectively.

The shape of the measured hysteresis loop depends on the frequency of the applied magnetic field due to eddy current loss and anomalous loss [10]. Here, the effect of the magnetizing frequency on the correlation between the magnetic parameters and the residual strain is especially investigated by experiments. The results obtained under the case with magnetizing frequencies of 6, 10, 14, 18 Hz are shown in Fig.5.

The effect of the magnetizing frequency on the dependency of individual magnetic parameter on the residual strain is limited. However, the magnetizing frequency changes both the slope and the intercept of fitted lines.



(a) Coercive force H_c vs. residual plastic strain ε_p of low carbon steel

(b) Hysteresis loss W_L vs. residual plastic strain ε_p of low carbon steel

(c) Maximum magnetic flux B_{max} vs. residual plastic strain ε_p of low carbon steel

(d) The first order harmonic amplitude of magnetic flux density b_1 vs. residual plastic strain ε_p of low carbon steel

(e) The first order harmonic amplitude of magnetic flux density b_3 vs. residual plastic strain ε_p of low carbon steel

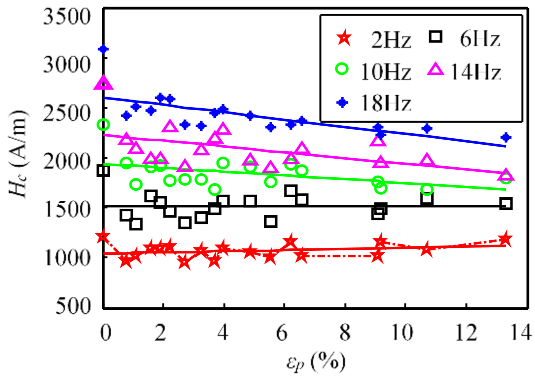
(*f*) The ratio of third to first harmonic amplitude of magnetic flux density b_3/b_1 vs. residual plastic strain ε_p of low carbon steel

Fig. 4. The relationship between magnetic parameters and residual plastic strain

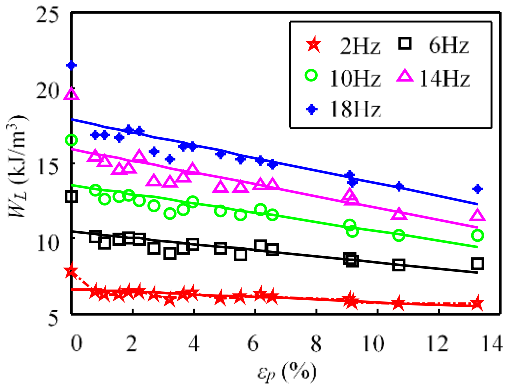
As the magnetizing frequency increases, the values of H_c and W_L increase while the value of b_1, b_3, b_3/b_1 decrease. Among the investigated parameters, the values of B_{max} and b_1 experiences minor changes as the magnetizing frequency changes. The linear regression coefficients R^2 for all the fitted lines in the Fig.5 are listed in Table. 3.

As compared to the rest parameters, the regression coefficients is higher than 0.9 for the cases of the parameters of B_{max} and b_1, indicating that the parameters of B_{max} and b_1 demonstrate good linear dependency on the residual plastic strain ε_p. In addition, the performance (regression coefficients) of the parameters of B_{max} and b_1 on characterizing the residual strain are nearly not affected by the magnetizing frequencies. Therefore, the parameters of B_{max} and b_1 are preferred parameters to characterize the residual plastic strain in the tested low carbon steel.

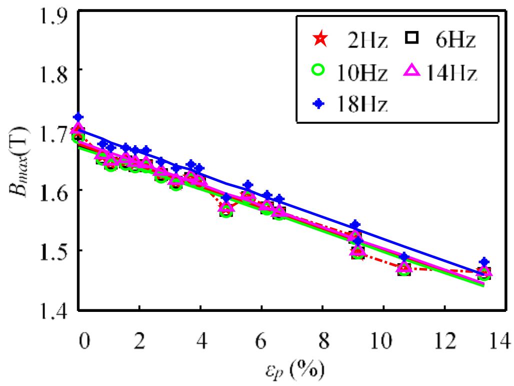
The eddy current loss and anomalous loss will generated when the magnetizing frequency increase, which will directly affect the coercive force H_c and hysteresis loss W_L. However, the maximum magnetic flux density B_{max} is insensitive to the eddy current loss and anomalous. So the values of B_{max} and b_1 experiences changes a little as the magnetizing frequency changes and the values of H_c and W_L change greatly.



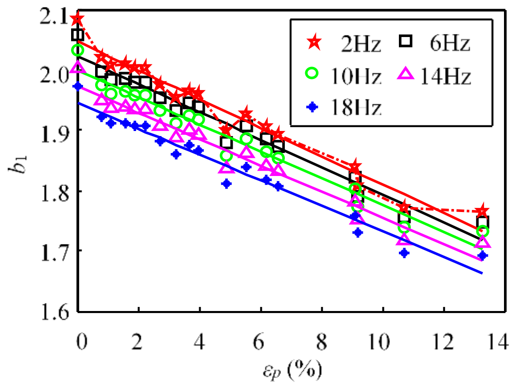
(a) Coercive force H_c vs. residual plastic strain ε_p of low carbon steel



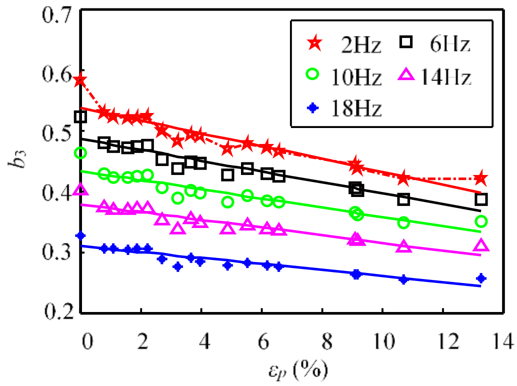
(b) Hysteresis loss W_L vs. residual plastic strain ε_p of low carbon steel



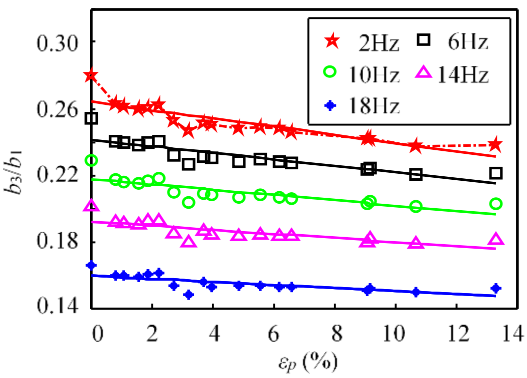
(c) Maximum magnetic flux B_{max} vs. residual plastic strain ε_p of low carbon steel



(d) The first order harmonic amplitude of magnetic flux density b_1 vs. residual plastic strain ε_p of low carbon steel



(e) The first order harmonic amplitude of magnetic flux density b_3 vs. residual plastic strain ε_p of low carbon steel



(*f*) The ratio of third to first harmonic amplitude of magnetic flux density b_3/b_1 vs. residual plastic strain ε_p of low carbon steel

Fig. 5. The relationship between magnetic parameters and residual plastic strain at different frequencies of applied field

Table 3 The linear regression coefficients R^2 for the cases with different magnetizing frequencies

	$R^2(H_c)$	$R^2(W_L)$	$R^2(B_{max})$	$R^2(b_1)$	$R^2(b_3)$	$R^2(b_3/b_1)$
2Hz	0.0682	0.5051	0.9654	0.9607	0.8845	0.7581
6Hz	0.0000	0.5769	0.9655	0.9612	0.8807	0.7201
10Hz	0.2184	0.6560	0.9673	0.9615	0.8687	0.6576
14Hz	0.2579	0.6701	0.9662	0.9623	0.8648	0.6100
18Hz	0.4672	0.7016	0.9652	0.9627	0.8450	0.5056

3. Conclusion

In this work, the magnetic hysteretic loops measurement technique was employed to characterizing the residual plastic strain occurred in low carbon steels. The reliability of magnetic parameters were studied and the influence of frequency of the applied magnetic field on the sensitivities of magnetic parameters were analyzed. It is found that under the conditions of the tested different magnetizing frequencies, the parameters of B_{max} and b_1 demonstrates linear dependency on the residual plastic strain of ε_p. The eddy current loss and anomalous loss will generated when the magnetizing frequency increase, which will directly affect the coercive force H_c and hysteresis loss W_L. However, the maximum magnetic flux density B_{max} is insensitive to the eddy current loss and anomalous. Furthermore, the magnetic properties is determined by the microstructure of the material, The change of microstructure with different residual strain need to further study to explain the change of magnetic parameters.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (Project Nos. 11527801 and 11402008).

References

[1] W. Liu, R. J. K. Rasmussen, H. Zhang: "Modelling and probabilistic study of the residual stress of cold-formed hollow steel sections", Engineering Structures, Vol. 150, pp.986-995(2017).
[2] D. Jiles: "Introduction to magnetism and magnetic materials", CRC press, pp.89-97 (2015).
[3] M. J. Sablik, D. Stegemann, A. Krys: "Modeling grain size and dislocation density effects on harmonics of the magnetic induction", Journal of Applied Physics, Vol. 89, No.11, pp.7254-7256 (2001).
[4] V. Moorthy, S.Vaidyanathan, T. Jayakumar, et al: "Effect of tensile deformation on micromagnetic parameters in 0.2% carbon steel and 2.25 Cr-1Mo steel", Acta materialia, Vol. 47, No.6, pp.1869-1878 (1999).
[5] J. Leng, Y. Liu, G. Zhou, et al: "Metal magnetic memory signal response to plastic deformation of low carbon steel". Ndt & E International, Vol. 55, pp.42-46 (2013).
[6] M. J. Sablik, T. Yonamine, F. J. G. Landgraf: "Modeling plastic deformation effects in steel on hysteresis loops with the same maximum flux density", IEEE transactions on magnetics, Vol.40, No.5, pp.3219-3226 (2004).
[7] Z. D. Wang, B. Deng, K. Yao: "Physical model of plastic deformation on magnetization in ferromagnetic materials", Journal of Applied Physics, Vol.109, No.8, pp.083928 (2011).
[8] J. Li, M. Xu, J. Leng, et al: "Modeling plastic deformation effect on magnetization in ferromagnetic materials", Journal of Applied Physics, Vol.111, No.6, pp.063909 (2012).
[9] Vértesy G, Mészáros I, Tomáš I: "Nondestructive magnetic characterization of TRIP steels", NDT & E International, Vol.54, pp.107-114(2013).
[10] D. Jiles: "Frequency dependence of hysteresis curves in conducting magnetic materials", Journal of Applied Physics, Vol.76, No.10, pp.5849-5855(1994).