ANALYSIS OF CHANGES IN RESIDUAL MAGNETIC FIELD IN LOADED NOTCHED SAMPLES

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ABSTRACT

The residual magnetic field (RMF) of a ferromagnetic element is a value which can be affected by several physical effects. These are: the magneto-mechanical effect, the effect of outer magnetic field leakage caused by discontinuity or structural inhomogeneity of the material, and the processes of mutual interacting of magnetic fields with dislocations and their cumulation. The following paper presents the results of measurements of the residual magnetic field of mechanically notched samples exposed to tensile loads. The distribution of the residual magnetic field was mapped for subsequent loads applied. There were substantial changes in the pattern of isolines and in all the components of the RMF of the samples in comparison to the initial state. That indicates a high sensitivity of the RMF to any changes in stress. The results obtained were compared to the calculated maps of stresses and deformation. A correlation was found out between these values. Measurements of the residual magnetic field make it possible to determine the notch effect and a qualitative determination of the distribution of inner stresses.

Keywords: residual magnetic field, residual stresses, magneto-mechanical effect

1. INTRODUCTION

The subject of the study presented in this paper are the irreversible changes of the residual magnetic field (RMF) of ferromagnetic elements caused by external loads. Such studies are not often carried out, but there has been an increased interest in them lately [1-5], which results from a higher demand from industry for methods to determine the state of stresses and deformation. And methods which use the RMF have the greatest potential for development.

The residual magnetic field of a ferromagnetic material is a value affected by several physical effects. These are: the magneto-mechanical effect, the effect of outer magnetic field leakage caused by discontinuity or structural inhomogeneity of the material, and the processes of mutual interacting of magnetic fields with dislocations and their cumulation [5-8].

The influence of stresses on magnetic properties is described by the magneto-mechanical effect. In a ferromagnetic material placed in a magnetic field the intensity of magnetisation varies according to stress. The change in magnetisation has a reversible component which fades after unloading, and a constant component. The relation between stress and intensity of magnetisation is a complex one. The intensity of magnetisation depends on the type of material, the intensity of the magnetic field, the magnetic history, strain and temperature. Local load changes in the ferromagnetic material will involve local changes in the intensity of magnetisation. That is why the distribution of the residual magnetic field reflects in a way the distribution of strain (stress) of the element in question [6-8].

In the manufacturing process, the magnetic texture of the metal is formed as the metal cools down below Curie point, together with crystallisation in the magnetic field of the Earth. Inhomogeneity of the crystal structure of materials results in a creation of fixing nodes in domain walls [7,8] where there is the highest concentration of structural inhomogeneity and defects in the crystal net (e.g. dislocation clusters).

The paper presents the results of study which was carried out to determine how the level and the distribution of stress, and the number of cycles of load changes affect the residual magnetic field of notched samples. The obtained distributions of the RMF were also compared to stress patterns.

2. EXPERIMENTAL DETAILS

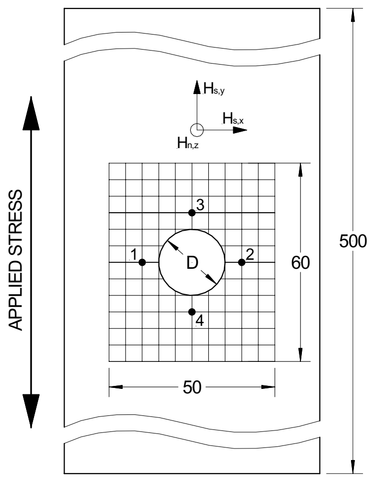


Fig. 1. Experimental sample

The samples were in the shape of a flat bar, 1.5mm thick with a round hole in the middle – Fig. 1. They were made of steel with the yield stress of $R_{0.2}$ = 150 MPa and ultimate stress of R_m = 310 MPa (results of a static tensile test). The samples were not preliminarily demagnetised. Their initial state of magnetisation was a consequence of the history of preparation and was not homogeneous.

Loads were applied to the samples on a tensile testing machine Galdabini Sun 10P. The desired loads applied, the samples were unloaded and examined beyond the testing machine. The examination was carried out always in the same place and with the same position of the sample.

The measurements of the magnetic field were made with an increment of 1mm along vertical and horizontal lines which were 5mm away from one another. These lines form a measurement net on an area of 50 by 60 mm around the hole (Fig.1). Magnetometer TSC-1M-4 with measuring sensor TSC-2M made by Energodiagnostika Co. Ltd Moscow were used for the measurements. The instrument was graduated in the Earth's magnetic field, with its value assumed at 40 A/m.

The measurements gave values of three components of the RMF on the sample surface (Fig. 1)

- $H_{s,x}$ – tangential component measured in the perpendicular direction to the load applied,
- $H_{s,y}$ - tangential component measured in the parallel direction to the load applied,
- $H_{n,z}$ – normal component.

3. EXPERIMENTAL RESULTS

3.1. Influence of the stress level.

Figure 2 schematically shows the course of the process of sample loading. The measurements of the magnetic field were made at the points marked. Point A represents the initial state of the sample. Points B and C show the state after the loads of 50 and 200 MPa, respectively, induced in a full (not weakened by a hole) cross-section of the sample, and removed.

The distributions of the RMF components (and their gradients) of the sample with a Ø 20 hole are shown in Fig. 3 to 7. Figure 8 shows the changes in the value of the RMF components in points situated 5mm from the edge of the hole (their position was shown in Figure 1).

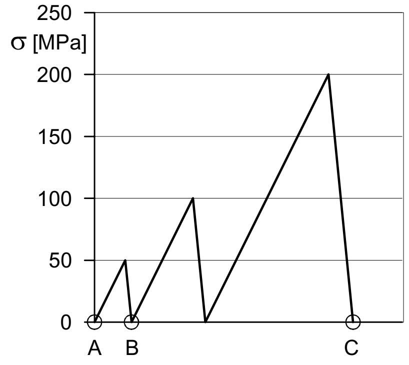
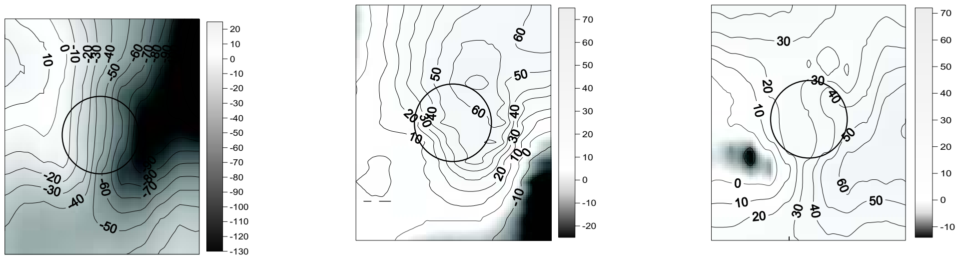
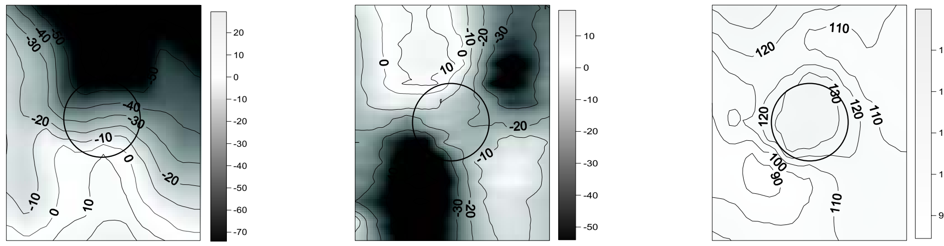


Fig. 2. Diagram of the process of sample loading with marked measurement points



a) normal component $H_{n,z}$ [A/m] b) tangential component $H_{s,x}$ [A/m] c) tangential component $H_{s,y}$ [A/m]

Fig. 3. Distribution of the residual magnetic field components of the sample – initial state

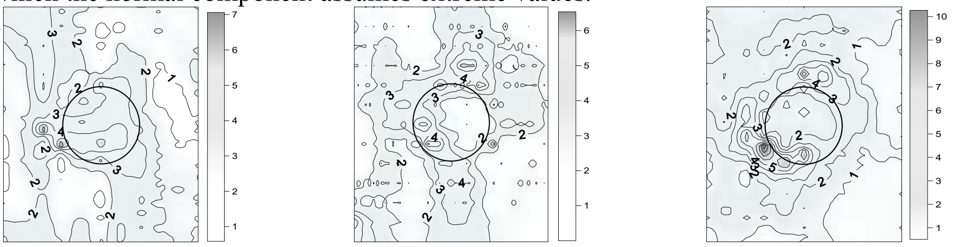


a) normal component $H_{n,z}$ [A/m] b) tangential component $H_{s,x}$ [A/m] c) tangential component $H_{s,y}$ [A/m]

Fig. 4. Distribution of the residual magnetic field components of the sample – state in Point B of the loading process

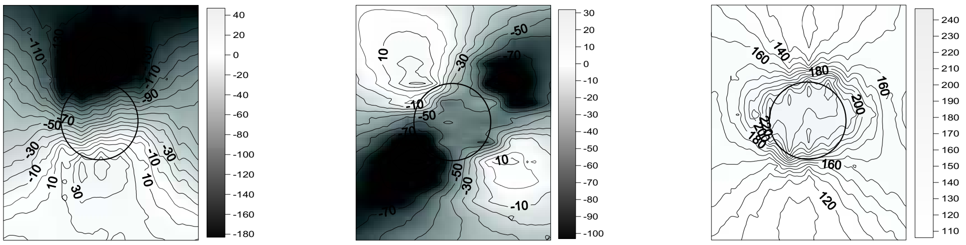
- There were substantial changes of the position of isolines and in the value of all RMF components of the sample in comparison to the initial state.
- In the critical section, the isolines of the normal component $H_{s,x}$ near the hole are perpendicular to the load direction. As they get farther away from the hole, they are

oriented at an angle of 45º to the sample axis. Over and under the hole there are areas in which the normal component assumes extreme values.



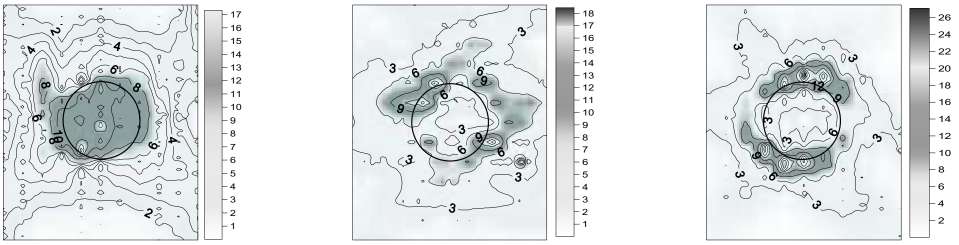
a) gradient of normal component grad $H_{n,z}$ [(A/m)/mm]   b)gradient of tangential component grad $H_{s,x}$ [(A/m)/mm]   c)gradient of tangential component grad $H_{s,y}$ [(A/m)/mm]

Fig. 5. Distribution of the gradient of the residual magnetic field components of the sample – state in Point B of the loading process



a) normal component $H_{n,z}$ [A/m]   b) tangential component $H_{s,x}$ [A/m]   c) tangential component $H_{s,y}$ [A/m]

Fig. 6. Distribution of the residual magnetic field components of the sample – state in Point C of the loading process

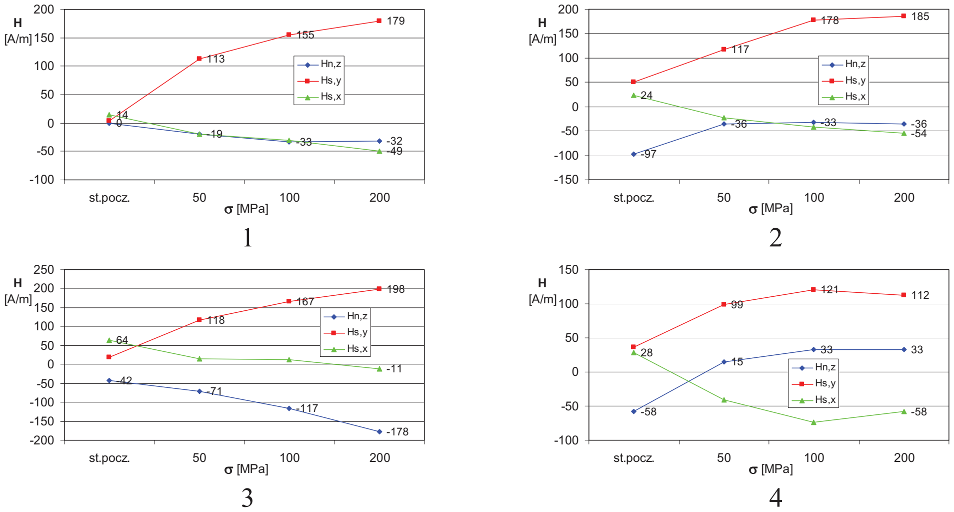


a) gradient of normal component grad $H_{n,z}$ [(A/m)/mm]   b)gradient of tangential component grad $H_{s,x}$ [(A/m)/mm]   c)gradient of tangential component grad $H_{s,y}$ [(A/m)/mm]

Fig. 7 Distribution of the gradient of the residual magnetic field components of the sample – state in Point C of the loading process

- The tangential component perpendicular to the load direction $H_{s,x}$ is characterised by the existence of areas with extreme values, which are located near the hole at an angle of 45º to the sample axis. The extremes of the same sign are located at opposite sides of the hole on a straight line running through its centre at an angle of 45º to the sample axis.
- The isolines of the tangential component parallel to the direction of the load are toroidally oriented in the area around the hole. As they get farther away from the hole, they are oriented at an angle of 45º to the sample axis.
- The best correlation with the stress level is for the tangential component which is parallel to the direction of the load. Its value increases with the increase of the stresses applied

earlier. It is caused by the fact that tensile loads increase the volume of the domains magnetised in the direction parallel to the direction of the stress [9].



1 2

3 4

Fig. 8. Changes in the components of the magnetic field of the sample in the points around the hole (Fig. 1)

- There is no homogenous trend of value change for the other components. An increase in stress causes greater inhomogeneity of their distribution.
- The distribution of the isolines formed in Point B of the loading process does not change under the influence of greater loads. With the load increase, the isolines of all RMF components become denser in areas of stress concentration.
- The greatest growth of the magnetisation value occurs at the first measurement after the stress induced at 50 MPa. Each next increase in stress causes smaller increments in magnetisation.
- According to Jiles' theory [10], under the influence of stress change in a steady magnetic field, the intensity of magnetisation changes according to the magnetisation curve. The theory predicts that, in the sample exposed to stresses, magnetisation will not grow in proportion with the load increase; it will do so in accordance with the curve shown in Fig.9.
- The gradient of the changes in the RMF component assumes the highest values near the hole. Its values rise together with load increase.

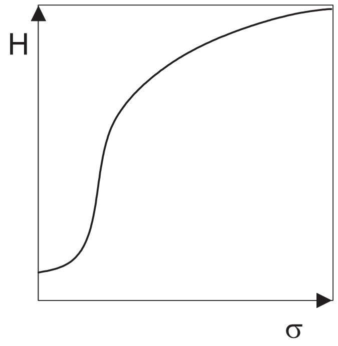
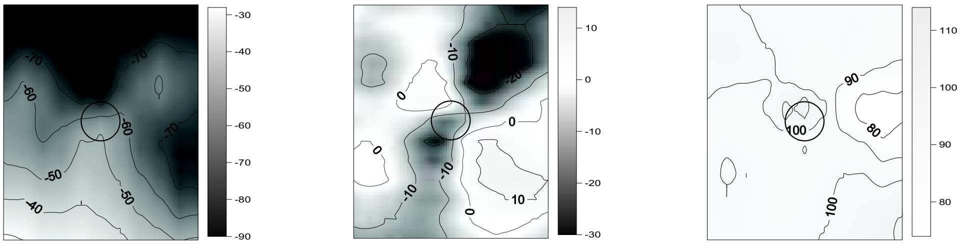


Fig. 9. Schematic correlation between a permanent change in magnetisation and tensile load.

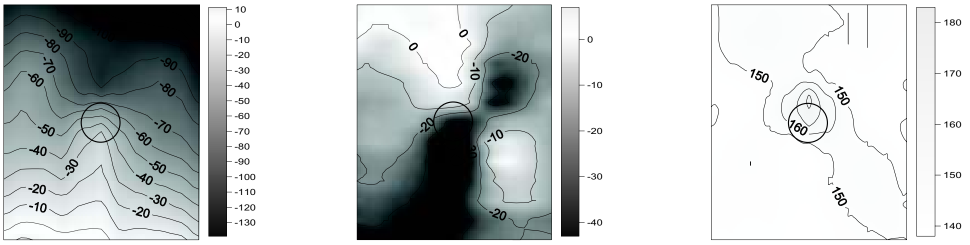
3.2. The influence of the number of load change cycles

Fig. 10 shows the distribution of the magnetic field components of the sample with a Ø 10 hole after 1 cycle of 0-50-0 MPa load. Fig. 11 presents distributions after N = 1040 of such cycles.



a) normal component $H_{n,z}$ [A/m] b) tangential component $H_{s,x}$ [A/m] c) tangential component $H_{s,y}$ [A/m]

Fig. 10. Distributions of the residual magnetic field components of the sample –state: 50 MPa



a) normal component $H_{n,z}$ [A/m] b) tangential component $H_{s,x}$ [A/m] c) tangential component $H_{s,y}$ [A/m]

Fig. 11. Distributions of the residual magnetic field components of the sample – state after N=1040 cycles

- The distribution of isolines formed after the first cycle of the loading process does not change with the number of cycles. The isolines of all RMF components become denser in areas of stress concentration with the increase in the number of load cycles.
- The greatest changes in the RMF components occur in the first few load cycles, and with each cycle the changes are smaller. In [5] it is said that a sudden increase in magnetisation will appear just before the sample is destroyed – cf. Fig. 12.

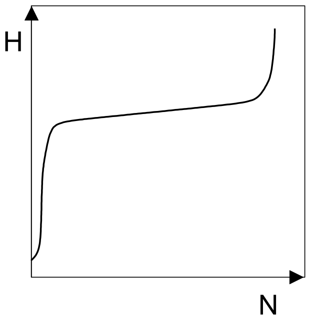


Fig. 12. Schematic correlation between the permanent change in magnetisation and the number of load change cycles.

4. COMPARISON OF THE DISTRIBUTIONS OF STRESSES AND RESIDUAL MAGNETIC FIELD COMPONENTS

The calculations of the stresses in the sample exposed to tensile loads were made with the programme ANSYS. The plane stress state was determined with the use of the perfectly elastic material model. The stress distributions shown concern a sample with a Ø 20mm hole. The area corresponding to the measurements of the magnetic field was put in a frame.

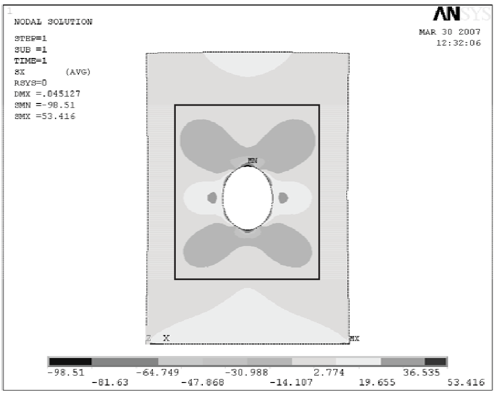


Fig.13. Stress component x

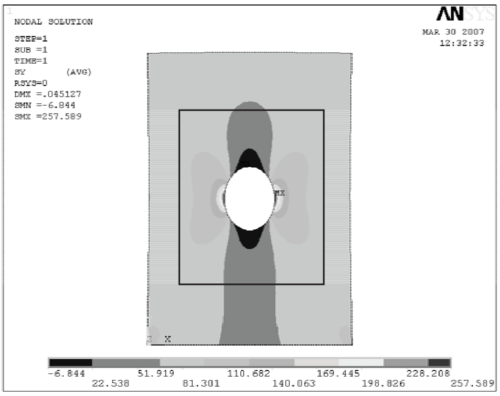


Fig.13. Stress component y.

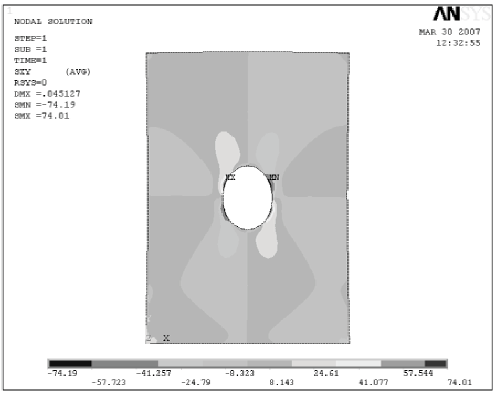


Fig. 15 Shear stress (xy)

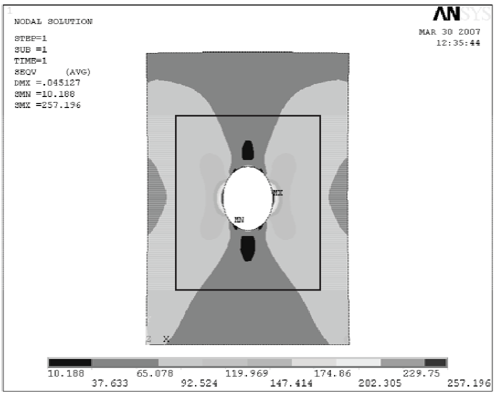


Fig. 16 Equivalent stress

The greatest similarity occurs between the distribution of shear stress (Fig. 15) and the tangential component perpendicular to the load direction $H_{s,x}$ (Fig. 6b). An analogy can also be drawn between the gradient of the normal component $H_{n,z}$ changes (Fig. 7a) and the equivalent stresses (Fig. 16). On the other hand, the tangential component parallel to the load direction shows the best correlation with the load history (Fig. 8).

5. CONCLUSION

The subject of the analysis were irreversible changes in the residual magnetic field of a sample which were the result of tensile loads. There were substantial changes in the position of isolines and in the values of all RMF components of the sample in comparison to the initial state. This indicates that the residual magnetic field is highly sensitive to stress changes. In the distributions of the RMF components there is also a clear influence of the notch. It is interesting how the RMF isolines are oriented at an angle of approx. 45° to the load direction. This direction conforms with the positioning of Chernov-Luders lines, which appear the moment that the material flow begins, and which are the evidence of a mutual shift of some crystals on the crystallographic planes. The tangential component parallel to the load direction is best correlated with the stress level. Its value rises with the rise in prior loads. These changes are not proportional to load changes but they conform with the perfect magnetisation curve. In cyclic loads the biggest changes in the field value occur in the first cycles of load change.

It appears that there are possibilities to determine the state of stress and deformation on the grounds of the RMF. However, the working out of transition algorithms will take a great deal of effort, both experimental and theoretical, in the field of magneto-elasticity.

REFERENCES

1. Yang En, Li luming, Chen Xing: Magnetic field aberration induced by cycle stress, Journal of Magnetism and Magnetic Materials 312 (2007) 72–77
2. Li Luming, Huang Songling, Wang Xiaofeng, Shi Keren, Wu Su Magnetic field abnormality caused by welding residual stress Journal of Magnetism and Magnetic Materials 261 (2003) 385–391
3. Roskosz M.: Possibilities of the Application of the Metal Magnetic Memory Method to the Analysis of Gear Durability. 9th European Conference on Non-Destructive Testing ECNDT Berlin 2006, Abstracts Part 2, P 85
4. John Wilson, Gui Yun Tian, Simon Barrans: Residual Magnetic Field Sensing for Stress Measurement and Defect Detection, 9th European Conference on Non-Destructive Testing ECNDT Berlin 2006, Abstracts Part 1
5. Dubow A.A.: Study of Steel Samples Exposed to Static and Dynamic Loads with the Use of the Metal Magnetic Memory Method. 4th International Conference on "Diagnostics of Instrumentation and Constructions with the Use of the Metal Magnetic Memory Method" Moscow 2007, s. 34-45. (in russian)
6. Deputat J.: Principal of the Metal Magnetic Memory Method. Dozór Techniczny 5/2002 s. 97-105. (in polish)
7. Dubow A.A.: Principal features of metal magnetic memory method and inspection tools as compared to known magnetic NDT methods. WCNDT 2004, Montreal Canada, http://www.ndt.net/article/wcndt2004/papers/359.ntm
8. Dubow A.A.: Physical base of the method of metal magnetic memory. Proc. of Workshop on Nondestructive Testing of Materials and Structures, NTM'02 Warsaw 2002, Wyd. IPPT PAN, str. 1-9.
9. Tomohiro Yamasaki, Shinji Yamamoto, Masahiko Hirao:Effect of applied stresses on magnetostriction of low carbon steel, NDT&E Internacional, Vol. 29,No 5, pp. 263-268,1996
10. D. C. Jiles, Theory of the magnetomechanical effect, J. Phys. D: Appl. Phys., 28 (1995) 1537 1546.