Magnetostriction Properties of $Fe_{40}Ni_{38}B_{18}Mo_4$ Amorphous Alloy

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Magnetization processes were investigated at room temperature as function of applied tensile stress for the amorphous alloy of nominal composition $Fe_{40}Ni_{38}B_{18}Mo_4$. The alloy had soft magnetic property with positive magnetostriction character. The average saturation magnetization (0.55 T) is almost independent of applied stress. Susceptibility at maximum magnetization, initial susceptibility and Rayleigh constant for different applied stresses were evaluated. Analysis of the magnetization process at high fields shows monotonic decrease of the anisotropy energy with increase of applied stress. The saturation magnetostriction constant is 9.10×10^{-6}. The amorphous ferromagnetic alloy is suitable candidate for magnetostrictive sensors fabrication.

Introduction:

The phenomenon of magnetostriction was discovered more than 150 years ago [1]. Since that time there has been both study of the basic science, and applications in areas such as the generators of sound, magnetoacoustic transformers, actuators for opto-electronic systems, devices for non-destructive control and remote detection and ranging. The recent development of modern technologies, such as microfabrication, and materials, such as rare earth based bulk materials and magnetic thin films, has produced new opportunities for the study and application of magnetostriction. Recent discovery of giant magnetostriction, enables to generate ultrasound and extend the usage of the non-destructive control techniques. The new field of the interest in magnetostriction as the strain derivative of magnetic anisotropy is relevant to magnetic recording industry, particularly as recorded densities go beyond 20 Gbits/in^2. As physical dimensions of devices are reduced the surface area to volume ratio increases, and surface anisotropy (magnetostriction) effects may become significant in terms of ultimate switching speeds or noise floor. Miniaturization within the sensor/actuator sector also may invoke such complications, and also now make magnetostrictive materials competitive with piezoelectric materials. The magnetostrictive materials sensors (magnetometers, position and rotation detectors) could be widely applied in science, technology, machinery, transport, robot and computer engineering as reliable and cheap tools for automated control and management. Recently magnetostrictive materials were used in thin film layered magnetic structures [2]. If a film with large enough magnetostriction is deposited on a nonmagnetic substrate, the whole structure will bend if the magnetization is rotated. This can be used for switches or actuators, such as in micropumps that are controlled by an external magnetic field.

This wide spectrum of magnetostriction applications, demands continuos study of the phenomenon properties in different materials. These studies help both further understanding of the phenomenon basic science and allows for further technological applications. In this work magnetostriction properties of a Fe Ni B Mo amorphous ferromagnetic alloy are experimentally studied through investigation of the stress dependence of the magnetization process, determination of the anisotropy energy and the saturation magnetostriction constant.

Experimental:

The sample used in the present study is $Fe_{40}Ni_{38}B_{18}Mo_4$ in a ribbon form, supplied by Allied Chemicals, USA. It was prepared by the roller quenching technique, and was supplied as quenched; that is, without any special optimization of magnetic or mechanical properties. This sample is a typical amorphous ferromagnetic alloy based on Fe and Ni with width 4.5 mm and thickness 20 μm. X-ray diffraction pattern used to assure the amorphous nature obtained using molybdenum source (0.7107 Å) is shown in Figure (1). The magnetic measurements were done using a ferrotester type TR-9801. A ribbon of 25 cm long was placed in the hole of the pickup coil and suspended vertically. A simple device was used to apply tensile stresses to the sample inside the measuring coil in order to measure simultaneously the referred magnetic properties. The applied stresses were large enough to produce significant changes of the magnetic properties, however, no effect due to a possible plastic deformation of the sample during the measuring time was observed. This ribbon length is suitable for the measuring coils and to minimize the demagnetizing factor. The demagnetizing field correction was also taken into account to calculate the initial suscepti-bility. An iron-metal standard sample was used for calibration. The measurements were done in a shielded off earth field at room temperature up to fields of 2.30 x 10^4 Am^{-1}.

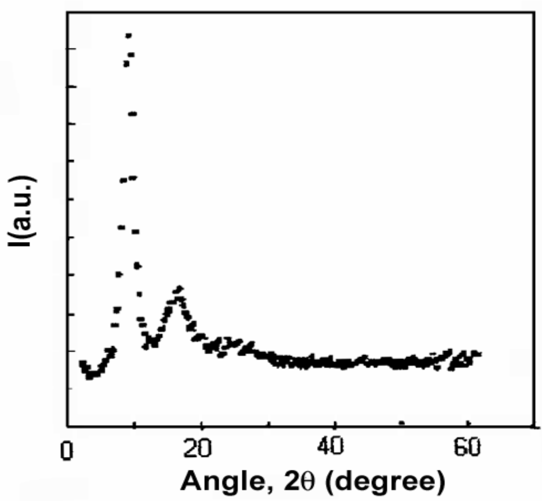

Fig. (1): X-ray diffraction pattern of $Fe_{40}Ni_{38}B_{18}Mo_4$ amorphous alloy.

Results and Discussion:

Figure (2) shows the stress dependence of the magnetization curves for different applied tensile stresses from zero up to σ = 4.18x10^7 Nm^{-2} (41.8 MPa) and a field up to 2.4 x 10^3 Am^{-1}. The curves show that the magnetization area increases with the increase of applied tensile stress indicating a positive magnetostriction. The measured average saturation magnetization M_s for the amorphous alloy $Fe_{40}Ni_{38}B_{18}Mo_4$ is 0.55 T.

This value is reached for lower values of H when applying large tensile stresses (21.8 MPa or greater) as shown in Fig. (2). The measured maximum magnetization is 0.63 T. The external stress makes the magnetization curves at low field much steeper, resulting in a more rapid approach to magnetic saturation. Reaching magnetic saturation at low magnetic fields reflects the soft magnetic property of this amorphous alloy.

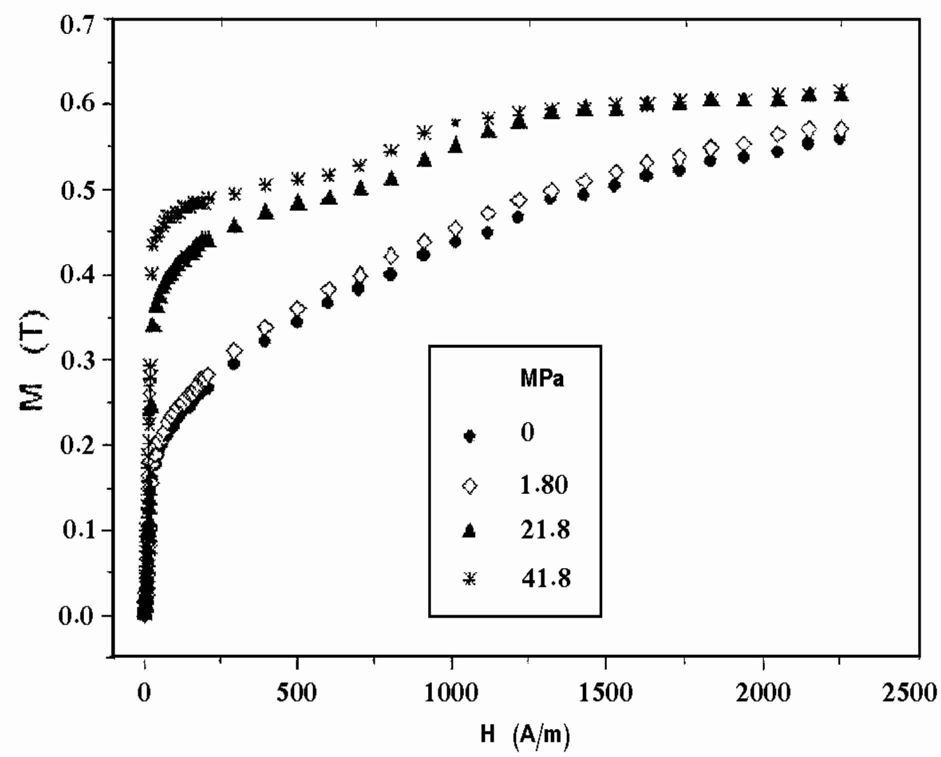

Fig. (2): Magnetization curves for different applied tensile stresses.

The magnetic susceptibility (χ) calculated from the M (H, σ) curves for the amorphous alloy studied is shown in Fig. (3). The results show that the susceptibility at maximum peak **(χ_m)** increases with the increase of stress. The values of χ_m as function of the applied tensile stresses are represented in table 1, together with the corresponding magnetization.

The magnetization process below complete saturation is stress dependent. This is similar to previously reported results for amorphous ferromagnetic alloys [3] and shows that for small applied stresses the magnetization process takes place predominantly by wall displacement in regions where the magnetization initially lies parallel to the axis of the ribbon. After this process, the magnetization increases by domain rotation [4]. For large applied stresses, magnetization takes place exclusively by rotational processes. The axis of ribbon (stress axis) becomes an easy axis of magnetization and the domain structure is identical with that of uniaxial crystal [5,6].

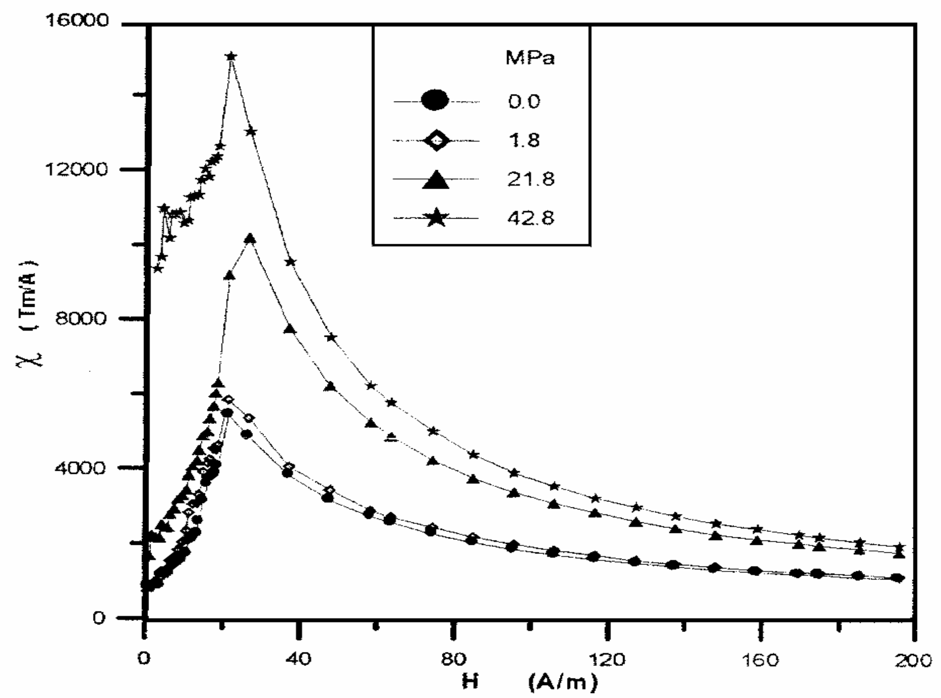

Fig. (3): Variation of magnetic susceptibility for different applied tensile stresses.

The linear dependence of M/H on H as found from Fig. (4) shows that for small magnetic fields (less than 11.0 Am^{-1}) the magnetization curves obeys Rayleigh's law:

$$M(H) = \chi_i H + \nu H^2 \quad (1)$$

where, χ_i denotes the initial susceptibility and ν the Rayleigh constant. The calculated values of initial susceptibility and Rayleigh constant for different applied tensile stress are given in table (1). Values of Rayleigh constant shows a slight increase with increase of external stress.

Table (1)

Stress $\sigma \times 10^{-6}$ ($N\,m^{-2}$)	Susceptibility at max. peak χ_m (T m / A)	Magneti-zation at χ_m (T)	Initial Susceptibility χ_i (T m / A)	Rayleigh constant ν ($T\,m^2/A^2$)
0	5500	0.16	600	101.4
1.80	5900	0.18	567	151.9
21.80	10100	0.34	1778	154.4
41.80	15500	0.43	9200	179.1

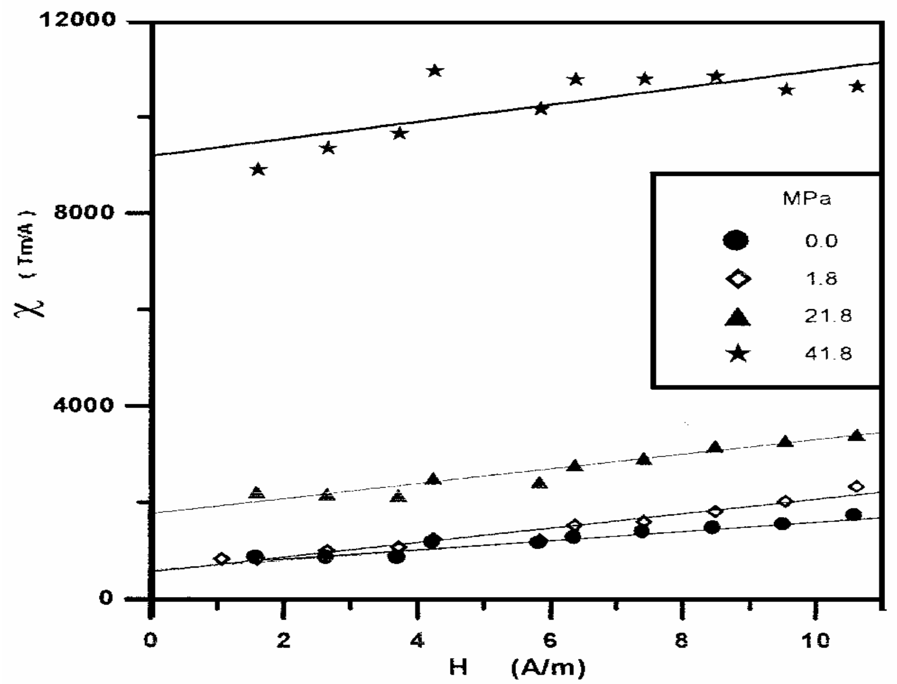

Fig. (4): Variation of magnetic susceptibility for small magnetic fields, and different applied tensile stresses.

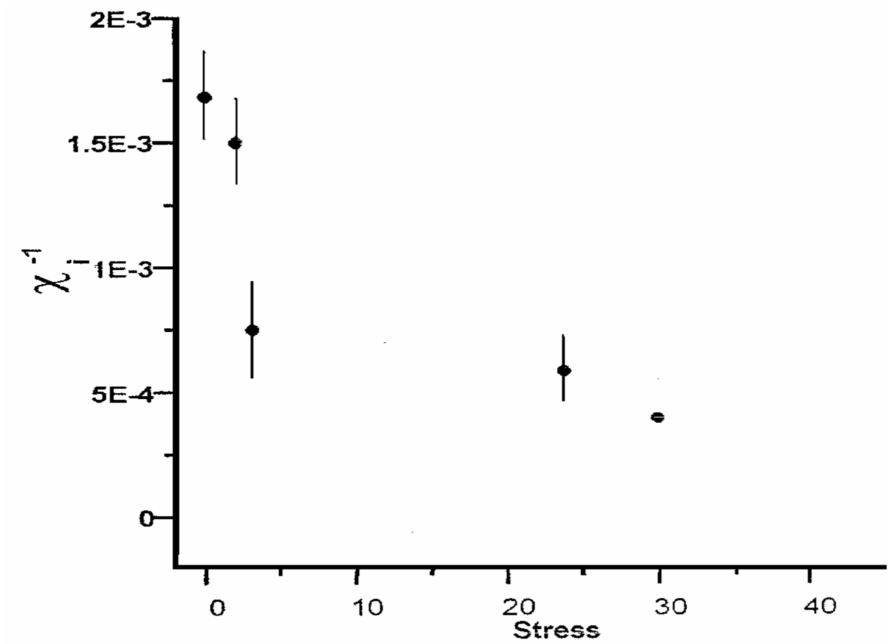

Fig. (5): The inverse of initial susceptibility as a function of applied stress.

In Fig. (5) the inverse of initial susceptibility χ_i^{-1} is represented as a function of the applied stress. The values of χ_i^{-1} decreases with applied stress, and the $Fe_{40}Ni_{38}B_{18}Mo_4$ amorphous ferromagnetic alloy shows a positive magnetostriction nature.

Plot of the magnetic susceptibility as a function of the applied magnetic field in the intermediate region of magnetic field (50 – 200 Am^{-1}) is shown in Fig.(6). For the same applied magnetic field, it is noted that the magnetic susceptibility increases with increase of tensile stress, while for the same tensile stress value, magnetic susceptibility decreases with increase of applied magnetic field.

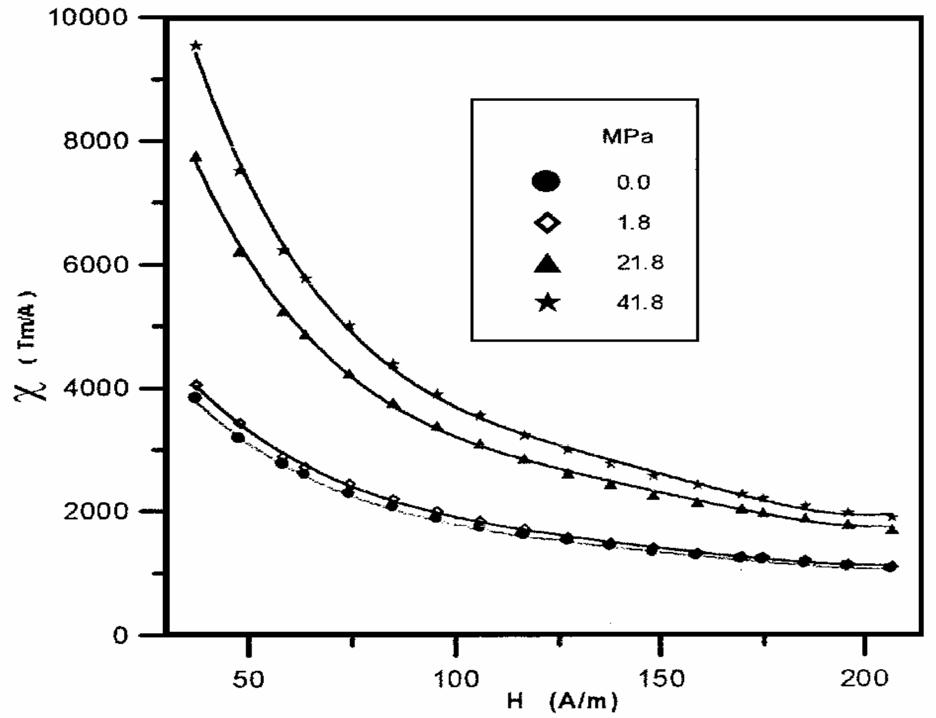

Fig. (6): Variation of magnetic susceptibility in the intermediate region of magnetic fields for different applied tensile stresses.

On the other hand, the variation of susceptibility χ with the magnetic field H in the high field region is shown in Fig. (7). Complete saturation is reached at high field (H > 5000 Am^{-1}) and susceptibility value is independent of the external stress applied. For the amorphous alloy $Fe_{40}Ni_{38}B_{18}Mo_4$ the measured high field susceptibility is χ_H = 30 Tm/A.

For the high field region, neglecting the very small field-induced increase in the spontaneous magnetization of domains, the approach to saturation is usually expressed in the following empirical form [7]

$$M = M_s\,(l - AH^{-1} - BH^{-2}) \qquad (2)$$

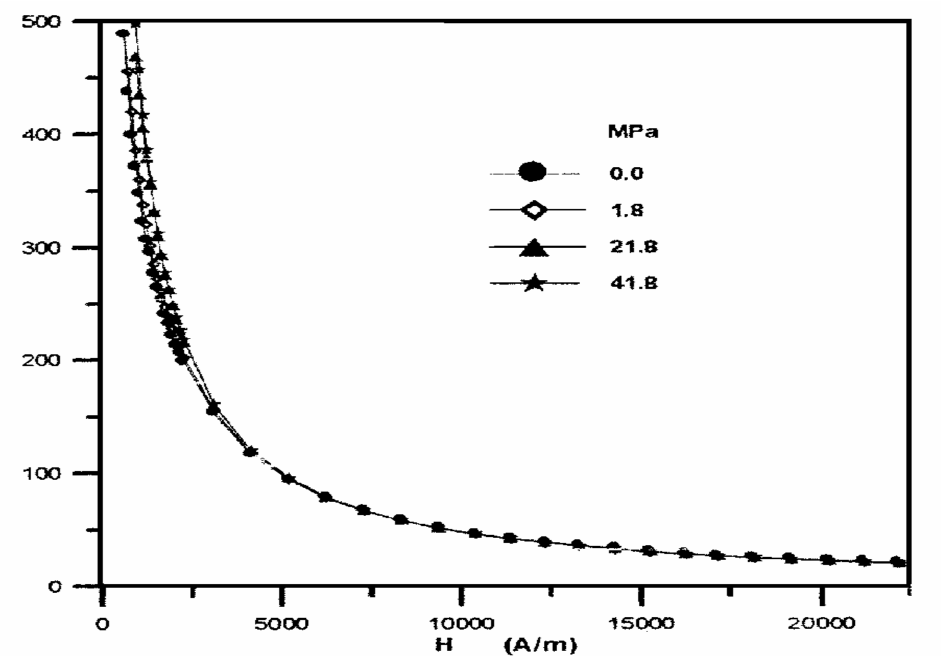

Fig. (7): Variation of magnetic susceptibility in the high magnetic fields region for different applied tensile stresses.

AH^{-1} is the term due to pinning of domain walls by the microstructure inhomogeneties, and BH^{-2} is due to rotations of the magnetization vector against the magnetic anisotropy with

$$B = 4K^2 / 15\, M_s^2 \qquad (3)$$

where K is the anisotropy constant, the energy density stored in a sample when it is magnetized to saturation [8]. Values of K are calculated from the magnetization curves using the relation

$$K = \int_0^M H\,dM \qquad (4)$$

which is simply the area between the M against H curve and the M axis shown partly in fig. (2). In table (2) values of K, M_s and B for different external stress values, obtained using equations (4) and (3) are given. At very high field, equation (2) is reduced to

$$M = M_S (1 - A H^{-1}) \quad (5)$$

and plotting M against 1/H (Fig.8) shows straight-line relations for the different values of the applied stress. From these relations values of A for different stress values are obtained and are also given in table (2).

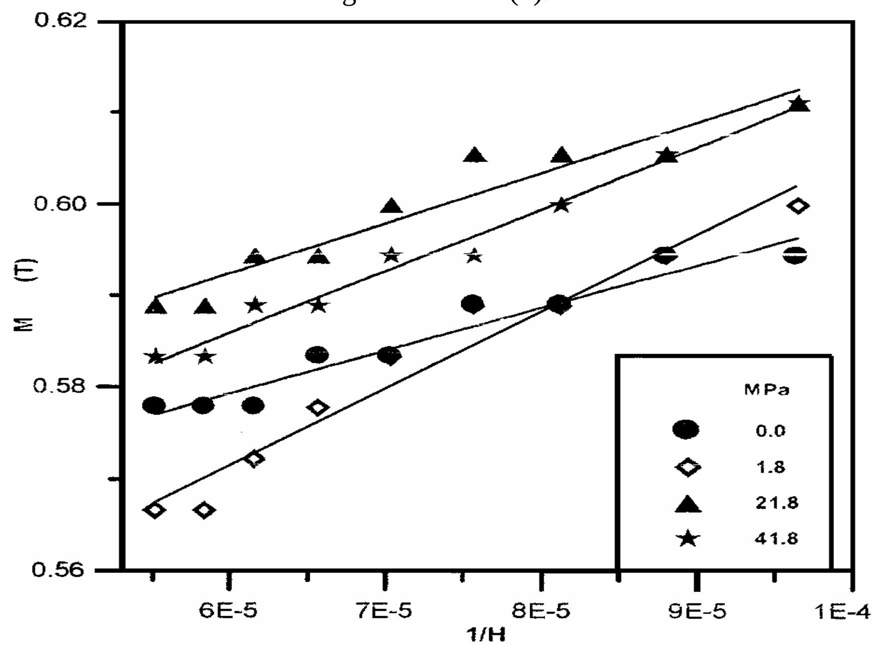

Fig. (8): Variation of Magnetization with inverse of magnetic field for different applied tensile.

Table (2)

Stress $\sigma \times 10^{-6}$ ($N\ m^{-2}$)	Anisotropy constant K ($J\ m^{-3}$)	Saturation magnetization M_s (T)	A ($m\ A^{-1}$)	B x 10^{-3} ($A^{-2}\ m^2$)
0	450.0	0.55	856.4	178.5
1.80	411.0	0.52	1620.2	166.6
21.80	182.9	0.56	988.6	28.4
41.80	71.2	0.55	1249.9	4.5

In Fig. (9) the variation of the anisotropy constant K as function of applied stress σ is shown. The density of energy stored in the sample decreases monotonically with increase of applied stress. This monotonous variation suggests that the amorphous ferromagnetic alloy under investigation is suitable for magnetostrictive materials sensors fabrication.

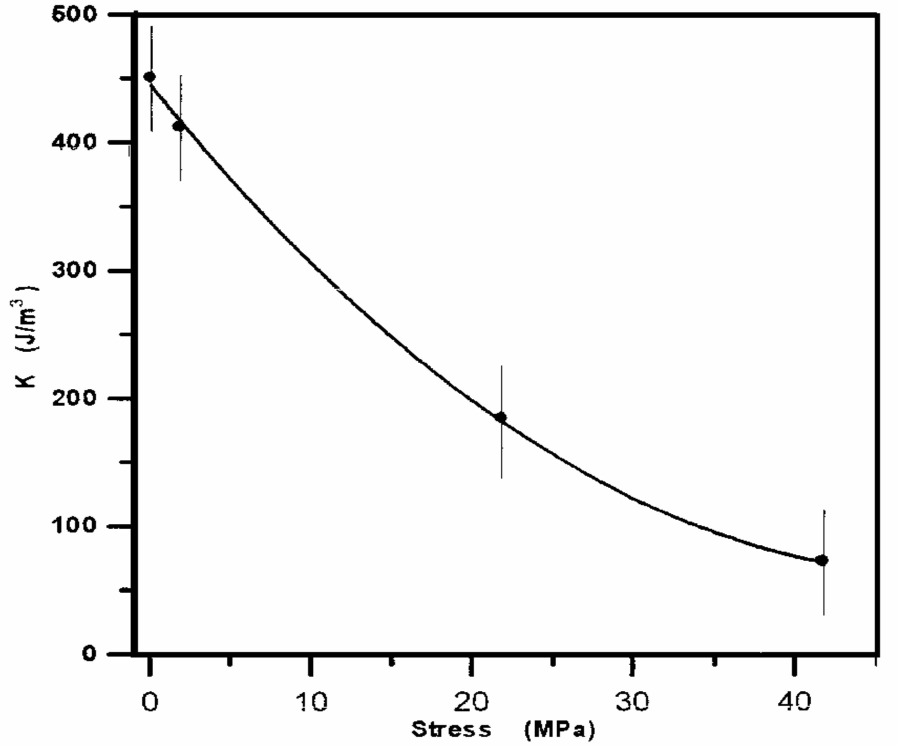

Fig. (9): Dependence of the anisotropy energy K on applied tensile stress.

For large applied stresses it is possible to derive the saturation magnetostriction constant λ_s from the relation,

$$\lambda_s = - d [K(\sigma)] / d\sigma \quad [4]$$

The obtained value of λ_s is 9.10 x 10^{-6} . This value for the amorphous alloy $Fe_{40}Ni_{38}B_{18}Mo_4$ has a good agreement with other iron-based amorphous alloys of comparable composition [10].

Conclusions:

The $Fe_{40}Ni_{38}B_{18}Mo_4$ amorphous ferromagnetic alloy shows soft magnetic properties and has positive magnetostriction nature. Its saturation magnetization (0.55 T) is independent of applied tensile stress and its saturation magnetostriction constant is 9.10 x 10^{-6}. The anisotropy energy decreases monotonically with increase of applied tensile stress and the material is suitable candidate for magnetostrictive sensor fabrication.

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