Application of Matteucci Voltage Pulses of Amorphous Wires in Sensing Both Direction and Magnitude of Twist

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ABSTRACT

In this work the effect of torsion on the Matteucci voltage pulses in amorphous wires has been studied. It has been shown that: Amplitude of the pulses decreases to zero at a twist angle that depends on the chemical composition of the wire. From zero torsion, the amplitude of the Matteucci voltage increases when the wires are twisted counter-clockwise. However, when the wires are twisted clockwise, the amplitude of the Matteucci voltage pulses decreases up to a minimum point (zero) before, finally, starting to increase. This is a clear distinction (in behaviour) between clockwise and counter-clockwise torsion, which can be employed to determine the direction of initial twist. Also, the low torsion region of the torsion-Matteucci voltage characteristic shows a clear possibility of employing the stress sensitive Matteucci voltage to determine the magnitude of torsion. The Matteucci voltage is quite sensitive to the torsion. It is thus expected to provide high sensitivity for measurement of torsion in the "low and very low torsion region". It has also been established that when the positioning of the amorphous wire in the magnetizing coil is reversed (wire ends are interchanged), the torsion-Matteucci voltage characteristic obtained is virtually a mirror image of the previous direction. For instance, if the zero amplitude Matteucci voltage was being obtained at a twist angle of 45° clockwise, it will now be obtained at an angle of the same magnitude, but for a counter-clockwise twist. The physics of this latter phenomenon too would be of interest to researchers of physics of magnetism.

1.0 INTRODUCTION

Studies on the effect of stress on various parameters of magnetostrictive amorphous ferromagnetic wires have been conducted to date (Nderu *et. al,* 1996, 1998, 1999) with the aim of understanding their fundamental magnetic behaviour under stress, as well as seeking possible applications based on such behaviour. Previously, the inversion of longitudinal M-

H loop in $Co_{72.5}Si_{12.5}B_{15}$ wire due to change of direction of twist from clockwise to counter-clockwise (while driving an ac current through the wire) was reported. Further, possible applications based on such behaviour were proposed (*Nderu et. al, 1999*).

However, it is considered that Matteucci effect would be particularly attractive in such sensor application, as there is an inherent transduction of magnetic to electrical signal without necessitating pick-up coils. The elimination of pick up coils is expected to simplify the sensor construction. With this in mind, the effect of torsion on the Matteucci voltage pulses has been investigated to establish how the pulses respond to both magnitude and direction of torsion.

This paper discusses the stress-Matteucci voltage characteristics obtained. The characteristics are discussed based on stress (internal and external) induced anisotropy and the domain structure models of the wires proposed previously (N*deru et. al, 1998*). The characteristics obtained in this work are important in providing a better insight into the fundamental magnetic properties of amorphous wires. Moreover, application of the stress-Matteucci voltage relationship in sensitively sensing both magnitude and direction of torsion is envisaged.

2.0 RESULTS AND DISCUSSION

Matteucci voltage is generated when the magnetization of a cylindrical ferromagnetic specimen is not lying perfectly parallel to the axis of the specimen, meaning that the magnetization vector can be resolved into a sine and cosine component. The sine component is perpendicular to the specimen axis, while the cosine one is along the axis. When such a specimen is excited by an ac magnetic field the sine component will continuously vary with the field. This means that the sample will be cut by a continuously changing sine component of the magnetization (magnetic flux). Normally, when a conductor is cut by a changing magnetic flux, voltage is induced across the conductor according to Faraday's law of electromagnetic induction. Thus, when the ferromagnetic specimen (which is a conductor) is cut by the changing sine component of the magnetization, voltage is induced across it. This voltage is termed Matteucci voltage, after the person who first explained the phenomenon. Considering the principle of generation of the Matteucci voltage, the voltage is expected to vary with any parameters that alter the rate of change of the sine component of the magnetization (for instance frequency of excitation field), and parameters that cause any redistribution of the flux (for instance stress) as shown by the experimental results discussed hereafter.

Figure 1 shows the dependence of the Matteucci voltage pulses on the amplitude and frequency of the excitation current (field). The Matteucci voltage pulse amplitude increases with the amplitude and frequency of exciting field, while their frequency increases with the frequency of excitation field. This is as expected because increasing the frequency of excitation field increases the rate of change of flux with time, while increasing the amplitude of the field increases the threshold flux participating in the flux change.

Figure 2 (a) shows the change of Matteucci voltage pulses due to torsion in $Co_{72.5}Si_{12.5}B_{15}$ wire. It is observed that for clockwise torsion, amplitude of the pulses decreases until it becomes zero at a twist angle of 80°. A similar behaviour is observed in $Fe_{77.5}Si_{7.5}B_{15}$, and $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ wires (as seen in Figs. (b) and (c)), except that the angles at which the zero amplitude of Matteucci voltage is attained depends on the wire concerned. This angle is about 45° and 40° for (125μm diameter, 6cm long) $Fe_{77.5}Si_{7.5}B_{15}$, and $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ wires, respectively.

The dependence of amplitude of Matteucci voltage pulses on torsion can be explained based on the change in domain (flux) distribution in wires under torsion and the anisotropy induced by the applied torsion. Torsion induces helical anisotropy, K, in the sample. The anisotropy is expressed as $K = \frac{3}{2}\lambda_s \xi \mu r$ (λ_s : saturation magnetostriction constant, ξ : torsional strain, μ : shear modulus, r : distance from sample surface to the sample axis). If K is large it means that more flux will tend to lie in the helical direction of the sample. As a result, Matteucci pulses of higher amplitude are expected to be generated across the sample. The anisotropy constant is directly proportional to the twist angle. From the foregoing, the amplitude of the Matteucci pulses is expected to vary linearly with the twist angle. However, this does not hold in the present case presumably due to other helical anisotropy, emanating from the internal stress existing in the sample prior to the application of external torsion. (*Nderu et .al, 1999*). Thus, it is observed from the experimental results discussed below that the amplitude of the pulses first decreases and then starts to increase after attaining a minimum value.

The fact that amplitude of the Matteucci voltage pulses decreases to zero at a non-zero angle of twist is qualitatively understood as follows: The wires have internal stress induced during preparation process by the rapid quenching method (*Nderu et. al, 1996*). This gives them an initial helical easy direction, an initial helical magnetization component, and therefore an initial amplitude of Matteuci voltage of a definite polarity. Now, suppose external torsion is applied. If the twisting is in such a direction that the resulting helical anisotropy has the same chirality as that of internal stress induced anisotropy, the amplitude of Matteucci pulses will increase due to increase of the helical component of magnetization, But, the same polarity as that of initial Matteucci voltage pulses will be maintained.

On the other hand, if twisting is in such a direction that it induces helical anisotropy of opposite chirality to that induced by internal stress, the initial external torsion will be used to overcome the effect of inherent helical anisotropy. Thus, initially the amplitude of the Matteucci pulses is expected to decrease. Since the two helical anisotropies have opposite chirality, amplitude of the pulses will, in this case, decrease and become zero when the two anisotropies are equal in magnitude. When the effect of the inherent anisotropy is overcome, only then will an effective easy helical direction appear in the direction of external torsion. This will cause the Matteucci pulses to re-appear, but with an inverted polarity. Thereafter, increasing torsion will increase the amplitude of the inverted pulses. The difference in the angle at which the zero amplitude of Matteucci voltage appears in wires of different compositions is then, presumably, only a reflection of the amount of energy required to overcome the effect of inherent helical anisotropy. This energy depends on the magnitude of stress, saturation magnetostriction constant as well as the initial domain structure of the wire, hence is different for wires of different composition. It is worth noting that torsion will simultaneously induce an easy as well as a hard helical direction of magnetization in the same wire, but having opposite chirality. Owing to this, all the wires are expected to behave similarly under torsion, irrespective of the sign of saturation magnetostriction constant.

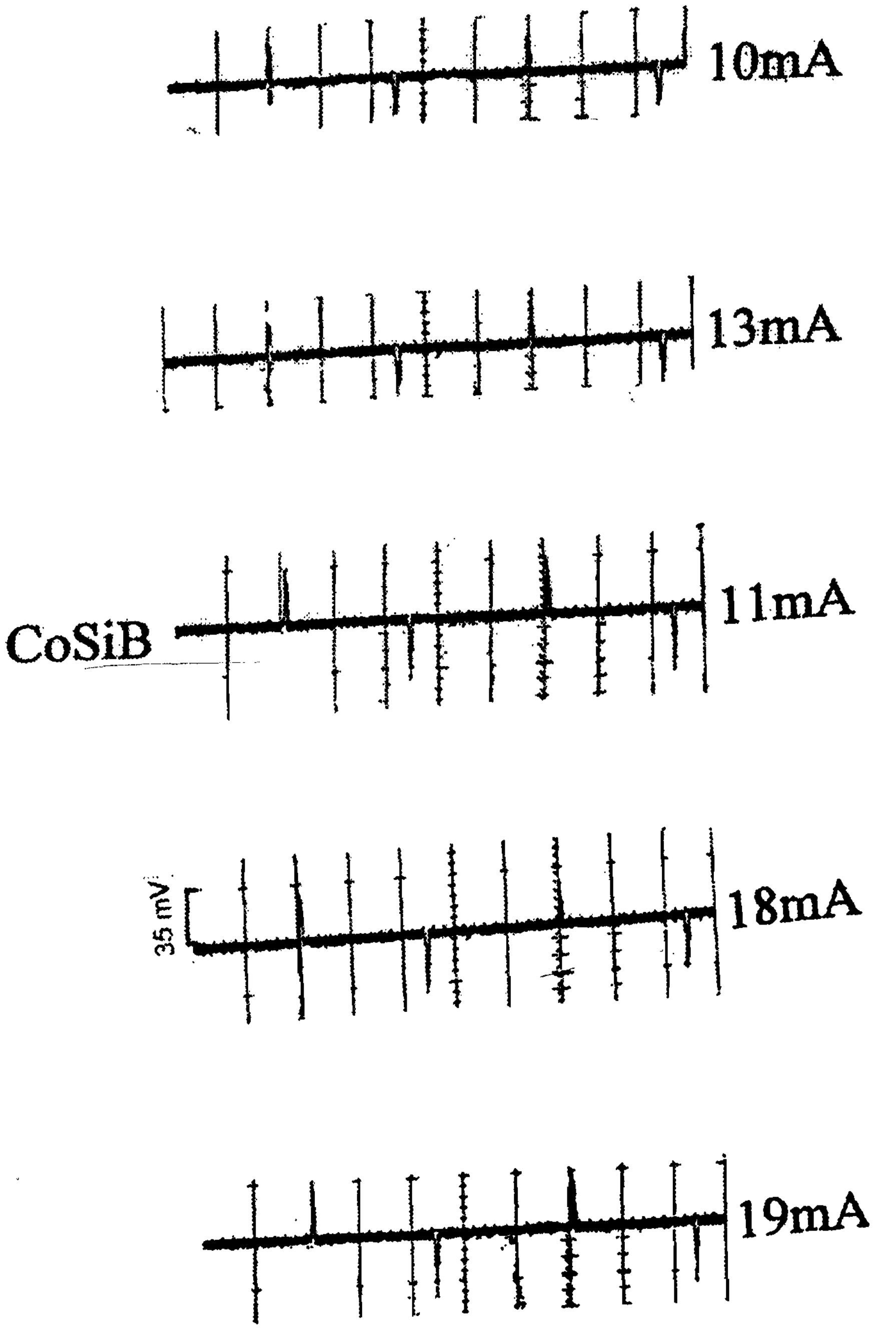

Figure 1(a). Dependence of Matteucci voltage on amplitude of excitation current (field)

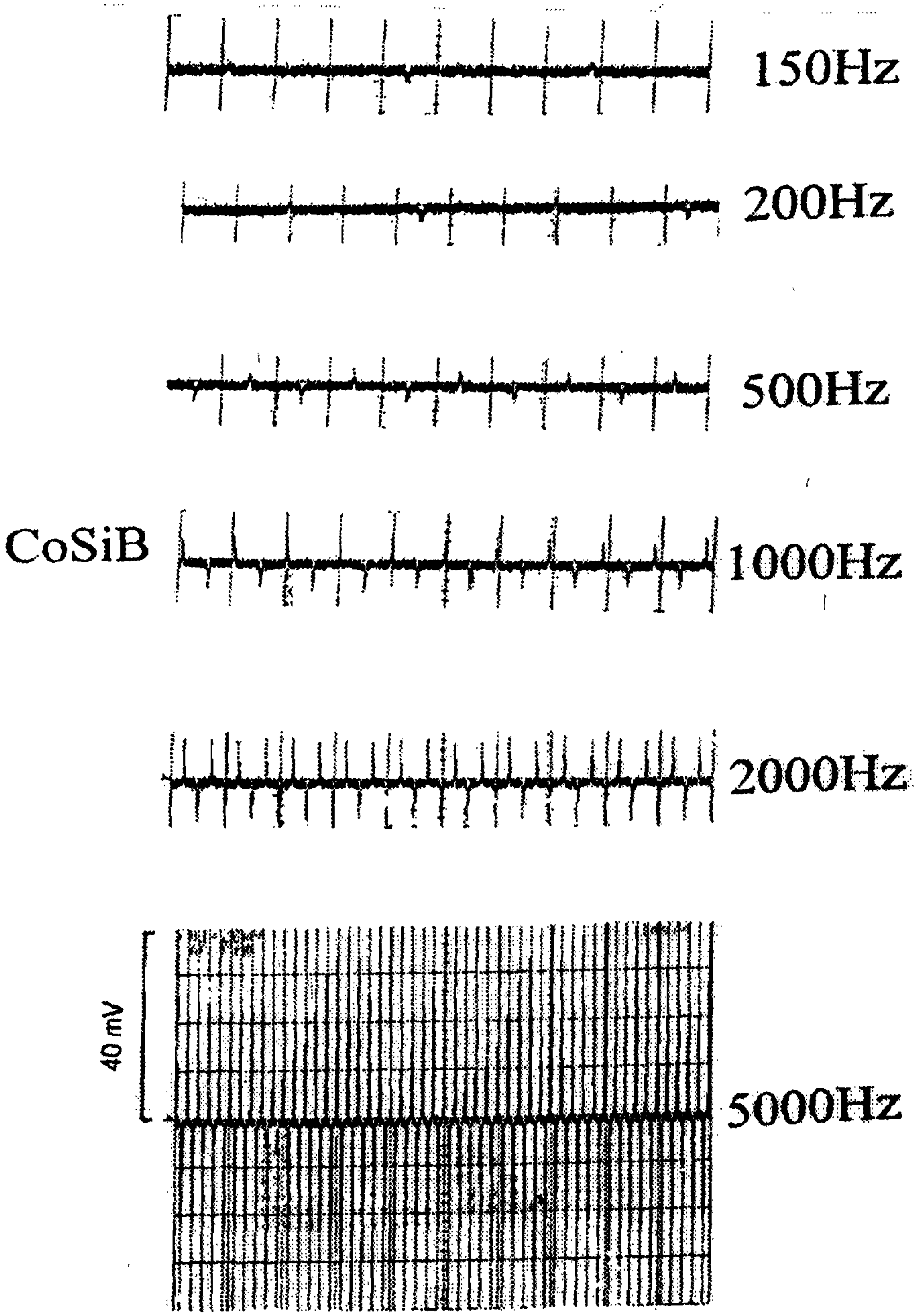

Figure 1(b). Dependence of Matteucci voltage on frequency of excitation current (field)

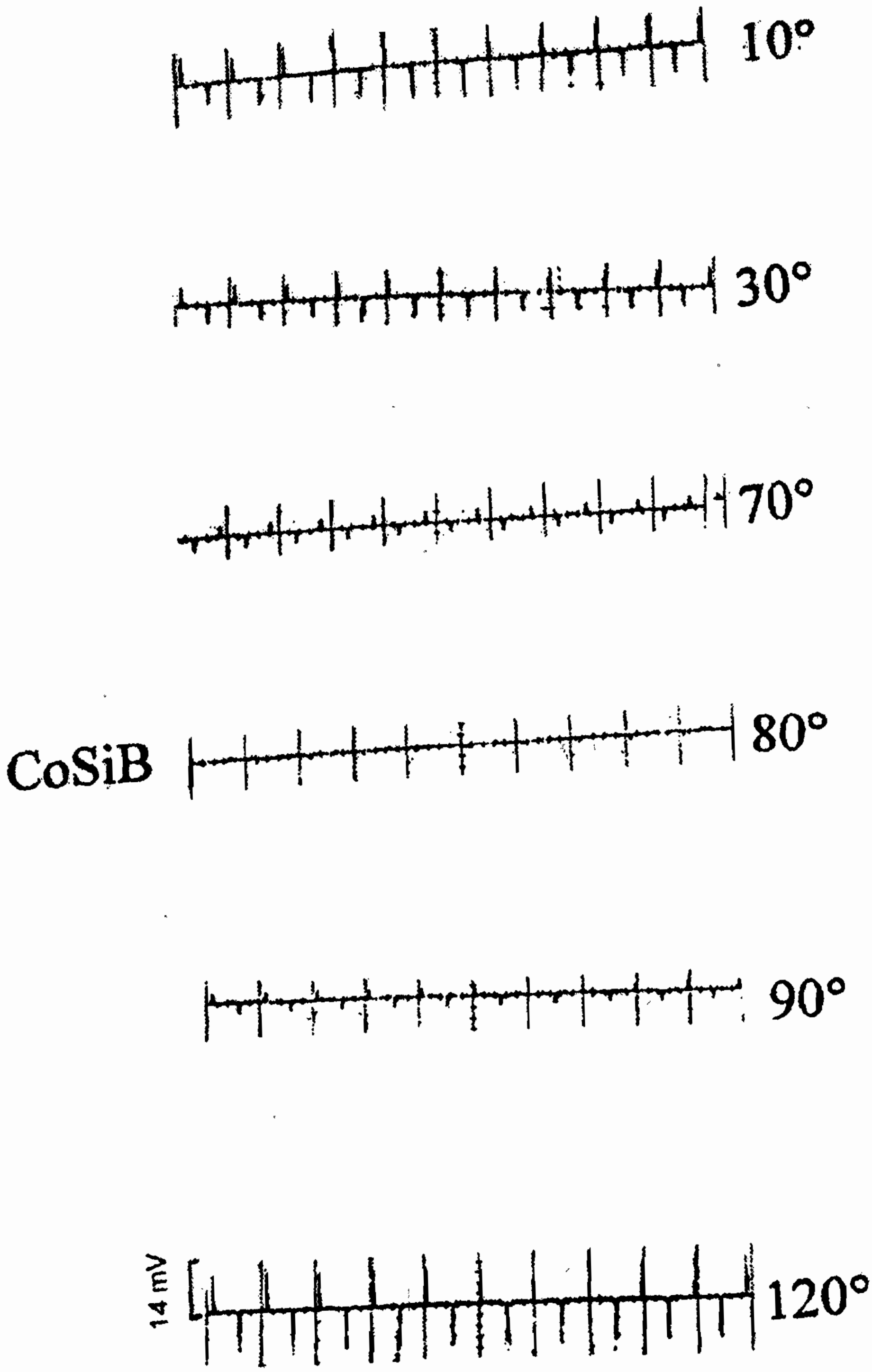

Figure 2 (a). Change of Matteucci voltage due to torsion in $Co_{72.5}Si_{12.5}B_{15}$ wire

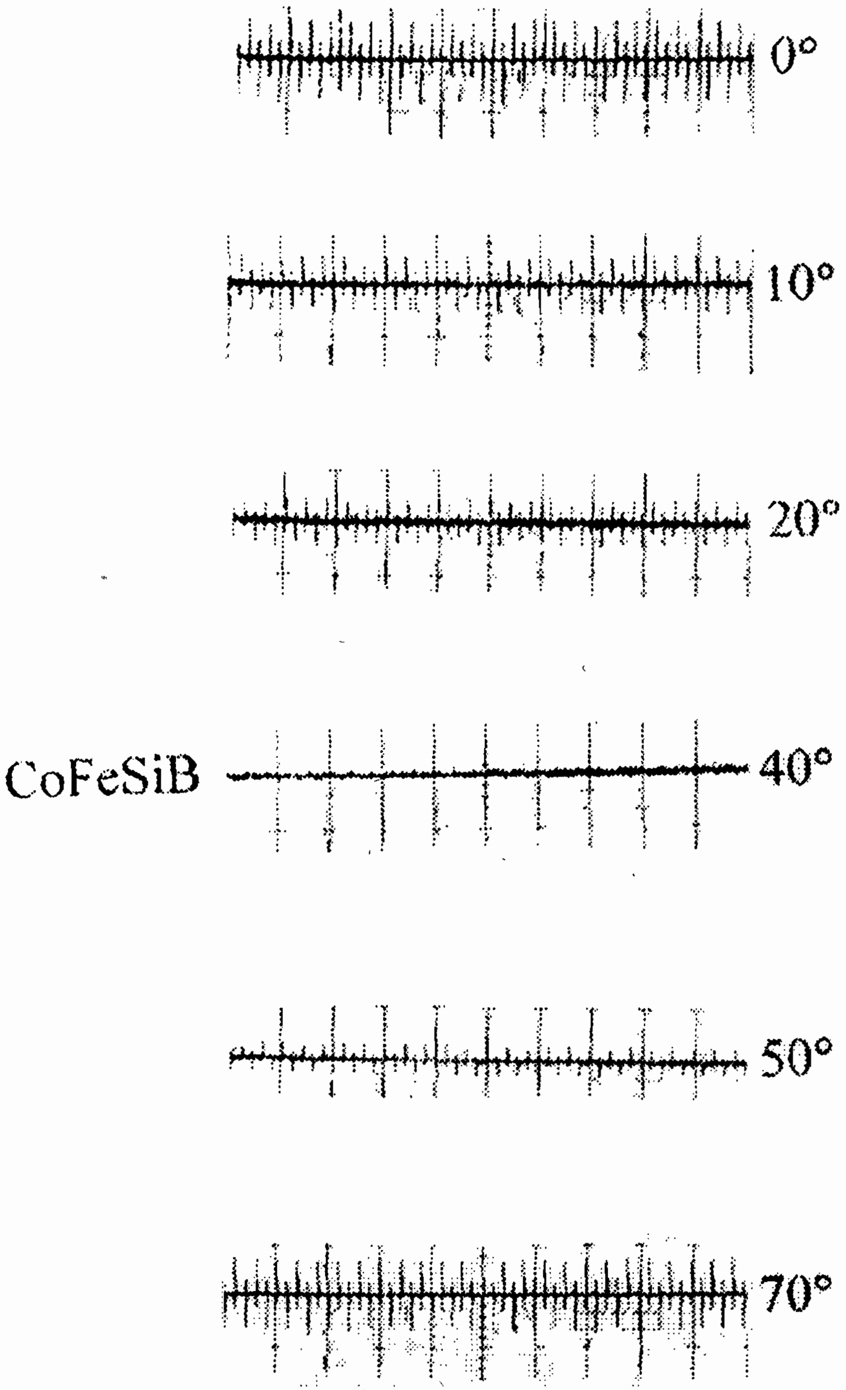

Figure 2 (b). Change of Matteucci voltage due to torsion in $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ wire

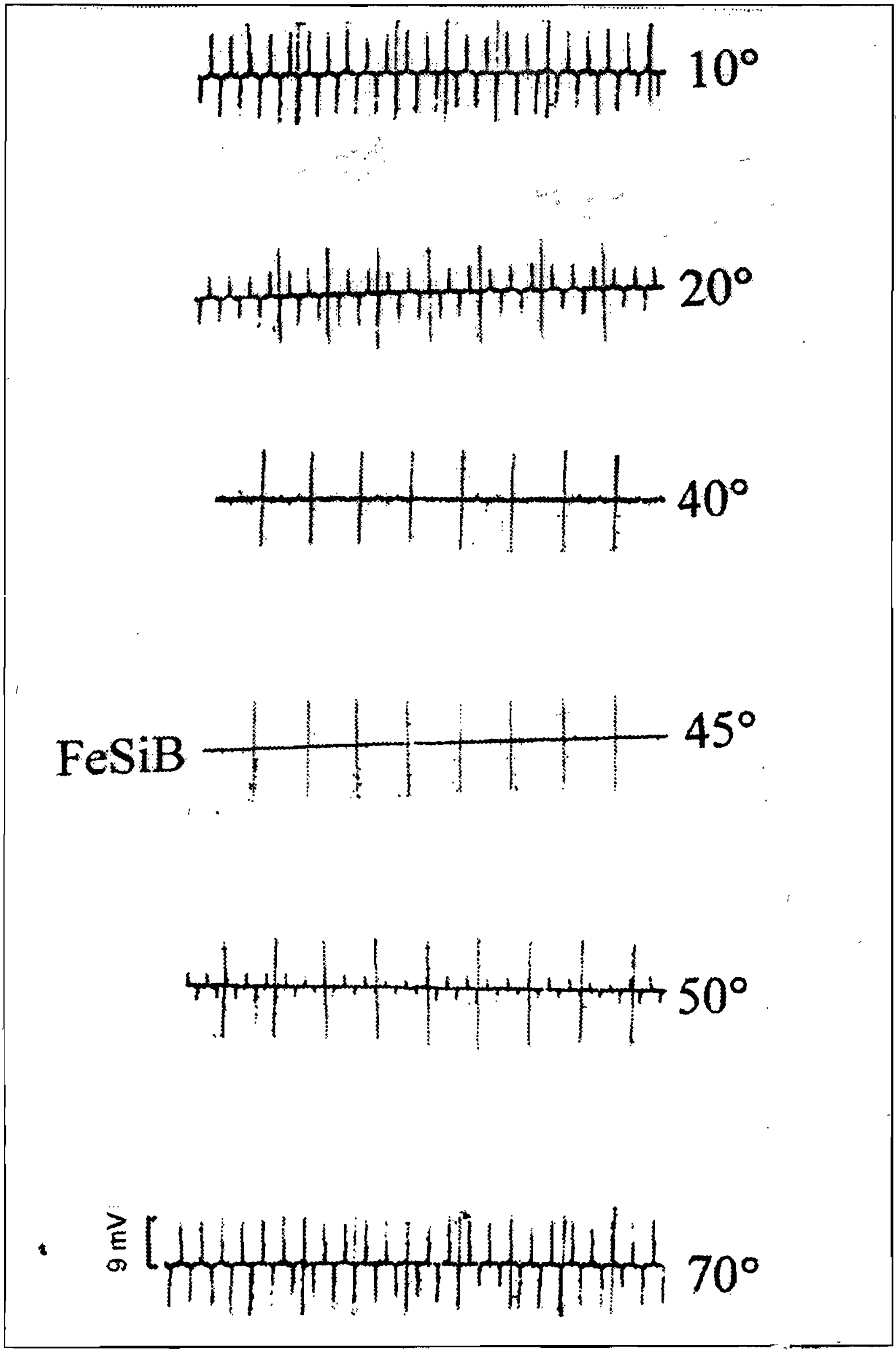

Figure 2 (c). Change of Matteucci voltage due to torsion in $Fe_{77.5}Si_{7.5}B_{15}$ wire

In Fig. 3 (a) the amplitudes of the Matteucci pulses shown in Fig. 2 have been graphed versus the respective value of applied torsion. Fig. 3 (b) shows the case when the amorphous wire is inverted (wire ends interchanged) in the excitation coil. Note that for the inverted case (Fig. 3 (b)) the actual Matteucci voltage pulses are not shown, only the graph of Matteucci voltage amplitude versus applied torsion is shown. Comparing the graphs in Fig. 3 (a) and (b) for the same type of wire, it is seen that the torsion-magnetic characteristic is virtually a mirror image of the previous direction. For instance, if the zero amplitude Matteucci voltage was being obtained at a twist angle of 45° clockwise, it will now be obtained at an angle of the same magnitude, but for a counter-clockwise twist. The above behaviour suggests that the wires have a definite and unique domain structure, presumably the continuous spiral domain proposed previously *(Nderu et al., 1998)*. The continuous spiral domain has a definite chirality which remains the same even when the sample is inverted in the exciting coil. Thus, if the twist direction before inverting the sample was such as to enhance the easy direction of magnetization emanating from the residual stress, the effect will be opposite if the sample is inverted and the direction of twist is kept the same, that is, the torsion will now act against the easy direction of the internal stress. Thus, if for instance, the Matteucci voltage amplitude was increasing it will now decrease and if the zero Matteucci amplitude was being attained at a twist angle $+\theta$ it will now be attained at a twist angle $-\theta$. The behaviour observed in Fig. 3 is therefore validating the domain model that was proposed previously for the amorphous wires *(Nderu et. al, 1998)*.

In Fig. 3 it is also seen that the amplitude of Matteucci voltage pulses decreases to zero at an angle of torsion that depends on the type of wire involved. Besides, it is observed that from zero torsion, the amplitude of the Matteucci pulses increases when the wires are twisted counter-clockwise. However, when the wires are twisted clockwise, the amplitude of the Matteucci voltage pulses decreases up to a minimum point (zero) before, finally, starting to increase (note that the reverse is true when the wire ends in the exciting coil are interchanged).

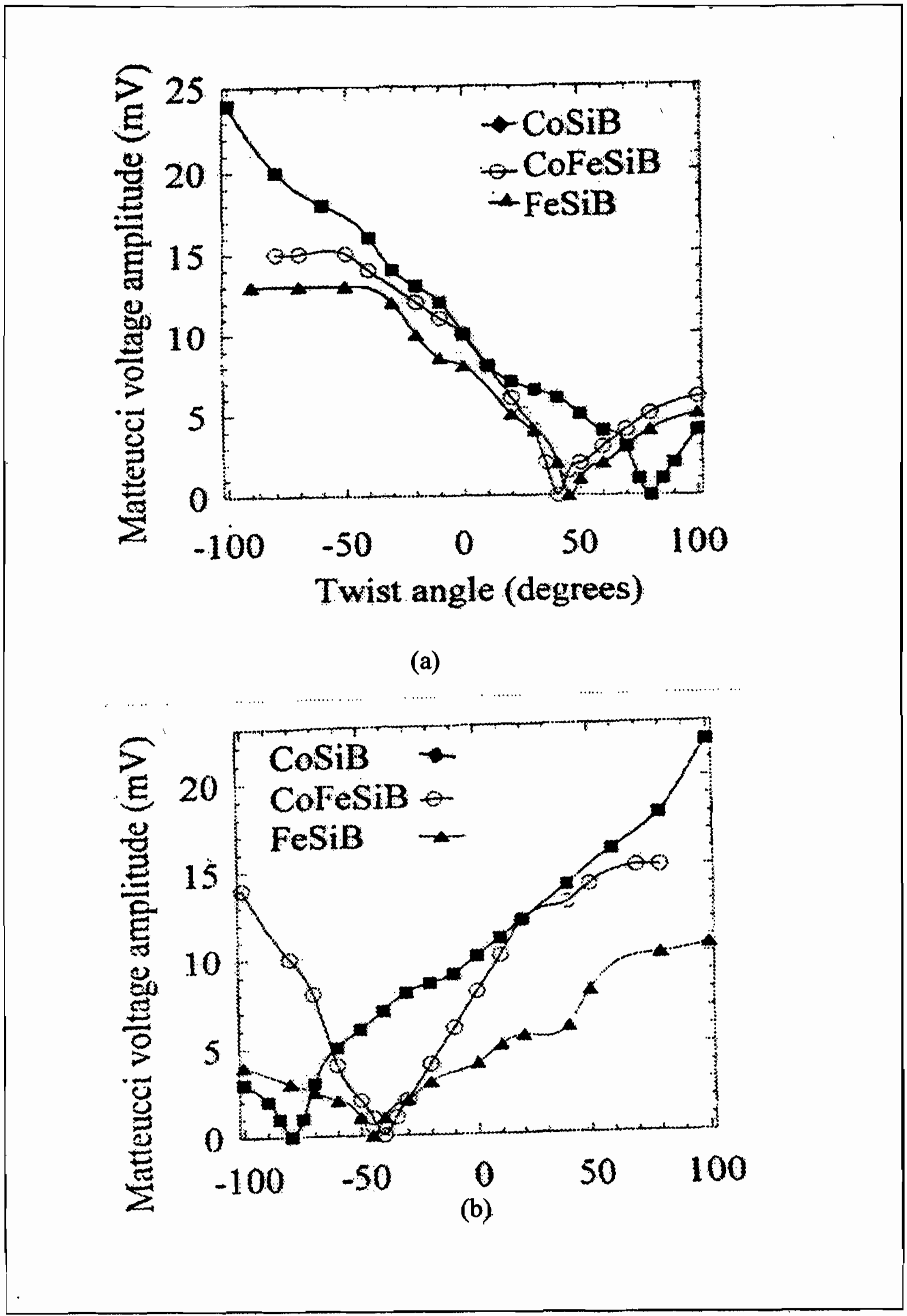

Figure 3. Change of Matteucci voltage-torsion characteristic due to change of wire direction in the exciting coil (compare Figs (a), (b))

This is a clear distinction (in behaviour) between clockwise and counter-clockwise torsion, which can be employed to determine the direction of initial twist. Also, it is observed that the low torsion-Matteucci voltage characteristic, especially for the $Co_{72.5}Si_{12.5}B_{15}$ wire, provides a possibility of employing the torsion-Matteucci voltage relationship to determine the magnitude of torsion to a high sensitivity. This is evident from figure 4. Figure 4 is an extract of data of $Co_{72.5}Si_{12.5}B_{15}$ wire from Fig. 3 (b) and drawn on an enlarged scale to reveal the possibility of using the wires to sense both magnitude and direction of torsion to a high sensitivity. The solid line drawn in the figure is the best straight line through the points. The error introduced by linearizing (drawing the best straight line through the points) is about 4 percent, which is quite reasonable. It is thus reasonable, for all practical purposes, to consider the relationship between the applied torsion and the Matteucci voltage amplitude, in the range covered in Fig. 4, linear.

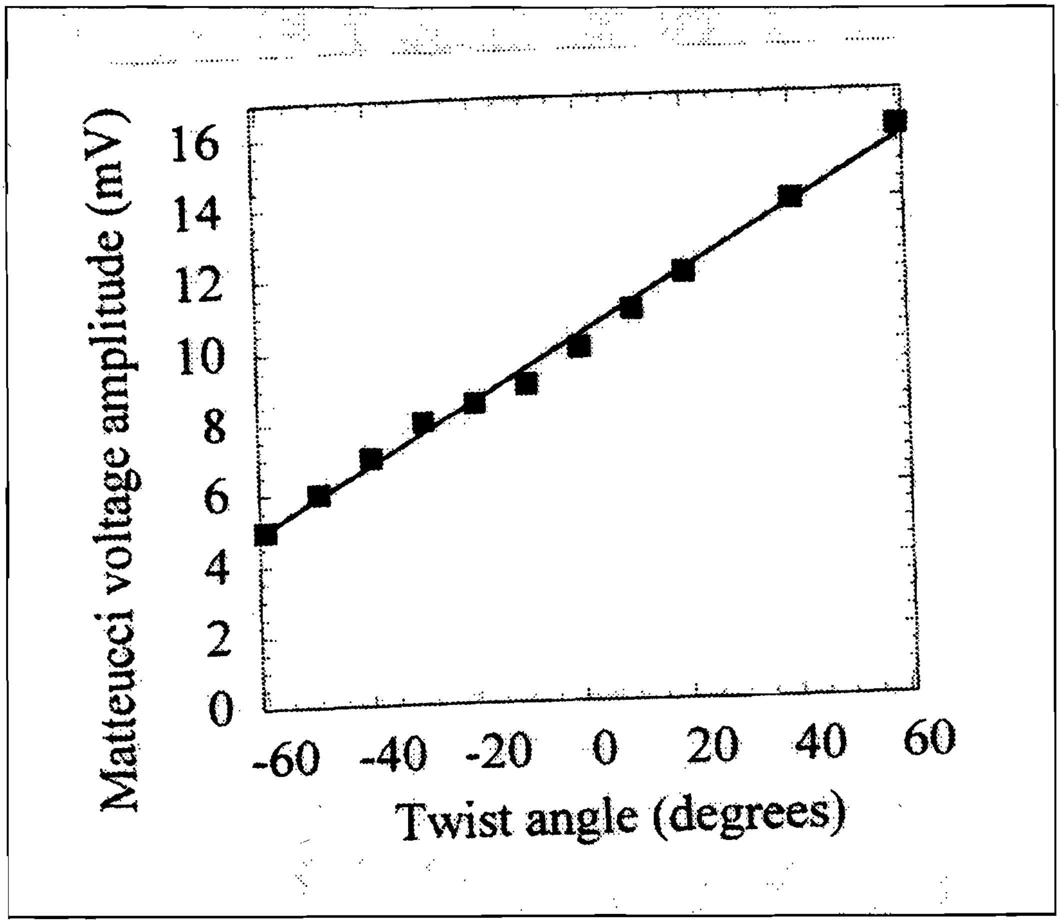

Figure 4. Extract of data of $Co_{72.5}Si_{12.5}B_{15}$ wire from Fig. 3 (a) and drawn on an enlarged scale

3.0 CONCLUSIONS

The effect of torsion on Matteucci voltage pulses in amorphous wires has been studied. It has been shown that:

The direction of rotation of the coolant employed in quenching the samples during fabrication of the amorphous wires introduces internal stress pattern that results in a unique domain structure. The direction of rotation of coolant thus plays a very important role in determining the magnetic characteristics of the wires.

The behaviour observed in the present work can consistently be explained based on the domain structure models proposed previously for the amorphous wires. This behaviour is therefore validating the domain model.

Though further analysis of the torsion-meter characteristic is necessary to establish the viability of the meter, it is possible, in principle, to sense both magnitude and direction of torsion using the stress sensitive Matteucci voltage.

Additionally, it is worth noting that passing an alternating current directly along the wire to produce a circumferential field at the wire surface could ultimately eliminate the exciting coil used to generate the magnetic field, further simplifying the sensor construction.

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