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MATTEUCCI (MS) EFFECT IN SINGLE IRON CRYSTALS, IRON WHISKERS AND THIN MARTENSITIC STEEL WIRES*

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Matteucci emf (MS) impulses in different ferromagnetic policrystalline metals and alloys and single crystals are presented. Different signs and amplitudes of the MS depend on chemical composition and crystallographic orientation of the examined ferromagnetic crystal.

It has been found that in ferromagnetic wires an emf can be generated similar to the MS, but without the torsional twist. In order to distinguish it from the MS, it has been designatet *S*. The sign of the *S* depends on the section of the wire in the excitation coil. When the measurement is performed between the two ends of the wire located at the opposite ends of the excitation coil, it under goes a cancellation due to the summation of the *S* having opposite signs in the opposite halves of the wire.

Introduction

It is well established that when an oscillatory longitudinal magnetic field is applied to a magnetic wire under torsional twist (see Fig. 1), emf (MS) appears between its ends in the form of short impulses [1, 2, 3, 4, 5, 6, 7]. The MS relies on circular or transverse components of magnetization [6]. By some authors, the MS effect is interpreted in terms of magnetostriction [2, 3]. Also, an analogy between MS effect and that of Hall has been considered [7] and a suggestion has been made that different signs of the MS in different ferromagnetic metals and alloys rely on two different magnetic moment carriers [8]. Such a suggestion is supported by the fact that, through interaction of the $3d$ electrons with valence electrons, different alloying elements have different effects on the MS in different ferromagnetic metals. For instance, alloyings of Si or Cr cause to cancellation of ferromagnetism in nickel, while in iron they do not. Considering that the MS impulse in nickel is negative,

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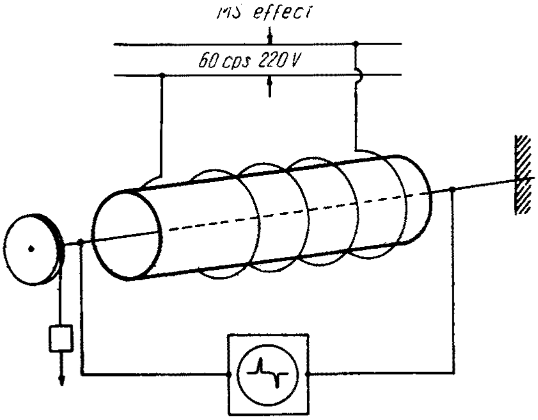


Fig. 1. Schematic representation of the MS investigation

these alloyings reduce only the negative part of the MS impulses of iron giving at the same time a considerable increase of the positive part [4]. In this discussion even more interesting is the fact that 75% Fe —25% Ni alloy is not ferromagnetic.

MS in polycrystalline ferromagnetic wires.

Figure 2, shows MS impulses of Fe, Ni, Co and Gd. At each impulse the sine wave of the ac passing in the coil (Fig. 1) is indicated.

Figure 3, shows the dependence on the intensity of the magnetic field of the MS amplitudes of Fe, Ni, Co, Gd and Fe — 3% Si wires at clockwise twist. Notice that the negative impulses of the Fe — 3% Si wire are considerably reduced with comparison to the pure Fe wire. Similar reduction of the negative part of the MS impuse of iron can be achieved as above mentioned by alloying Cr with iron [4].

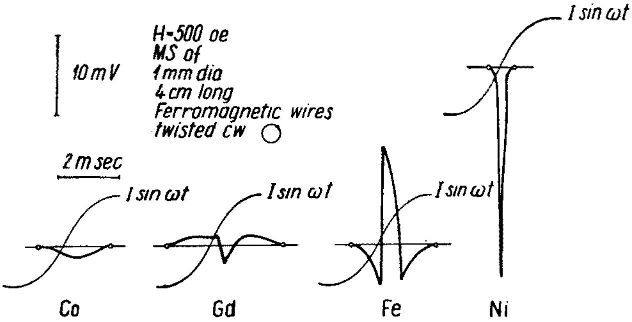


Fig. 2. MS single impulses generated in Co, Gd, Fe, and Ni wires

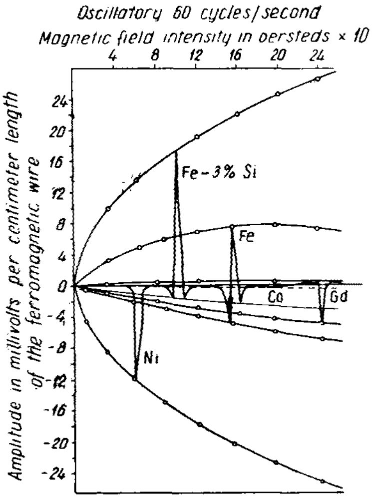


Fig. 3. Dependence of MS amplitude from the intensity of the magnetic field

MS generated in single crystals

The following single crystals were examined: pure Fe, Fe — 4% Si, and Fe— 20% Cr. The samples were in the form of 1 mm diameter, 15 mm long rods (The examined length was 10 mm). Such rods were machined in three major directions: [100], [110] and [111], out of bulk 15 mm diameter single crystals (grown from the melt by Czochralski's method). The field intensity most of the time was 500 Oe — 60 cps, unless otherwise indicated on the appropriate graphs. In addition to the above crystals, iron whiskers were extensively investigated. Through *X*-ray examinations, it was found that simply by considering the cross-sections of the whiskers, one can tell the crystallographic directions in which the whiskers were grown. The square cross-section of a whisker indicated that it was grown in the [100] direction. The regular hexagonal cross-section and the extended hexagonal cross-section indicate the growth in [111] direction and [110] direction respectively.

Figure 4. shows three oscillograms of the MS generated in the [100] direction of single crystals twisted clockwise of pure Fe, Fe — 4% Si, and Fe — 20% Cr. The sine wave relates to the ac generating magnetic field in the coil (Fig. 1.). The impulses have the sign consistent with that of nickel twisted clockwise. Notice that alloyings of Cr and of Si in iron cause cancelation or even inversion of that part of the impulse which in the case of the pure Fe crystal occurs before the ac changes the sign in the coil. This explains why the negative parts of the MS undergo a cancellation in polycrystalline Fe—Si or Fe—Cr alloys [4].

Plate I shows oscillograms of the MS generated in the [110] direction of the single crystals. The sine wave of the ac in the excitation coil is not shown there, but it was found that the change of its sign took place at the peak of the MS impulse in pure Fe crystal and at the zigzag center at the peaks in the case of Fe — 4% Si and Fe — 20% Cr single crystals. These zigzags indicate that MS impulses are resultants of two components being out of phase relative to the horizonal display of time. This phenomenon will be discussed at the end of this paper.

Very interesting investigations of the MS appear in the [111] direction, which is the most difficult direction of megnetization in iron single crystal. Plate II summarizes this investigation of the MS in [111] direction of single crystals of Fe (Photo *A* and *A*), Fe — 4% Si (Photo *B*), and Fe — 20% Cr (Photo *C*). Photograph *D* is the MS oscillogram from a strip of Fe — 3% Si transformer sheet textured in [111] direction. Notice that MS in *D* is very similar to that in *B*. The Photograph *E* shows single MS impulses in Fe — 4% Si single crystal along [111] direction generated by a switch on dc in the coil (Fig. 1) at five different voltage differences across the coil: 5 V, 10 V, 20 v, 30 V, and 40 V. (See the corresponding diagonal lines relating the dc magnetic field increasing with time.) Notice that in each case the characteristic reverse impulses appear when the magnetic field reaches 316 Oe. In the same investigation it has been found that in the case of pure iron single crystal or of iron whisker with the hexagonal cross-section these reverse impulses appear at 410 Oe, and in the case of Fe — 20% Cr at 260 Oe. These data appear to be related to the intensity of magnetic field at which magnetic saturation of these crystals in [111] direction occurs [8].

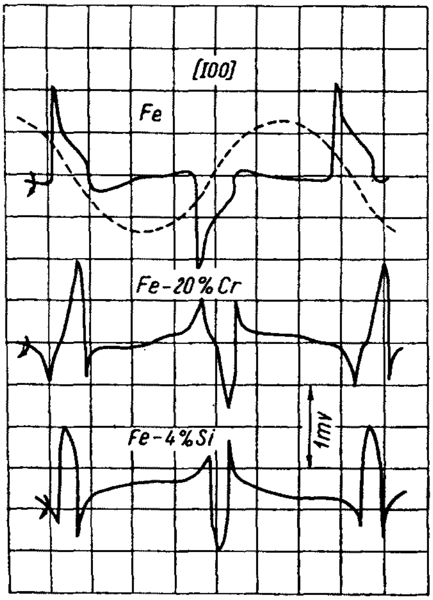
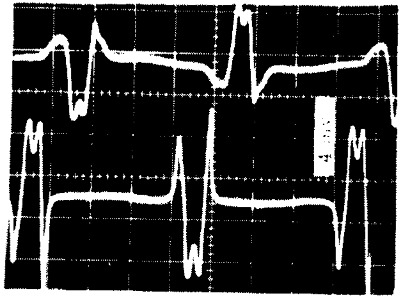


Fig. 4. MS impulses generated in 100 direction of single crystals of pure iron, Fe — 20% Cr, and Fe — 4% Si

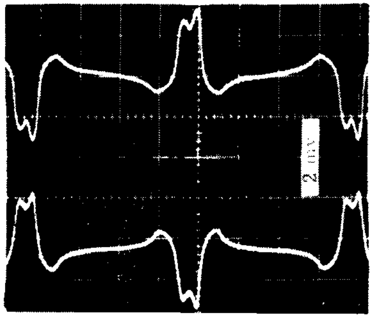
Is worthwhile to mention that examination of the MS in thin strip cut from several textured transformer sheets was performed. These strips were cut as follows: the first parallel to the texture or the [100] direction, the second across the texture or parallel to the [110] direction, and the third diagonally to the texture or parallel to the [111] direction.

PLATE I

A. Fe SINGLE CRYSTAL [110]
Twisted c-cw.

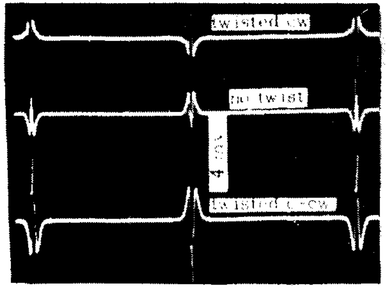


B. Fe-4% Si SINGLE CRYSTAL
Top-twisted cw.
Bottom-twisted c-cw.

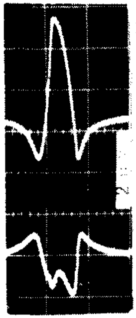


C. Fe-20% Cr SINGLE CRYSTAL [110]
Top-twisted cw.
Bottom-twisted c-cw.

D. Fe-6% Si SINGLE CRYSTAL [110]



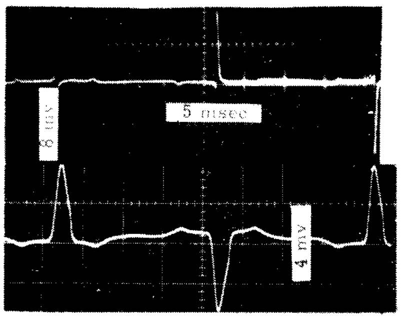
E. Fe-3% Si TRANSFORMER STEEL SHEET strip: 0.3mm x 1mm x 10mm. Normal to the rolling direction, texture in [110].



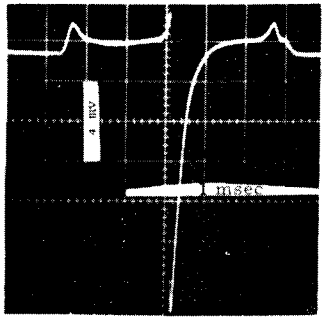
F. POLYCRYSTALLINE Fe WIRE with a helical cw. cold work. /
Top-twisted cw consistant with the cold work.
Bottom-twisted c-cw inconsistant with the cold work.

In all cases, 500 Oe - 60 cps.
All samples, but E, 10mm long, 1mm diameter.

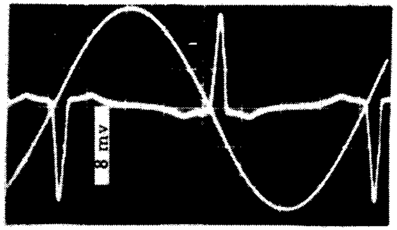
PLATE II



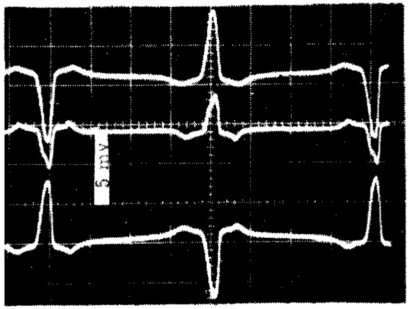
A. Top-Fe WHISKER [111]
15mm long, twisted cw.
Bottom ; Fe SINGLE CRYSTAL [111]
10mm long, 1mm dia., twisted c-cw.
500 Oe - 60 cps.



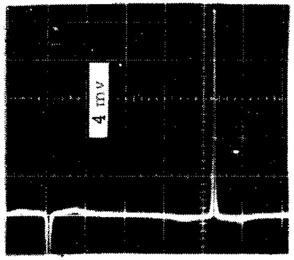
A'. Fe WHISKER [111]
15mm long, twisted c-cw
3400 Oe - 60 cps.



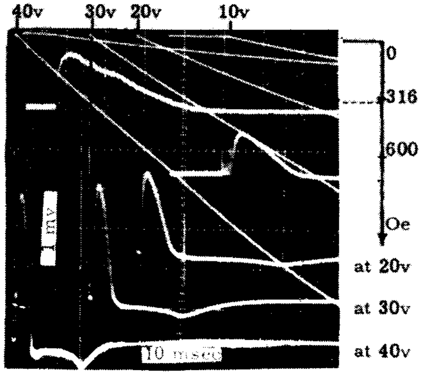
B. Fe-4% Si SINGLE CRYSTAL [110]
10mm long, 1mm dia., twisted cw
Shown is the sine wave of magnetizing
current. 500 Oe - 60 cps.



C. Fe - 20% Cr SINGLE CRYSTAL [111]
10mm long, 1mm dia.
500 Oe - 60 cps.



D. Fe-3% Si TRANSFORMER
STEEL SHEET
Cut at 45° to the rolling
direction, which is textured
in [111]. Strip: 0.3mm x
2mm x 10mm, twisted cw
500 Oe - 60 cps.



E. Single MS impulses in crystal B,
at switch on, diagonal lines
relate to d. c. magnetic field
increasing with time.

The appearance of the MS in these strips was in full conformrity with the MS appearance in single crystals in these directions. For this simple conclusion, one example, *D*, is shown in Plate II.

Study of ferromagnetic wires — without torsional twist

It will be shown that in the case of martensitic steel and in some other alloys emf similar to the MS will appear even when the wire is not under torsional twist. We distinguish this emf from MS by designating it *S*. The table lists the wires which were investigated for the *S*. In order to obtain martensitic structure in wires 1, 2, and 3, they were extended horizontally between two electrodes 110 cm apart, electrically heated in an argon atmosphere, and in that position were quenched in salt water at —4°C. The temperatures from which these wires were quenched were 30° above the transition temperature from gamma phase to alpha phase.

At this point it should be mentioned that the *S* appearance in these wires was essentially the same in annealed state as in the martensitic state. However, the advantage of the later state relies on better rigidity which was convenient in handling the wires during the experimentation.

TABLE I

Materials investigated

No	Diameter	Chemical composition	State
1	1 mm	0.43% C plain carbon steel	martensitic
2	1 mm	0.64% C plain carbon steel	martensitic
3	1 mm	0.91% C plain carbon steel	martensitic
4	1 mm	0.43% C plain carbon steel	annealed
5	1 mm	17% V+83% Fe	annealed
6	1 mm	40% Cr+60% Fe	annealed

Figure 5 illustrates the experimental arrangement for *S* investigations in these wires. It consists of a long coil with a core in the form of a wire which was the examined sample. The wire is marked by four points. Between these points observations of the *S* were made. The oscillograms of the *S* relative to those observations in wires No 1, 3, and of the MS in 4 are shown below and accordingly marked. In Figure 5, below the coil there are two sets of oscillograms obtained in No 1 and No 3 martensitic steel wires. It can be seen that *S* impulses in wire No 1 have opposite signs to those in wire No 3 in each section of the wire in the coil. This fact is even better displayed by the *S* oscillograms (shown in lower right corner) in the form of two loops obtained in the two wires, separately, 4–3 when the upper beam amplifier was connected to horizontal deflection plates. The loops are indicated by the appropriate carbon content in the wires. The *S* loops in the section 2–1 of the wires were reverse to the 4–3 and there is no need to show them. For a comparison, the appropriate MS loops obtained in the annealed steel wire No 4 being torsionally twisted, are also shown in the bottom right hand corner of the Figure 5. Notice that unlike the S, the direction of the MS impulses does not conform with the tilt of the main part of the loop. This indicates that the MS impulses react against the external torsional twist. In Figure 5 there are no oscillograms of S generated by wire No 2, No 5, and No 6. However, it was found that S oscillograms obtained in wire No 2 were similar to those of wire No 3. But, between the ends 4–1, the cancellation of the S was almost complete in wire No 2 while in the wire No 3, it was not. The S oscillograms obtained in the wire No 5 and No 6 had the signs consistant with those of No 1.

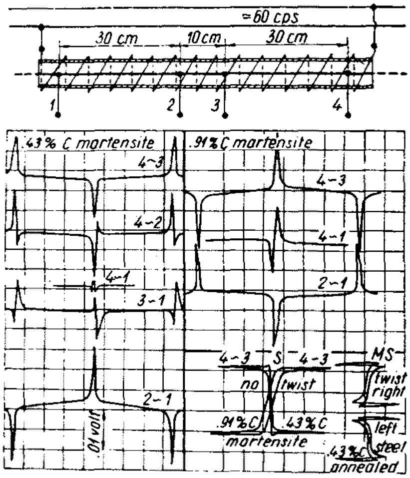


Fig. 5. The figure shows schematical arrangement for the S study in magnetic wires. The oscillograms on the left pertain to the martensitic wire No 1. The positions at which they were taken in the coil are indicated. On the right the oscillograms pertain to the wire No 3. The right bottom corner shows oscillograms when the upper beam amplifier was connected to the horizontal deflection plates. There are two loops pertaining to the martensitic wires as indicated and two loops of the MS obtained in the No 4 wire. See the difference between them and the S loops

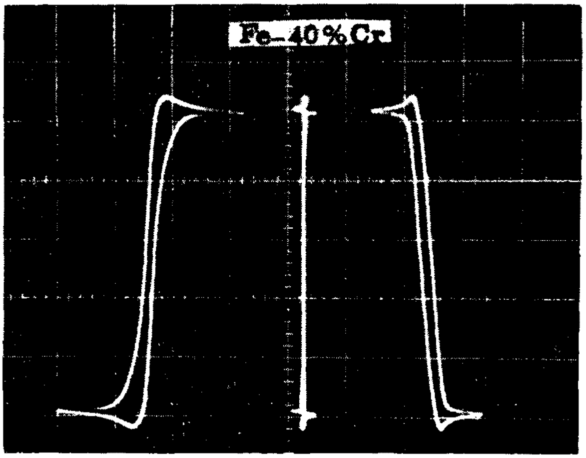


Fig. 6. S effect in form of the loop obtained in wire No 6

Figure 6 shows three loops obtained in wire No 6. The left one was obtained at the connection 2–1–, the central at the connection 4–1, and the right one at the connection 4–3. Notice that left and right are mirror images. The same loops were observed in case of wire No 5. Notice that the central loop undergoes a cancellation as a result of the summation of the left and right loops. This indicates that longitudinal oscillatory magnetic field produces an opposite internal static torques in the opposite sections of the wire. This effect to the author's knowledge has not yet been given theoretical consideration. Instead, the effect of a constant magnetic field on torsional vibration has been taken into account [9, 10, 11]. Conceivably the solution to the present problem relies on a torque wave concept that exchange torque [12, 13] between the left and right atomic moments undergo separation along the wire, when in the oscillatory magnetic field, resulting in the opposite static internal torsion in the two opposite sections of the wire.

It can be shown how a MS impulse may be a resultant of two components of opposite signs. An example of this is shown in Figure 7. On the left bottom of the figure there are three oscillograms of MS impulses obtained in 1 mm diameter, 4 cm long wires of Fe — 5.5% Al and of pure Ni and the impulse obtained when both wires were connected in parallel. The right of the picture shows that the latter impulse is the resultant of the summation of the former two $(A+B)$. Essentially different from the above

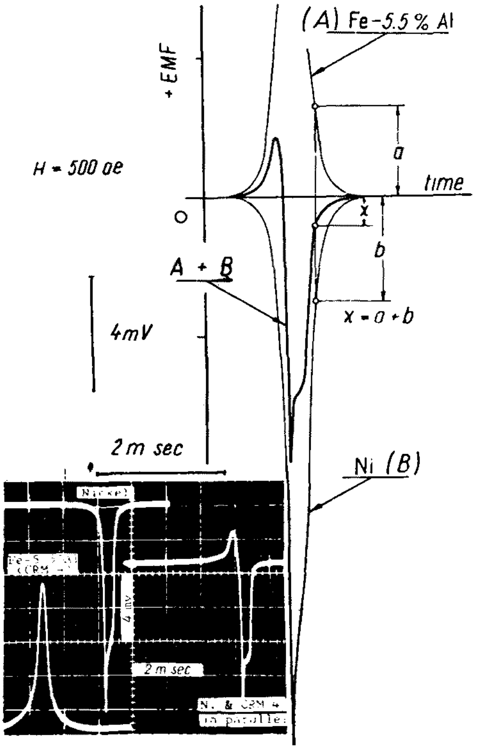


Fig. 7. Representation of the summation of the MS impulses of two ferromagnetic wires connected in parallel

example is the summation of the MS generated in magnetic tubes inside of which a reverse magnetic field appears when the tube longitudinally magnetized. Figure 8 shows such a MS impulse produced by a 5 cm long nickel tube (do/di = 5 mm 4.7 mm and it is indicated by $A+B$. A relates to the MS impulse generated in 5 cm long and 1.5 mm diameter nickel wire. The mass of this wire per cm length is approximately the same as the mass of that tube per cm length. B has been obtained by geometrical subtraction of impulse $A+B$ ($A+B-A = B$) and is attributed to the reverse field inside the tube.

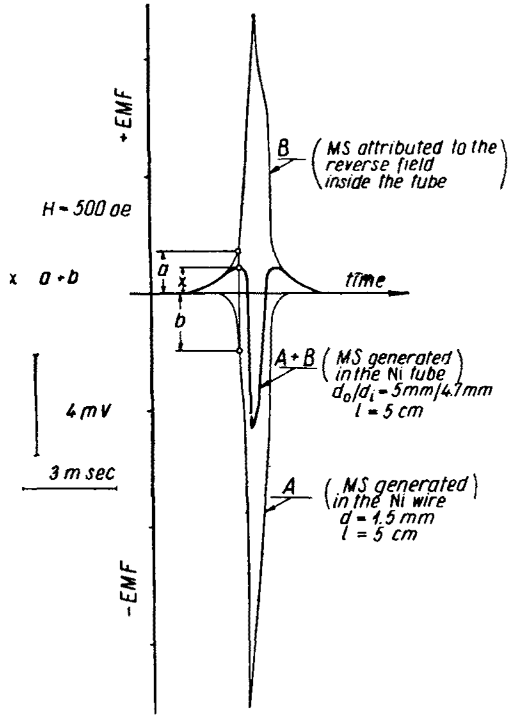


Fig. 8

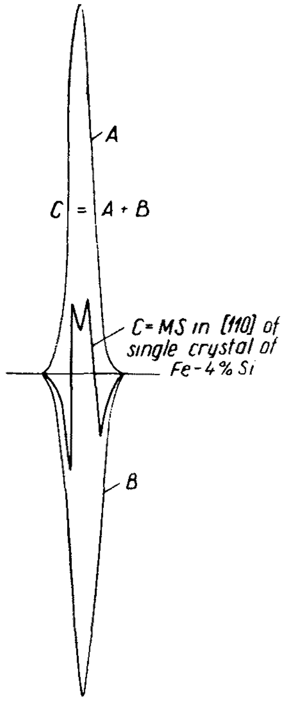


Fig. 9

Fig. 8. MS generated in nickel tube. The reverse impulses are attributed to the reverses magnetic field inside the tube

Fig. 9. MS impulses (C) in [110] direction of Fe-4% Si single crystal — represented as resultant of A and B impulses

The S impulses observed between the points 4–1 in the wires No 1 (shown in Figure 5) resemble the MS impulses obtained in the [110] direction of single crystals of Fe — 4% Si and Fe — 20% Cr alloys shown in the Plate I. Their possible resultants being of two components have already been indicated. By an analogy to the Figures 1 and 8 a MS impulse generated in Fe — 4% Si single crystal along [110] direction is represented in Figure 9 as being resultant of two components having opposite signs. The appearance of the MS in those crystals seems to be due to two kinds of magnetic moment carries being present in the crystal. The sign of the resultant MS impulse depends upon which of the two magnetic moment carriers are prevailling. When the amount of the two kinds of magnetic moment carriers in a ferromagnetic wire is about the same and if their responses (having opposite signs) to the outside oscillatory magnetic field are in phase, the resultant MS impulse may be very small. An example of this may be the MS of cobalt wire (compare Fig. 3). On other hand if the responses of the two kinds of magnetic moment carriers in a wire are out the phase, the MS impulse may be composed of two parts of opposite signs. This has been found in the non magnetostrictive permalloys of 80% Ni and 20% Fe content wires. The fact that these wires generate MS impulses of very high absolute amplitudes shows beyond any doubt that the interpretation of the Matteucci effect by the magnetostriction [2] is irrelevant. Also, magnetostriction is irrelevant to the S effect as it would be impossible to assume that magnetostriction changes in different sections of the wire in the way as S changes. Similarily it has been already pointed out, that MS in [100] direction of the Fe single crystals has sign consistant with that of the MS of Ni wire, but the magnetostriction of the Fe crystals in [100] direction is positive or inconsistant with that of Ni.

In conclusion there are left and right magnetic moment carriers. Balance between the two magnetic moment carriers in ferromagnetic metals can be effected by different alloyings. The saturation magnetization depends on the total number of the magnetic moment carriers regardless of their sign. The coexistance „side by side" of such the left and right atomic moments in a solid is possible because of the positive exchange torque between them, and so they may form ferromagnetic domain [12], [13]. However, if in a solid there is only one kind of atomic moments either right or left, their exchange torque is negative, they may be bonded by opposite polarity, and instead of ferromagnetic domain may form antiferromagnetic domain.

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