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ART. VII.—*Apparent Hysteresis in Torsional Magnetostriction, and its relation to Viscosity*; by C. BARUS.

1. IN the present paper I shall describe a series of phenomena bearing on the permanence of torsional magnetostriction in iron and nickel magnetized by circular and by longitudinal fields, which have been encountered in different ways by others, but which appear here not only with greater clearness and in a more elementary form, but in a manner indicating a certain uniformity in the behavior of all metals. The phenomena are evoked by purely magnetic action. They are obtained by twisting the wire alternately back and forth over a definite angle within the elastic limits and examining the change of rigidity produced by circular or by longitudinal magnetization immediately after each new twist and after several repetitions of the magnetizations. The first magnetization succeeding any twist operates on the magnetic configurations surviving from the preceding twist and magnetizations; the remaining magnetizations (current alternately made and broken) for the same twist operate on the new configurations produced by the twist in question and the first magnetization applied to it. The results are very different as the following observations show. The former are viscous (temporary), the latter elastic (permanent) in character.

To explain the phenomena I shall make use of Maxwell's theory of viscosity in which (as I have ventured to interpret it) any deformation due to molecular instability is a viscous deformation. Now when the breakdown is gradual in character, which it must be if dependent on temporary local intensities in the distribution of heat motion, the deformation will be gradual as actually observed in ordinary viscous phenomena.

If, however, the breakdown is instantaneous, due for instance to the molecular shake-up accompanying magnetization or its withdrawal, then viscosity is instantaneously a minimum, the deformation sudden and the phenomenon "static." There seems to be no theoretical gap here.

2. The method of work is the same as that employed in preceding experiments.* The two identical wires to be compared, ab , cd , are fastened coaxially one above the other and a mirror, m , is attached between them. The top and the

bottom of the system are soldered to corresponding torsion heads, D , E , and the wires are insulated from each other at the mirror. The lower wire is kept submerged in a tube of flowing water, ww , and the means† are at hand for passing an electric current through it without interfering with the torsional adjustment. Hence the lower wire is under the influence of a circular magnetic field and thermal discrepancies are reduced to a minimum. Again a helix, AA , is placed around the tube for a longitudinal field the water bath being retained.

As the two identical wires make a single system any degree of twist may be locked up in it and the change dn of rigidity n due to the magnetic field is $dn/n = d\theta/\theta$, nearly, where θ is the twist imparted and $d\theta$ the change of twist due to the action of the field and observed at the mirror.

In describing the experiments L will denote the length of each wire in centims., D their common diameter in centims., C the current passed either through the lower wire or through the helix in amperes.

3. The effect to be observed expresses itself in a shifting of the fiducial zero, i. e., the position of the spot of light on the scale when the magnetic field is nil. The amount of deflection obtained in the first and second magnetizations therefore differs because the zero is markedly changed and in the case of a circular field always in such a way as to diminish the deflection; in longitudinal fields on the contrary, in a way to increase the deflection.

* This Journal, [4] x, pp. 407-418, 1900.

† The vanes $v v$ dipping in the salt solution contained in an annular trough (not shown), deaden vibrations and carry off the electric current for the circular field, entering at E . The weight W suitably stretches the system with the aid of a slot adjustment in the torsion head E .

In figure 1 for example (to begin with the circular fields) a nickel wire ($L = 41$, $D = .05$, $C = 4$) is twisted $+45^\circ$ and -45° alternately, as shown by the abscissas. The deflections observed are given by the ordinates in the order shown by the arrows. The two observations recorded at each twist correspond respectively to the first and the second (or succeeding) magnetizations. The deflection of the former is always the larger. The initial deflections or changes of rigidity due to circular magnetization lie along a line, a , the succeeding deflections along a line, b , of smaller slope. The fiducial zero in the successive twists suffers displacements due to the circular magnetization alone and would be represented by a zigzag line as will be more definitely instanced below.

If the deflections are studied between three successive twists the result is even more striking as seen for example in figure 2, for twists successively 0° , -45° , 0° , $+45^\circ$, 0° . The lines for initial and final deflections might again be drawn but they would confuse the figure. The displacement of the zero is such as to indicate two successive displacements in the same direction.

The phenomena are independent of the direction of the current and a larger angle of twist does not magnify them in an easily discernable way.

The nickel wire being relatively thick and the current closed but a short time, no attention was paid to the heat produced in the wire by the current. In the following experi-

ments with a thinner wire of iron, this was kept submerged in the tube of flowing water specified. The residual diminutions of rigidity given by the line b in figure 1 may, therefore, be of thermal origin.

4. The decrement of rigidity due to the effect of circular magnetization on a submerged iron wire ($L = 41$, $D = .024$, $C = 3$) is so nearly like the above results for nickel, that a few sample curves will suffice to introduce the subject. The diameter being relatively small larger twists are admissible as lying well within the elastic limits.

In figure 3 the twists are alternately $+180^\circ$ and -180° , though the observations begin and end with zero. The arrows are a sufficient guide as to the sequence of results. The lines

a and b show the decrement of rigidity due to the initial and subsequent circular magnetizations for each twist. In figure 4 three twists are successively applied. Lines corresponding to the initial and final magnetizations are omitted. An inspection of all the figures shows that the displacements of the zero due to twisting between two angles a and $-a$, is less than the aggregated displacements due to twisting from a to 0° and 0° to $-a$, under otherwise identical conditions. We have here also the key to certain results in a previous paper in which increasing positive twists return with larger positive displacements and increasing (absolutely) negative twists return with increasing negative displacements.

The curves given correspond to mean currents. The scale of the phenomenon increases with the strength of the current. For 1 ampere, figure 5, the decrements of rigidity due to the initial magnetizations line *aa* are still of marked value; the subsequent effects (line *bb*) lie within the errors of observation. For 6.5 amperes all decrements have been greatly magnified as seen in figure 6.

Finding that a more systematic series of results would facilitate the discussion below, I have added figures 3' to 6', for the same sample of (submerged) wire and a circular field (current 6.5 amperes), and for twists increasing from 45° to 360° , applied to each wire. These were 35 centims. long and .024 centims. in diameter. The cycles were many times repeated as the figures show at once. The striking feature of all these experiments is the remarkable constancy (for the same wire and current) of the slopes of the cycles, i. e., of lines connecting the means of initial and subsequent deflections. This slope shows no certain variation between 45° and 360° of twist. The marked contrast between the temporary slopes, *a*, due to the first magnetization and the permanent slopes, *b*, due to the ensuing magnetizations is sustained. All slopes are negative.

The displacements of the fiducial zeros or slips observed at the end of the cycles do not increase as fast as the twists. They show their chief increase between 45° and 90° . To better exhibit the displacement of the zero I have given the successive scale readings in the zigzag curves *c*, attached to each figure. The position of the spot is marked off vertically to scale, and the successive observations are charted at equal distances apart horizontally, for distinction, and joined by straight lines. The field is alternately made and broken beginning with no field. When the sign of the deflection (positive, up) and that of the twist (given by the attached sign) agree, rigidity is increased. The curves show that rigidity is diminished on closing the current and increased on breaking it. Moreover, after the first closing, the diminution of rigidity is enormously greater than on subsequently closing the current for the same twist. This is particularly true for small twists.

5. The endeavor must now be made to elucidate these phenomena. With regard to the relatively small decrement of rigidity obtained in the circular magnetizations succeeding the first (i. e., the permanent decrements), I have already shown (l. c.) that they may be reproduced in brass wire by the same means; and until specially refined experiments are made, they may be regarded as the mere result of the accession of heat. The phenomena are thermal and elastic in their nature. So much, therefore, for the slopes of the lines, *b*.

The interesting feature of the experiments are thus the lines, *a*, together with the corresponding displacements of the fiducial zeros given by the zigzags, *c*. These phenomena cannot be reproduced in brass* stressed within the elastic limits. Hence I infer that they are viscous in character and due to the breakdown of unstable magnetic configurations (in Maxwell's view) resulting from the new magnetization. For although the viscosity of a magnetic wire and of a non-magnetic wire are identical, the period of breakdown which follows the first magnetization must be rich in unstable configurations and, therefore, temporarily low in viscosity. I conclude, therefore, that the displacement of the zero is due to the molecular instability which accompanies the act of magnetization when first applied; that in subsequent magnetizations the molecular disturbance is less because the configurational effect of the first magnetization is largely permanent. Fixed configurations are merely deflected in their elements without being broken up anew. Further discussion would be of little value because of the heat discrepancy, occurring in spite of the submergence.† The essential data are to be incorporated with the remarks made for longitudinal fields.

6. After these results it seemed necessary to reconsider in detail the corresponding phenomena in a longitudinal field since here the *heat discrepancy* can be quite *eliminated*. This was done with the same precautions. The helix was supplied with currents of about 2, 4, and 8 amperes, respectively, evoking longitudinal fields of roughly 200, 400, and 800 c. g. s. units. The identical annealed iron wires were each of about 35 centims. long and .024^{cm} in diameter. They were insulated from each other so that a current could be passed through the lower alone, which was submerged in flowing water while the upper wire was suspended freely in air. Both wires were stretched in the same vertical line. Cf. figure above.

But one observation was made with the weak field for $C=2$ amperes, as shown in figure 7, the twists being alternately $+90^\circ$ and -90° . The interesting features are the directions *a* and *b*, corresponding respectively to the first and subsequent magnetizations, and, therefore, to the temporary and the persistent effects. Both are increments while in the above cases of circular magnetism they were decrements. The displacement of the zero, however, here and above has the same direction and corresponds to diminished viscosity (high molecular instability)

* I also tested the effect of a current on a submerged brass wire stressed a little beyond the elastic limits. The results showed that whereas the rigidity is decidedly modified by the presence of a current, the viscosity of the wire is not noticeably different in the two cases. The effects are due to heat.

† See preceding paper in this Journal, IV, x, p. 417, 1900.

of the magnetized wire in the initial magnetization. As this is the important result I will again record the successive scale readings as shown by the zigzag lines c , with the subscript referring to the figure. It is not necessary to give more than four observations for each twist since all subsequent elongations are like the second in magnitude. For the first and third points the field is off, for the second and fourth it is on.

If the twist be positive (shown by the attached sign), an increased scale reading denotes increased rigidity of the magnetized wire, and vice versa.

It is preferable to discuss these results in connection with figures 8–11, for a larger field ($C = 4$ amperes) and twists

respectively between 45° , 90° , 180° , and 360° both sides of 0° . In figure 8 the line *aa* shows that the initial magnetization has produced a decided decrement of rigidity; line *bb* that the persistent effect of longitudinal magnetization is an increment of rigidity. The series of zigzags *c* (except the first which is reached from zero or no apparent strain) bear this out very fully. The first magnetization produces a deflection in a direction opposite to the acting stress. On breaking the current this deflection is increased (rigidity further diminished). The second and subsequent magnetizations increase rigidity but the original reading is not again reached.

Figure 9 for twists between $+90^\circ$ and -90° is similarly explained. The original magnetizations are indecisive, sometimes corresponding to increase sometimes to decrease of rigidity. On the whole the initial slopes, *aa*, are nil. Slopes *bb* correspond to marked increase of rigidity as usual. Full account is given by the zigzags *c*.

Figures 10 and 11 apply for twists between $+180^\circ$ and -180° , and between $+360^\circ$ and -360° , respectively. Both the initial and the subsequent magnetizations produce marked increments of rigidity, as shown by the lines *aa* and *bb* for each case and by the lines *c*. The scale of the phenomenon increases as the limits of twisting increase. The displacements, however, do not increase; in other words the vertical breadth of the cycles is not much greater for 360° than for 45° . There appears to be a pronounced tendency for the displacements to pass through maxima of slip for intermediate angles. Finally, so far as can be discerned the slopes of the cycles are the same throughout, rather an unexpected result. This means that the mean increments of rigidity are proportional to the twists, *caet. par.*

Repetitions of the experiments with the same sample of wire and small angles reproduced the original results as shown for instance in figures 12 and 13.

In view of the small effects produced in fields for $C=2$, and $C=4$ amperes, respectively, it seemed advisable to investigate the effect of further doubling the strength of the longitudinal field. The data are given on the same plan as in §6, in figures 14, 15, 16, 17. The displacements (vertical width of the cycles) have remained about as large as before and tend to pass through a maximum for intermediate angles of twist. The slopes of the cycles have definitely increased, so that for mean values, rigidity increases proportional to twist at a faster rate in stronger fields.

A rough summary of the principal data will be in place here.

TABLE I.—Magnetostriction of soft iron in longitudinal fields.

Current Field.	Twist.	Slope <i>a</i> .	Slope <i>b</i> .	Cycle slope.	Displacement.
2 amp.	+ 90°	+ 0·5	+ 6·0	+ 3·0	+ 5·5
200					
4 amp.	+ 45	− 3·0	+ 6·0	+ 1·5	+ 4·5
400	90	− 1·0	5·5	3·0	6·0
	180	+ 1·0	5·0	3·0	7·5
	360	+ 2·0	3·5	2·5	5·0
4 amp.	45	− 2·0	6·0	2·0	4·0
400	90	− 1·0	6·0	2·5	7·0
					4·0
8 amp.	+ 45	− 2·0	+ 6·0	2·0	4·0
800	90	− 0·5	6·5	3·0	7·0
	180	+ 2·0	5·5	4·0	6·0
	360	+ 3·0	4·0	3·5	4·0

Length, 35^{cm}. Diam., ·024^{cm}. Deflections in scale parts (·001 radian or ·057°) per 90° of twist of each wire.

Hence with increasing twist the temporary deflection *a* and the permanent deflection *b* make respectively from large negative and from large positive values toward the same intermediate positive limit, which is larger for the larger field. The slopes of the cycles pass from small values rapidly into constant values as twist increases but they probably also pass through maxima as above. Finally the displacement of the zero for increasing twist marches through a definite maximum located at small angles of twist when the field is greater.

8. To obtain further relevant data it will next be necessary to twist between three angles, the middle one being zero and

the others equidistant from it. These results are shown in figures 18, 19, 20, the field corresponding to $C=8$ amperes. Soft iron wire ($L=35^{\text{cm}}$, $D=.024^{\text{cm}}$) was here used as above.

In figure 18 for instance, beginning with the twist -90° , the wire is magnetized twice, giving the temporary and the permanent effect: then untwisted and again magnetized twice giving the two corresponding effects; next twisted $+90^\circ$ and magnetized twice as the figure shows; finally untwisted again and magnetized twice, etc., for succeeding double cycles. In figure 19 the limits of twist are $\pm 180^\circ$; in figure 20, $\pm 360^\circ$.

The general characteristic of these figures is the very large zero displacement, or rather the large return displacements. In other words, the slip phenomenon is much larger on removing twist than on adding it, positively or negatively. The deflections are laid out on a larger scale for increasing twists and they are in general symmetrical. Temporary slopes a are usually negative and even at 360° not strongly positive. Permanent slopes are positive and about of the above values. The following data may be given. When the lines a and b are constructed either side of 0° , they are designated a' and b' .

TABLE III.—Magnetostriction of soft iron in longitudinal fields. Current, 8 amperes.
Field 800 c. g. s. units

Twist.	a .	b .	Cycle slope.	$+a'$.	$-a'$.	$+b'$.	$-b'$.	Displ. at 0° .	Displ. at elongation.	Displ. non-mag. at 0° .
$\pm 90^\circ$	+2.5	+6.3	+4.5	-2.0	-3.0	+6.0	+6.5	5	4.7	2.0
180	3.0	5.4	4.2	-1.0	-1.0	5.3	5.5	8	5.5	5.2
360	2.9	3.9	3.4	+0.5	+0.5	8.0	8.0	10	4.0	8.5

9. The next question at issue is the amount of displacement due to magnetization at the zero of twist, which may be produced by merely twisting the wire to different angles and back again to zero, *without magnetizing it when twisted*. These results are also inserted in figures 18, 19, 20, and marked N, N'. They increase rapidly as the twist (without magnetization) increases. At 360° it makes little difference whether the twisted wire is magnetized or not, so far as the displacement at the zero of twist is concerned; in all cases, however, magnetization at the elongation increases the slip at 0° .

Finally a perfectly fresh wire was adjusted, twisted to 360° without magnetization and then freed from twist. The result (amount of displacement due to magnetization at the zero of twist) did not differ essentially from the figure.

10. In conclusion a few words on the interpretation of the above phenomena may be added. The point of view taken has already been indicated in §1. In Maxwell's sense any defor-

mation due to molecular instability is legitimately termed viscosity.

The initial longitudinal magnetization of the wire does two things: it increases its rigidity (see preceding paper, l. c.) in marked degree, and it decreases its viscosity during the act of magnetization. The subsequent magnetization merely increases rigidity without the accompanying viscous effect. The phenomenon now becomes purely elastic. Thus the first magnetization after any twist has been imparted is the one which reconstructs the magnetic configurations; the subsequent magnetizations (to refer to the mechanism of Ewing's theory) merely deflect the set molecular magnets.

It follows also that with each fresh twist molecular configurations are broken down. This is similar to what occurs in cases of the tempering of a glass-hard or hard drawn magnet. The prepondering amount of the magnetization is wiped out by the simultaneous decay of the hardness.*

Finally, whenever a wire is strained certain groups of molecules lag behind the stress: they may be gradually disintegrated by time (sæcular viscous deformation); more rapidly by rise of temperature (viscous deformation); or suddenly as in the present instances, by magnetization. It is not necessary to assume that the breakdown is identically the same even apart from time in all these instances. In other examples (tempering, etc.) whereas the decay of hardness wipes out magnetization, the decay of magnetization does not influence temper; but such cases are easily interpreted.

If we endeavor to follow the figures 7-11, 14-17, after the first magnetization, we encounter a case in which magnetically increased rigidity is to be imparted to a body of simultaneously decreased viscosity. The wire momentarily contains groups of unstable molecules and is thus in a condition to yield to the mechanical stress (torque) to which it has been subjected.

If now we consider the system of two wires and imagine these occurrences to be consecutive, the increment of rigidity would produce a deflection in the same direction as the twist, or work would be done by the magnetized wire upon the non-magnetic wire, against the existing torque. The yield of the wire due to the presence of unstable configurations would produce a deflection in the opposite direction to that of the twist; or work would be done by the non-magnetic wire upon the magnetized wire. After the first magnetization the greater of these effects will supervene. The result is uncertain as to sign. After subsequent magnetizations for the same twist the

* Barus and Strouhal. Bull. U. S. Geolog. Survey, No. 14, p. 154-5, 1885; cf. Wied. Ann., xx, p. 662, 1883.

viscous effect has vanished and the result is simply increased rigidity in definite amount during the continuance of each magnetization.

In figures 8, 9, and the corresponding figures 12, 13, 14, 15 (cf. the zigzag curves *c*), i. e., at low strains, 45° and 90° , the viscous effect preponderates. On first making the current after a fresh twist, rigidity is decreased; on breaking it rigidity is further decreased by a greater amount; on again making the current rigidity is increased definitely and the same occurs after all subsequent magnetizations.

In figures 10, 11, and 16, 17, the increased rigidity preponderates after the first magnetization. There is increased rigidity on first making the current, a numerically larger decrement on breaking, and thereafter definite increments of rigidity during the continuance of each subsequent making of the magnetizing current. Thus it follows that the magnetic increment of rigidity increases and decreases faster than the coexisting decrement of viscosity due to the first magnetization.

So understood, moreover, the observed hysteresis is a mechanical phenomenon and the magnetization acts as does ordinarily heat in producing the instabilities essential to viscous deformation. The molecular shake-up due to magnetic action is practically instantaneous, whereas the heat motion within the body is gradual in its action: hence the kaleidoscopic displacement of molecules in the one case seemingly without resistance, and the viscous displacement of molecules in the thermal case (seemingly with resistance). Again the displacement of the zero if due to viscosity should under like circumstances be of about the same order both in the cases of longitudinal and of circular magnetization (aside from the heat effect in the latter, which makes it larger). A comparison of figures 3' to 6', with the subsequent figures 7 to 17 show displacements of about the same order for both.

11. Simpler in its nature is the evidence contained in figures 18–20, for the displacement of the zero after the first magnetization. If the wire is twisted to say 360° and back again to zero, the resulting strain does not correspond to the zero of stress. Certain configurations lag behind in the direction of the twist which has last acted. The first magnetization, however, produces the necessary molecular shake-up to bring the strain back again to zero in correspondence with the stress. Hence the subsequent magnetizations produce no deflection since the wire is without twist. Residual strain has been wiped out.

Figures 18–20 show that the residual strain when stress is zero, increases with the preëxisting stress, being greater at

360° than at 90°, for instance. This is the natural explanation of the greater displacement corresponding to the greater stress and of the change of sign of the displacement with the pre-existing stress. Again the residual effect at zero is greater if the twist has been accompanied by magnetization before removal. Cf. N, N' . Combined magnetization and twist (say at 360°, for instance) correspond to a greater value of stress in the absence of magnetization; for the magnetization wipes out the lagging or unstable configurations, bringing the strain at 360° in correspondence with the stress.

Why, it may next be asked, is the displacement at zero after removal of twist 360°, greater than the displacement at 360°, for instance. We meet here, I think, the usual occurrence in viscous deformation.* For example, if a strained or hard metal is tempered at 100° C., it is then molecularly stable or shows no deformation or change of temper at temperatures below 100° or for smaller values of strain, even when the deformation at the original temperature (100°) and strain still continue.

If the wire is twisted to 360° (say) not only is strain stored up in the wire, but at the same time new instabilities are evoked by the process of twisting. When the stress is withdrawn or the wire untwisted to zero, instabilities are not encountered at nearly the same rate; for the preceding larger strain has wiped them out for the diminishing smaller strains. Hence the wire is less viscous when twisted and more viscous when untwisted for like stages or angles of twist. Now any twist no matter how small or within the elastic limits stores strain in the wire, which action possibly, is but another expression for the configurations broken during the process. This, as I understand it, is the explanation of figures 18–20, in which the slip at zero following a reduced strain is so much larger than the slip at 360° following a growing strain.

12. If the interpretation given be correct, then on shaking out a strain with longitudinal magnetization, the wire should be free from slip for circular magnetization; and vice versa. This is the case as shown in figure 21, p. 100, where the successive scale readings are given (vertically) at equal intervals (abscissas) apart, the current being alternately made and broken beginning with no field. L denotes a longitudinal field, C , a circular field if first in action; L' and C' , the corresponding fields if they succeed the action of other fields. The twist is alternately +180° and –180°. Mere inspection shows that from the cases L' and C' slip has practically been wiped out. It is markedly present in cases L and C , the first deflection being

* Barus and Strouhal, Bulletin U. S. Geolog. Survey, No. 14, p. 57, 1885; Wied. Ann., xi, p. 965, 1880.

respectively about half as large for L or twice as large for C as the second deflections due to the making of the field. Figure 21 also shows that if the residual strain or slip is wiped out for a longitudinal field it is also wiped out for a circular field. In cases L there is increase of rigidity and decrease of viscosity; in cases C decrease of both rigidity and viscosity. The differential and summational results are well given in the figure. In cases L' and C' there is increase and decrease of rigidity only with no viscous effect.

To sum up the argument it is briefly this: Magnetization is regarded as a means of shaking up the molecular mechanism and thus to produce temporary molecular instability or momentarily very low viscosity. Hence if mechanical strain has been stored up in the metal it will be instantly released and the metal will correspondingly yield to external stress. This view seems to give a good account of all the hysteresis-like phenomena met in torsional magnetostriction and makes it possible to describe the behavior of all paramagnetic metals in a single explanation.

The one quantity by which the experiments seem to be characterized is the cyclic slope, or the mean slope determined by the temporary (viscous) and the permanent (elastic) deflections, which increases (numerically) with the strength of the field and is nearly independent of the twist imparted, remembering that the remarks have no meaning beyond the elastic limits. It would seem, therefore, that in terms of this parameter the phenomena as a whole for any field or metal, may be simplified. Whether the slip constitutes a kind of molecular "back lash," and whether there is any meaning to its obvious analogy to the action of a "coherer" cannot here be answered.

Brown University, Providence, U. S. A.