MAGNETOSTRICTION WITH THE MICHELSON INTERFEROMETER

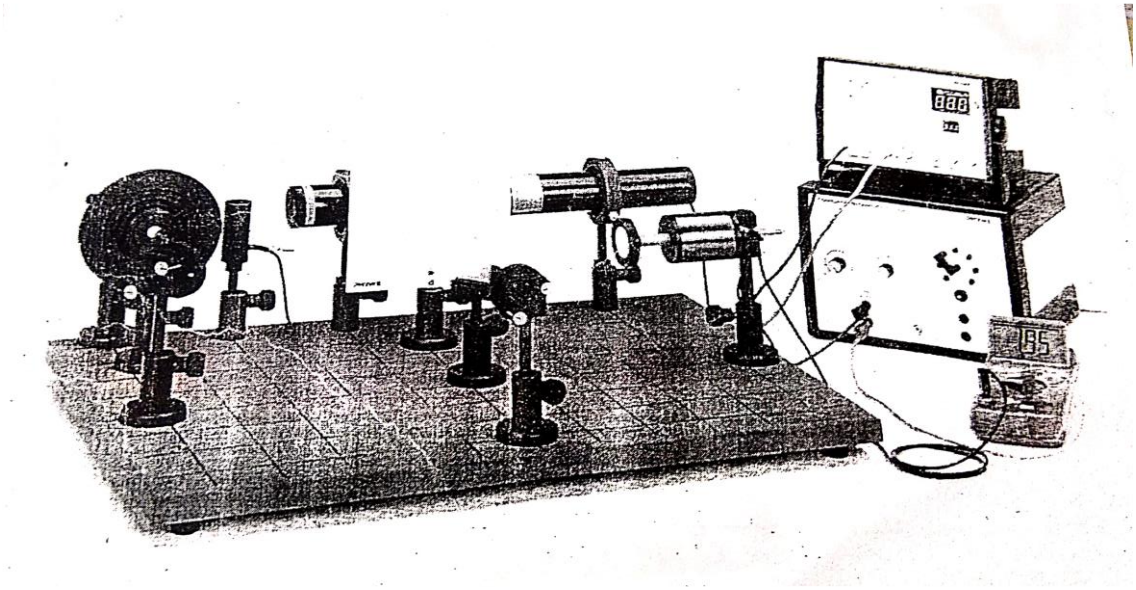
Related Terms

Interference, wavelength, diffraction index, speed of light, phase, virtual light source, ferromagnetic material, Weiss molecular magnetic fields, spin-orbit coupling.

Principle

With the aid of two mirrors in a Michelson arrangement, light is brought to interference. Due to the magnetostrictive effect, one of the mirrors is shifted by variation in the magnetic field applied to a sample, and the change in the interference pattern is observed.

Fig. 1. *Experimental set-up*



Tasks

1. Construction of a Michelson interferometer using separate optical components.
2. Testing various ferromagnetic materials (iron and nickel) as well as non-ferromagnetic material (copper) with regard to their magnetostrictive properties.

Set-up and procedure

In the following, the pairs of numbers in brackets refer to the co-ordinates on the optical base plate in accordance with Fig.1. These co-ordinates are only intended to be a rough guideline for initial adjustment.

1. Perform the experimental set-up according to Fig.1 and 1a. The recommended set-up height (beam path height) is 130mm.
2. The lens L [1,7] must not be in position when making the initial adjustments.
3. When adjusting the beam path with the adjustable mirrors **M_1** [1,8] and **M_2** [1,4], the beam is set along the 4th y co-ordinate of the base plate.
4. Place mirror **M_3** onto the appropriate end of a sample (nickel or iron rod) – initially without the beam splitter **BS** [6,4] and screw it into place.
5. Now, insert the sample into the coil in such a manner that approximately the same length extends beyond the coil on both ends so that a uniform magnetisation can be assumed for the measurement. Fix the sample in position with the laterally attached knurled screw.
6. Next, inset the coil C's shaft into a magnetic base and place it at position [11,4] such that the mirror's plane is perpendicular to the propagation direction of the laser's beam (see Fig.1a).
7. Adjust the beam is a manner such that the beam reflected by mirror **M_3** once again coincides with its point of origin on mirror **M_2**. This can be achieved by coarse shifting of the complete unit of coil with magnetic base or by turning the sample rod with mirror **M_3** in the coil and by meticulously aligning mirror **M_2** [1,4] with the aid of its fine adjustment mechanism.
8. Next, position the beam splitter **BS** [6,4] in such a manner that one partial beam still reaches mirror **M_3** without hindrance and the other partial beam strikes mirror **M_4** [6,1]. Die metallized side of BS is facing mirror **M_4**.
9. Two luminous spots now appear on the screen **SC** [6,6]. Make them coincide by adjusting the mirror **M_4** until a slight flickering of the luminous spot can be seen.
10. After positioning lens **L** [1,7], an illuminated area with interference patterns appears on the screen. To obtain concentric circles, meticulously readjust mirror **M_4** using the adjustment screws.
11. Subsequent to the connection of the coil to the power supply (connect the multimeter in series between the coil and the power supply to measure the current, measuring range 10 AC), set the DC-voltage to maximum and DC- current to minimum value. Then slowly readjust the current. For the measurement the resulting currents lie between 0.5 and maximally, 5A. Count the changes from maximum to maximum (or minimum to minimum) in the interference pattern. In addition, pay attention to the direction in which the circular interference fringes move (source or sinks!). Repeat this procedure using different samples and different current strengths / between 0.5 and 5.0 A (I > 3 A only for a short time!).

Note

The materials require a certain amount of premagnetisation: therefore, the current should be run up and down several times for each individual determination before performing the intensity change measurement.
The black trial with a cooper rod as sample should serve to demonstrate that the longitudinal deformation effect is due to magnetostriction and not to other causes.

Theory and evaluation

If two waves having the same frequency ω but different amplitudes and different phases are coincident at one location, they superimpose to

$Y = a_1.\sin(\omega t - \alpha_1) + a_2.\sin(\omega t - \alpha_2)$

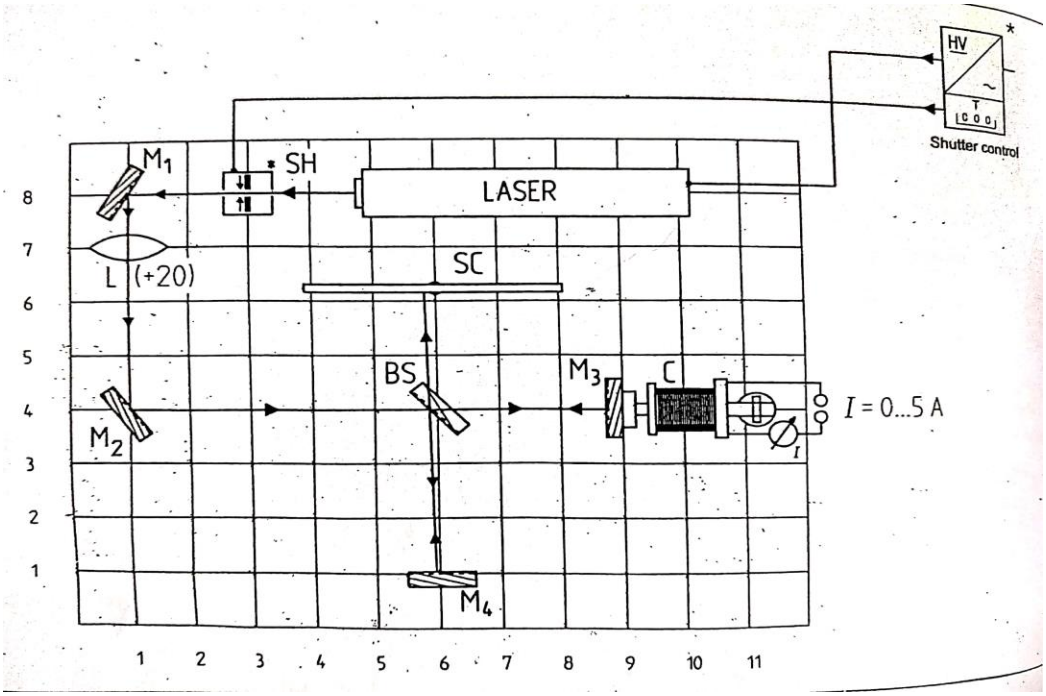


Fig. 1a. *Experimental set-up of the Michelson interferometer for the measurement of magnetostriction of different ferromagnetic materials (*only necessary with the 5-mW laser)*

The resulting wave can be described by the following:

$Y = A . \sin(\omega t - \alpha)$

With the amplitude

$A^2 = a_1^2 + a_2^2 + 2a_1a_2(cos\delta)$ (1)

And the phase difference

$$\delta = \alpha_1 - \alpha_2$$

In a Michelson interferometer, the light beam is split by a half silvered glass plate into two partial beam (amplitude splitting), reflected by two mirrors, and again brought to interference behind the glass plate (Fig.2). Since only large luminous spots can exhibit circular interference fringes, the light beam is expanded between the laser and the glass plate by a lens **L**. If one replaces the real mirror $\mathbf{M_4}$ with its virtual image $\mathbf{M_4}$, which is formed by reflection by the glass plate, a point **P** of the real light source appears as the points **P'** and **P"** of the virtual light sources $\mathbf{L_1}$ and $\mathbf{L_2}$.

As a consequence of the different light paths traversed, and using the designations in Fig. 3, the phase difference is given by:

$$\delta = \frac{2\pi}{\lambda} \cdot 2 \cdot d \cdot \cos\theta \qquad (2)$$

Λ is the wavelength of the laser light used.

According to (1), the intensity distribution for $a_1 = a_2 = a$ is :

$$I \sim A^2 = 4 \cdot a^2 \cdot \cos^2 \frac{\delta}{2} \qquad (3)$$

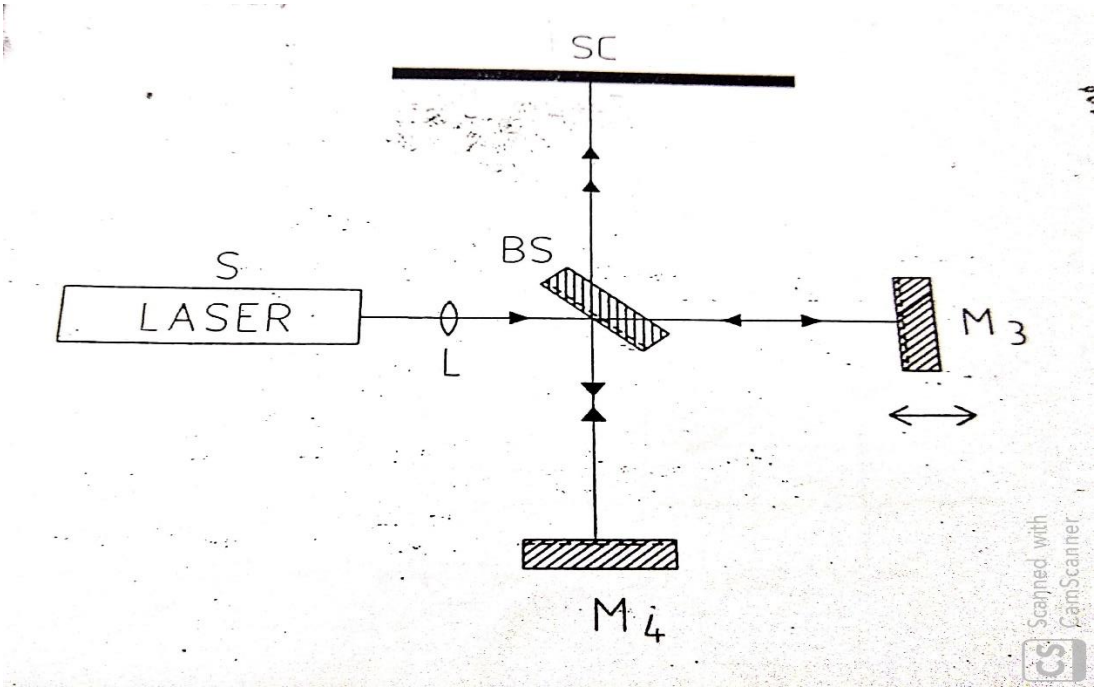


Fig. 2. *Michelson arrangement for Interference. S represents the light source; SC the detector (or the position of the screen)*

Maxima thus occur when δ is equal to a multiple of 2π, hence with (2)

$2 \cdot d \cdot \cos\theta = m \cdot \lambda : m = 1,2,\ldots$ (4)

i.e. there are circular fringes for selected, fixed values of m, and d, since θ remains constant (see Fig.3).

If one alters the position of the movable mirror **M₃** (cf. Fig.1) such that *d*, e.g. decreases, according to (4), the circular for this ring. Thus, a ring disappears each time *d* is reduced by λ/2. For *d* = 0 the circular fringe pattern disappears. If the surfaces of mirrors **M₄** and **M₃** are not parallel in the sense of Fig.3, one obtains curved fringes, which gradually change into straight fringes at *d* = 0.

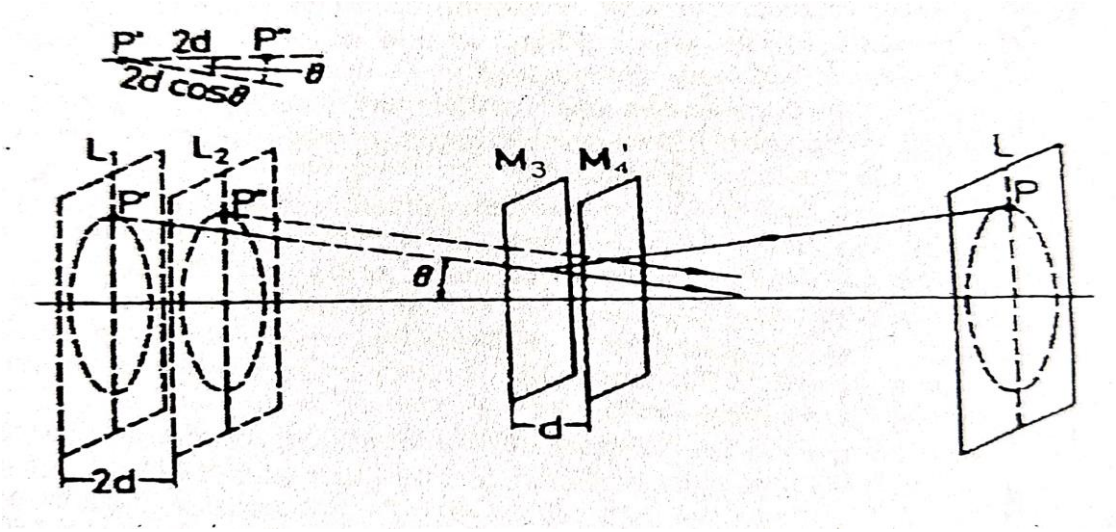


Fig.3. *Formation of circular interference fringes*

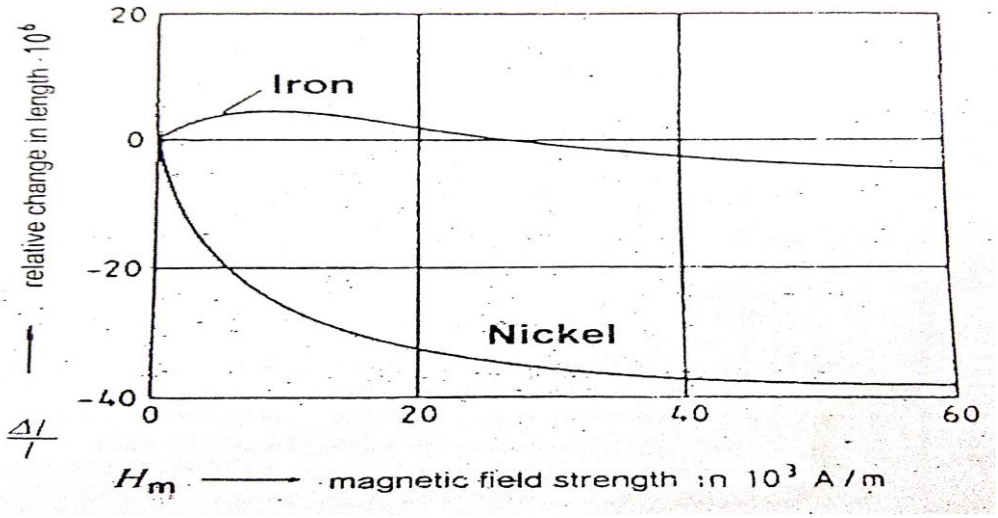


Fig.4. *Magnetostriction of different ferromagnetic materials with their relative change in length* Δ/l *plotted against applied magnetic field strength* H_m.

<u>On magnetostriction</u>

Ferromagnetic substances undergo so-called magnetic distortions, i.e. they exhibit a lengthening or shortening parallel to the direction of magnetization. Such changes are termed positive or negative magnetostriction.

The distortions are on the order of $\Delta l/l$ – 10^{-8} to 10^{-4} in size. As is the case in crystal anisotropy, the magnetostriction is also ascribable to the spin-orbit mutual potential energy, as this is a function of the direction of magnetization and the interatomic distances.

Due to magnetostriction, which corresponds to a spontaneous distortion of the lattice, a ferromagnet can reduce its total=anisotropic and elastic – energy.

Inversely, in cases of elastic tension the direction of spontaneous magnetization is influenced. According to the principle of the least constraint, this means the following:

In case of positive magneteostriction (in the case of iron (Fe)), under tensile stress the magnetisation is oriented parallel to the stress; in cases of compressive stress the magnetization orients itself perpendicular to the pressure axis. In nickel (Ni) the situation is exactly reversed.

A true metal (ferromagnetic material) consists of small uniform microcrystals in dense packing, whose crystallographic axes are however irregularly distributed in all spatial directions.

The individual crystallites are additionally subdivided in Weiss molecular magnetic fields consisting of many molecules which form the elementary dipoles (*).

If the material has not been magnetized, all six (in nickel all eight) of the magnetic moment directions possible within a crystallite are present with equal frequency and consequently neutralize one another externally as a result of this irregular distribution. The magnetization of the Weiss molecular magnetic fields is a function of temperature and occurs spontaneously below the Curie temperature.

However, as a consequence of the application of an external magnetic field this non-uniform distribution of the directions of magnetization can be altered by the transition of a large number of Weiss molecular magnetic fields in the preferred light magnetization directions, which have the smallest angle to the direction of the external magnetic field.

On magnetic crystal anisotropy

In monocrystals one observes a marked anisotropy of the maganetisation curve. This is due to the so-called magnetic crystal energy. The source of this anisotropic energy in the transition metals (Fe, Ni and Co) is in their spin-orbit coupling energy, which is based on the relativistic interaction between spin and orbital movement.
In a rotation (directional alteration) of the spin, which is coupled by the mutual exchange energy, the orbital moments experience a torsional moment such that they also experience rotation. In an anisotropic electron distribution (d electrons) this effects a change in the overlapping of the electron clouds of adjacent atoms and hence an alteration of the total crystal energy.
One thus differentiates between the longitudinal magnetostriction, a length change parallel to the field direction and a transverse magnetostriction of the length alteration perpendicular to the external field direction.
The relative length change $\lambda = \Delta l/l$generally increases with increasing magnetization and reaches a saturation value λ_s at $m = M_s$ (M_s : saturation magnetization).

The relative volume change $\Delta V/V$ (i.e. volume magnetostriction) is usually considerably smaller, since longitudinal and transverse magnetostriction nearly always have opposite signs and compensate each other to a large extent.
In this experiment only the longitudinal magentostriction is considered (see Fig.4). One must take into consideration that the magnetization is a function of temperature and that pre- magnetisation is necessary. Additionally, the magnetostriction in alloys is also dependent on the composition of the metals and the appropriate pre-treatment (see Fig.5).

Thermodynamic description of magnetostriction

Magnetostriction can be described quantitatively and thermodynamically using:
S: elastic tension
s: elastic deforatioin (i.e. : $\Delta l/l$)
B: magnetic induction
H: Magnetic field strength
μ: magnetic permeability with $\frac{1}{\mu} = \frac{\partial H}{\partial B}$
E : Elasticity module with
$E = \frac{\partial S}{\partial s}$
As a result of thermodynamic relationships, it can be shown that the direct and reciprocal magnetostriction effects are mutually linked via

$$\frac{\partial S}{\partial B} = \frac{1}{4\pi} \cdot \frac{\partial H}{\partial s} \qquad (5)$$

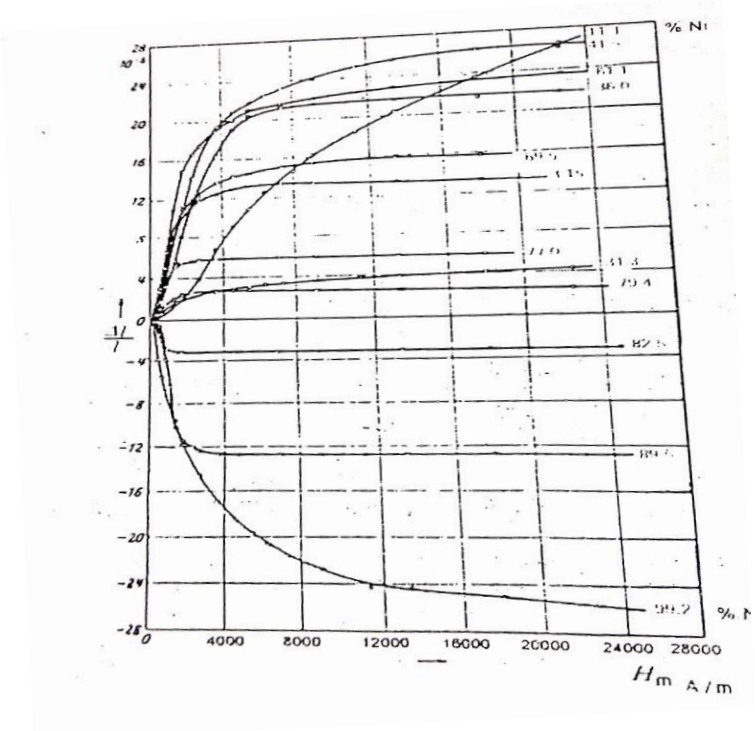


Fig. 5. *Magnetostriction of different ferromagnetic alloys with their relative change in length* $\Delta l/l$ *plotted against applied field strength* H_m.

For a free rod (unloaded and not clamped in position), the following is true:

$$s = -\gamma . \frac{B}{E} \quad (6)$$

with the substance-specific quantity

$$\gamma = \frac{\partial S}{\partial B}$$

In other words, the relative longitudinal change is given by

$$s = -\gamma . \mu . \frac{H}{E} \quad (7)$$

In this context, γ cannot be a constant as otherwise a linear increase in the relative length with the magnetic field strength would result. This is however not the case, since a saturation value is reached as of a specific field strength.

l =
W =
N =

Current (mA)	Magnetic Field(mT)	
	Scale	Reading
201	20	
302	20	
405	200	
500	200	
606	200	
680	200	

<u>On the evaluation of the measuring results</u>

The magnetic field strength of a cylindrical coil is given by:

$$H_m \frac{N.I}{\sqrt{4.r^2 + l_S^2}} \quad (8)$$

where

H_m : magn. field strength at the centre of the coil in A . m^{-1}
r : Radius of a winding (here: 0.024 m)
l_s : Length of the coil (here: 0.06 m)
N : Number of windings (here: 1200)

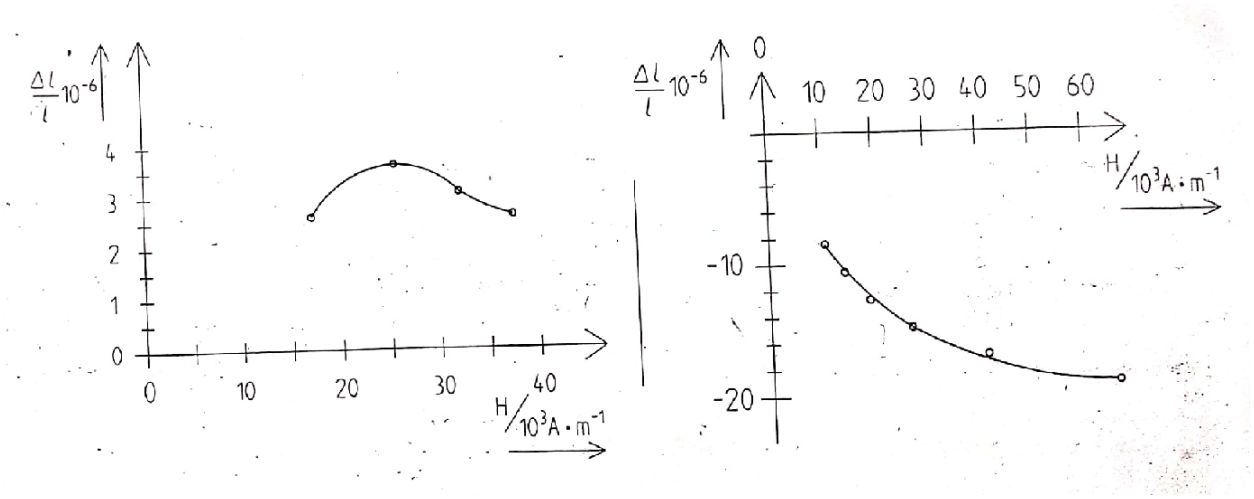


Fig. 6. *Measuring results of the magnetostriction of iron (steel) with the relative change in length $\Delta l/l$ plotted against applied field strength H.*

On condition that the field is homogenous, the field strength is by the following for $l \gg r$:

$$H = \frac{N.I}{l} \qquad (9)$$

For this measurement we assume, as a first approximation, that the magnetic field strength H_m acts on the entire length of the rod *($l = 0.15\ m$)*.

The alteration in length Δl is obtained from the number of circular fringe changes n; in the process the separation per circular fringe change alters by λ/2 (λ = 632nm):

$$\Delta l = n\,.\,\lambda/2 \qquad (10)$$

In Tables (1) and (2) the results of the measurements on nickel and iron are summarized. In the measurements, the direction of magnetostriction also became apparent:

In iron the radii of the interference rings increased with increasing magnetic field strength (source!): thus the rod must have become larger (see Fig. 6 and Table 1).

Table 1

l/A	*H/A/m* (see (9))	Ring changes/*n*	Δ/m (see (10))	$\Delta l/l$ with l = 0.15m
0.83	16600	≈ 1 1/4	$0.395 \cdot 10^{-6}$	$2.63 \cdot 10^{-6}$
1.27	25400	≈1 3/4	$0.554 \cdot 10^{-6}$	$3.691 \cdot 10^{-6}$
1.6	32000	≈ 1 1/2	$0.475 \cdot 10^{-6}$	$3.164 \cdot 10^{-6}$
1.67	37400	≈ 1 1/4	$0.395 \cdot 10^{-6}$	$2.630 \cdot 10^{-6}$

Fig. 7. *Measuring results of the magnetostriction of nickel with the relative change in length $\Delta l/l$ plotted against applied field strength H.*

In nickel the rod became shorter (sink of circular interference fringes): therefore, a negative magnetostriction existed in this case (see Fig. 7 and Table 2).

Table 2

l/A	*H/A/m* (see (9))	Ring changes/*n*	Δ/m (see (10))	$\Delta l/l$ with l = 0.15m
0.53	10600	4	$-1.27\cdot 10^{-6}$	$-8.44\cdot 10^{-6}$
0.71	14200	5	$-1.58\cdot 10^{-6}$	$-10.55\cdot 10^{-6}$
0.94	18800	6	$-1.90\cdot 10^{-6}$	$-12.67\cdot 10^{-6}$
1.33	26600	7	$-2.21\cdot 10^{-6}$	$-14.77\cdot 10^{-6}$
2.04	40800	8	$-2.53\cdot 10^{-6}$	$-16.87\cdot 10^{-6}$
3.28	65600	9	$-2.84\cdot 10^{-6}$	$-18.98\cdot 10^{-6}$

The comparison with the literature values (Fig. 4) exhibited good agreement. In copper no alteration in length can be detected for a rapid current elevation. It may be possible that a slow heating of the material would show changes in the circular interference rings over a long period of time.