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The Coercive Force of Carbon Steel and NÉEL's Theory

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In the present paper, we verified experimentally the NÉEL's theory on coercive force. NÉEL's theoretical formula of coercive force is given as the function of the size of non-ferromagnetic inclusion. We seperated the measured curve of coercive force to a part due to internal stress and to a part due to the size of non-ferromagnetic inclusion, and then compared the latter with NÉEL's theoretical formula.(1) This experimental result was in good agreement with theoretical one.

1. Introduction.

Recently L. NÉEL proposed a theory of coercive force, taking into account the cavities or non-magnetic inclusions dispersed in ferromagnetics, which cause the increase of area of domain boundaries and magnetostatic energies when boundary moves. Though his theory seems very plausible, no satisfactory experimental proof has yet been given. The present paper concerns an experimental verification of NÉEL's theory. As specimens tempered carbon steels were used, as their magnetic and mechanical properties are well-known and controllable by heat treatments. Difficulties in determining the size of non-magnetic precipitates have been overcome by use of electron microscope.

2. Specimens.

Two kinds of specimens of carbon steel, one with 0.4% and the other with 0.83% carbon content, were supplied from Nippon-Seikôsho Ltd. They were normalized in an electric furnace at 800°C for one hour, and then quenched into cold water and tempered for one hour at various temperatures. The variation of temperature did not exceed ±10°C during the tempering.

3. Coercive forces of tempered steels.

The coercive forces of tempered carbon steels have been indeed reported by many investigators, but it was worth repeating the measurement of coercive forces for the two specimens tempered at various temperatures, for the values might be expected to be strongly structure sensitive. The specimen previously magnetized with an electromagnet to complete saturation, was exposed to an opposite magnetic field produced by a solenoidal coil, and the field necessary to effect complete demagnetization was measured. The results are shown in Fig. 1.

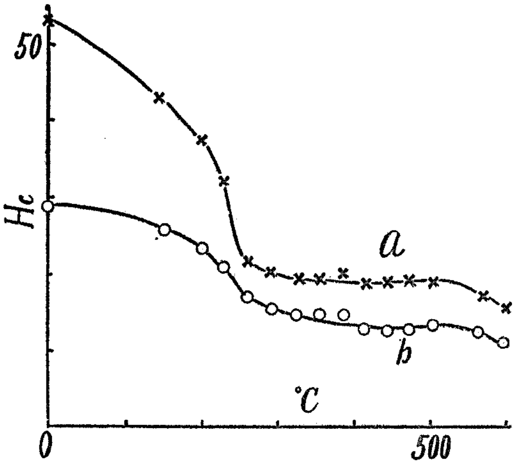


Fig. 1. Variation with temperature of coercive forces of steels.
a: eutectoid steel.
b: 0.4% carbon steel.

The curve representing the coercive force as a function of tempering temperature shows a radid decrease up to 250°C, and beyond this temperature becomes flattened showing slight increase up to 500°C, where it begins to decrease again. These features are common to both 0.4% carbon and eutectoid steels.

From the stress theory of coercive force one can hardly understand these peculiar behaviors.

4. Mechanical hardness.

The mechanical hardness was measured by Vicker's hardness tester. The results are illustrated in Fig. 2. In this case the value of hardness decreases slowly up to 250°C, beyond which it decreases more rapidly. This behavior sug-

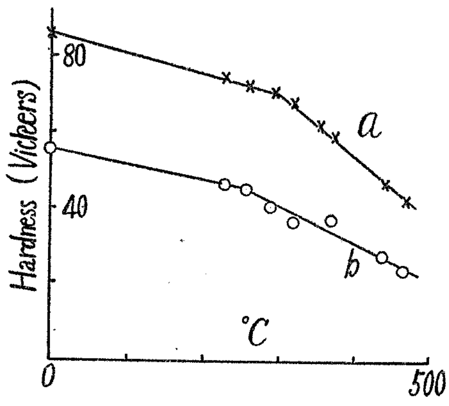


Fig. 2. Variation with temperature of VICKER's hardness of steel.
a: eutectoid steel.
b: 0.4 carbon steel.

gests monotonic decrease of internal stress, hence the inadequacy of the stress theory of coercive force. In Fig. 3 curve I gives the ratio of the coercive forces of 0.4% carbon and eutectoid steels and curve II that of the mechanical hardness of both kinds of steels.

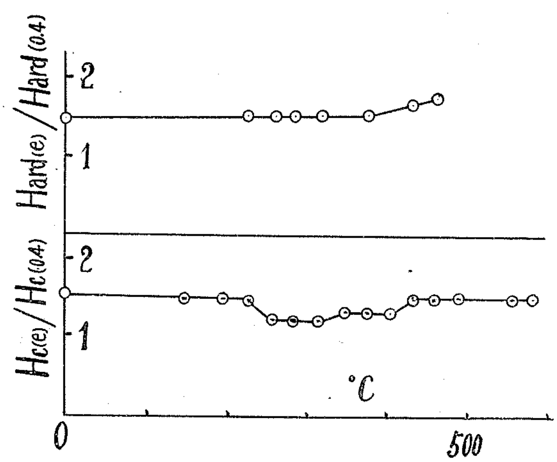


Fig. 3.

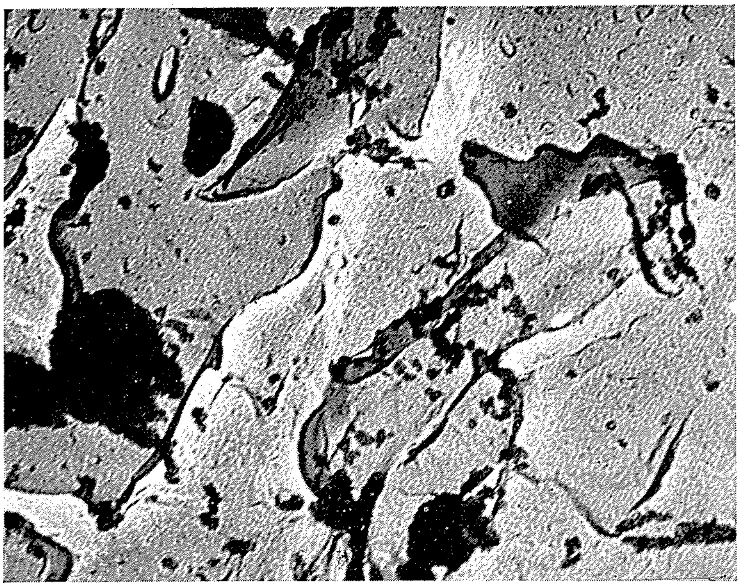
The ratio of the hardnesses is nearly independent of temperature, showing that the softening mechanism is simple and common, while the ratio of the coercive forces drops more or less above 200°C, which indicates that the mechanism of the change of coercive force with temperature is not so simple and probably different below and above 250°C. From these facts it is suggested that the cementite grains which appear frequently above 250°C play an important role in this case as predicted from NÉEL's theory.

5. Electron microscopic examination of grain size of cementite.

Metallographically the tempered steel is the so-called troostite that is considered to be the decomposing martensite, or α-phase of iron including finely dispersed submicroscopic cementite grains. In the present work the small grains of cementite were searched out by means of an electron microscope. As specimen we took only eulectoid steel.

The polished surface of specimen, after being etched with 5% alcohol solution of picric acid, was covered with the solution of methyl-meta-acrirate and quietly dried. The poly-acrirate film torn off from the specimen was then coated with aluminum film by the evaporation method. By dissolving the organic part of the film in acetone, we could get the thin aluminum film which served as the specimen for electron microscope. Although this two-step replica method was somewhat troublesome, we could not find any better method of sampling adapted for use in electron-microscope. The photograms taken are shown in Fig. 4.

a



b

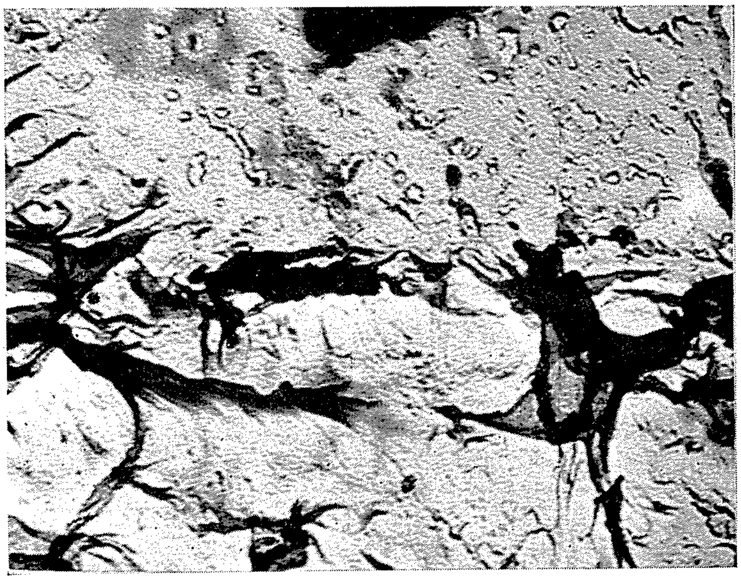


Fig. 4. a: 560°C tempered eutectoid steel.
b: 500°C tempered eutectoid steel. ×40,000

The unfavorable point of the electron microscopic examination lies in its narrow field of vision. Besides, we have no standard photogram of tempered steels. But as a result of careful examination of the photograms in sequence of tempering temperatures, we arrived at the conclusion that the small droplets, as seen in the figures, must be cementite grains. The mean size of cementite grain is given in the following table. It must however be noticed that the statistical conclusion is not satisfactory, since the number of measured grains is rather small.

Tempering temperature	290°C	380°C	440°C	470°C	500°C	560°C
Mean diameter of cementite	0.042	0.050	0.044	0.057	0.063	0.083

It was observed that the cementite grain begins to appear when the tempering temperature exceeds 250°C and that the grain size increases with increasing temperature.

According to NÉEL's theory, the size of non-ferromagnetic inclusions has a critical value in its influence. Namely, below and above the critical value the grain growth causes the increase and the decrease of coercive force respectively.

Such a critical size is thought to be of the order of the thickness of the boundary wall of magnetic domains.

Coercive force H_c due to inclusions is given by: when the grain size is smaller than the critical value,

$$H_c = [4.73 \times 10^9 \rho - 0.99 \times 10^{14} \rho^3] \alpha^{2/3} \tag{1}$$

where ρ is the radius and α the volume fraction of the grain; when the grain size is greater than the critical value,

$$H_c = 1/d \times 2.02 \times 10^{-3} \tag{2}$$

where d is the diameter of the grain.
Now, if the coercive force were to depend only on internal stress, the curve should have the form (b) in Fig. 5, which is in accordance with the curve of mechanical hardness. Subtracting the assumed curve (b) from the actual curve (a), we obtain the curve (c), which is to be considered as that part of coercive force which depends only on the non-magnetic inclusions i. e. cementites.

Above-mentioned consideration is indeed not exact, for the coercive force depends, according to BECKER-KERSTEN's and NÉEL's

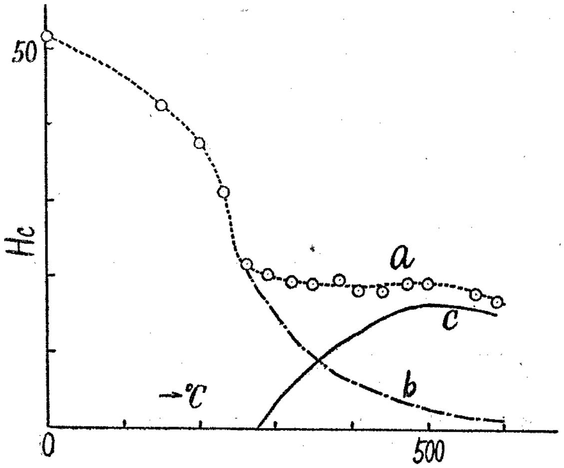


Fig. 5. a: measured curve.
b: the curve of coercive force due to internal stress.
c: the curve of coercive force due to precipitation of cementite.

theory, on the internal stress, the size of inclusions and the thickness of domain wall, the last one being in itself the function of internal stress, so that the effect of internal stress and that of inclusions are not additive. However, the above consideration would not make a serious error, because the internal stress is small in the temperature region, where the inclusion becomes significant. In fact, the curve (c) is found to be in good agreement with the expression (1), the maximum point of the curve (c) corresponds to the temperature at which the mean diameter of cementite grain is $0.08\,\mu$; this is just the right size expected from the thickness of the wall of magnetic domains.

6. Acknowledgement.

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(1). Néel. L., Cahiers Phys., 25 (1944), 21-44.