On the Mechanism of Cold Brittleness in Metals

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On the Mechanism of Cold Brittleness in Metals*

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I. Introduction.

The brittleness of a metal is usually discriminated by an impact test: that is, when the absorbed energy of a notched test-piece decreases more or less abruptly at a narrow range of temperature, the material is said to be brittle below that temperature. When the phenomenon appears below room temperature, it is especially known, as a cold or low temperature brittleness and is distinguished from a relatively slow and slight transition observable at higher temperatures up to about 600°.

Many experiments on the cold brittleness, especially with iron and steel, have been carried out, and although the results were more or less influenced by the testing conditions such as the capacity of a testing machine or the dimension of a test-piece, the transition temperature has been usually regarded as characteristic to a metal and treated in practical purposes as if a mechanical constant of a metal. But there are very few theories on the mechanism of the cold brittleness. The representative ones may be briefly described below.

Mauer and Mailänder(1) have interpreted the phenomenon as follows: The ratio of the strength of a cleavage plane to the resistance of a slip plane decreases with the decrease of temperature and at a certain temperature the brittle failure along the cleavage plane happens more easily than the failure due to a slip. In the vicinity of this critical temperature, there will be a range at which the ductility of a metal rapidly diminishes. The width of this temperature range is dependent on the rate at which the cohesion and the slip resistance will change with temperature. For example, in alloy steels, the impact value slowly decreases in a wide range of temperature and this shows that the change of the above mentioned ratio with temperature is small.

But this interpretation is no more than that the phenomenon is expressed in different words. It is surely the observed fact that the slip resistance more depends on temperature than the cohesion(2), but unless it is indicated beforehand how each quantity varies with temperature, the above explanation will not be accepted as a reasonable theory.

Based upon the Mauer-Mailänder's conception, Heindlhofer(3) has explained the difference of the transition temperature for cold brittleness in tensile, torsional and impact bending tests. The ratio of the maximum normal stress to the maximum shearing stress is respectively 2:1 and 1:1 in the former two tests, but is far greater than 2:1 in the third. Thus, in a tensile test, the diminishing of ductility will take place at the temperature at which the ratio of the cohesion to the slip resistance falls to 2:1. For example, in iron this is observable at about −155°. In a torsional test, the brittle failure will occur at the temperature at which the ratio falls to 1:1, and in iron this temperature is below −185°. In the case of an impact test, as the ratio is greater than 2:1, the transition will begin at higher temperature than that in the other two cases, and in iron the brittle failure is actually observable at about −20° in a notched bar impact test.

Though this explanation has endowed the Mauer-Mailänder theory with some quantitative nature, the transition temperatures above mentioned are merely the experimental results and moreover according to this view, the cold brittleness in a metal is dependent on the kind of loading but not affected by

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the other testing conditions such as straining speed. Therefore this theory cannot satisfactorily explain the experimental results.

Generally the mechanical properties of a solid are not coherent but are structure-sensitive. That is, they are greatly influenced by the testing conditions such as the history of the material, the circumstance of the test-piece, the velocity of testing or the method of loading. The reason for this is due to various structural defects inherent to the preparation of the material. Taking into account this actual circumstance of a solid state, the mechanism of deformation and the failure of a crystalline substance come to be explained not by a mere classical elastic theory but atomistically or crystallographically. As above described, although the cold brittleness, especially in ferrous alloys, has widely been investigated and the transition temperature is accepted as practically coherent to a material, no satisfactory explanation has yet been given. So it is desirable to examine extensively the phenomenon under various conditions and to investigate its mechanism based on the atomistic theory of deformation.

II. Results of Experiments.

Tensile tests and the Charpy impact tests were made with Flodin iron, 0.3 and 0.7 percent carbon steels, zinc and aluminium, at temperatures ranging from that of liquid nitrogen up to about 200°. The material were all annealed in vacuum. The form of the tensile test-piece was an ordinary type with parallel part of 60 mm, its diameter being 5 mm. The six different types of the impact test-pieces were made as shown in Fig. 1, all having the same minimum section of 7×10mm^2, the sharpness of the notch being varied.

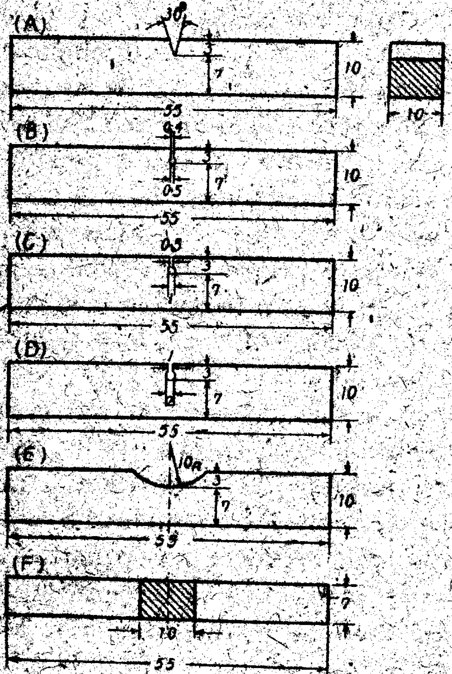

Fig. 1.

As the typical example of the experiments, the results for 0.3 percent carbon steel are shown in Fig. 2. In a technical usage, the absorbed energy is referred to the sectional area of the notched portion in the test-piece. But this procedure has no physical significance, and as the principal object of the present investigation is to examine the nature of the phenomenon rather than to give quantitative information, the full energy absorbed in the breaking of a test-piece was taken in every case as a discriminating numeral. For comparison the results of tensile tests are also plotted in the figure: the curves (1), (2) and (3) refer respectively to the whole work done up to the break-down in stretching with the rate of 0.05, 9.0 and 29.0 mm/min.

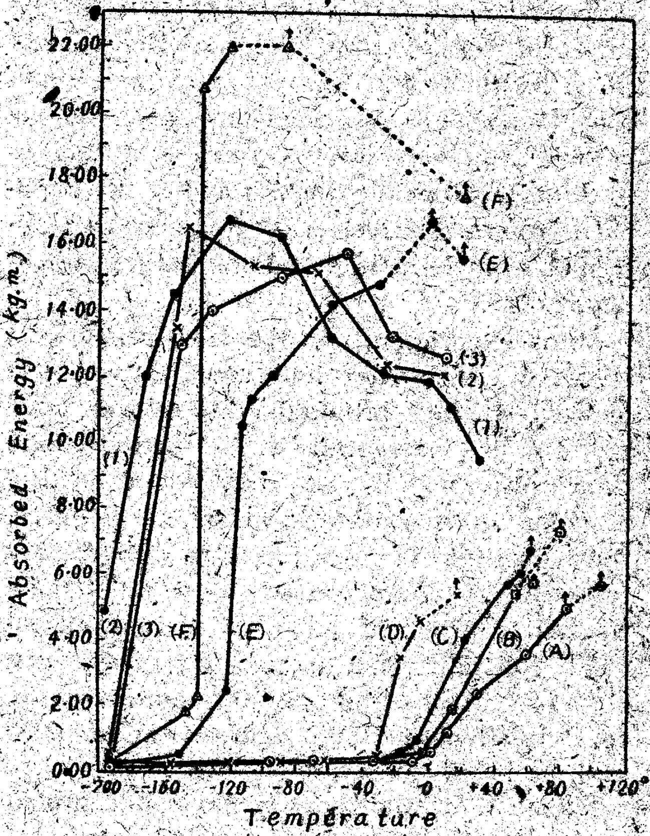

Fig. 2.

From the figure, it will be seen at once that the transition temperature of cold brittleness is considerably influenced by the shape of the notch, that is, as the sharpness of the notch increases, a brittle failure occurs at higher temperature and with it the transition itself becomes more slowly, ranging over a wider temperature interval. In the tensile tests, the phenomenon has taken place at lower temperature than that in the impact tests with the test-piece of rectangular section without a notch, and the transition temperature falls as the testing rate decreases.

The results for 0.7 per cent carbon steel were similar. As shown in Fig. 3, in the test-pieces of type A with the sharpest notch, the transition has taken place slowly at temperatures ranging from 90 to 170°, whereas in type *F* without notch, it occurs abruptly at about −40°. In other test-pieces, the phenomenon is observable between the above two temperature ranges, in regular order according to the sharpness of the notch. Comparing with the results for the 0.3 per cent carbon steel, it will be seen that the transitions are shifted to higher temperatures. The results of the tensile tests are also in the similar relations with those in Fig. 2, that is, while the material in the former case comes rapidly to be brittle at about the temperature of liquid nitrogen, the same occurs, with the 0.7 % *C* steel at a somewhat higher temperature of about −160°.

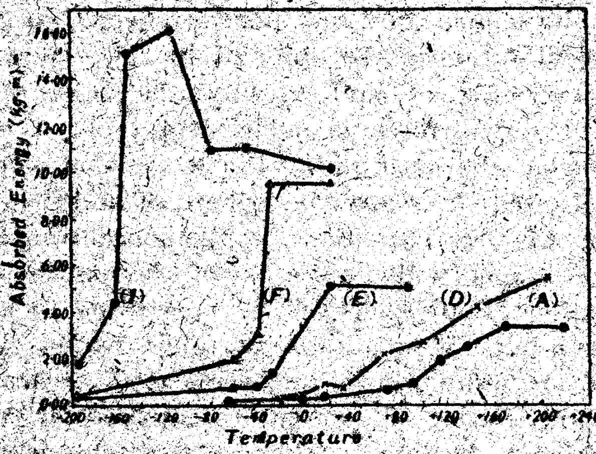

Fig. 3.

In Fig. 4 some results for zinc are shown. The results of the impact tests for the test-pieces of type *A* with the sharpest notch and of type *F* without notch, and that of a tensile test are plotted in the figure. Other results with different test-pieces were situated in regular order according to the sharpness of the notch, but to avoid a confusion these are not shown in the figure. It may be noted that in the test-piece of zinc the depth of the notch was made 2 *mm*, in order to obtain somewhat large impact value.

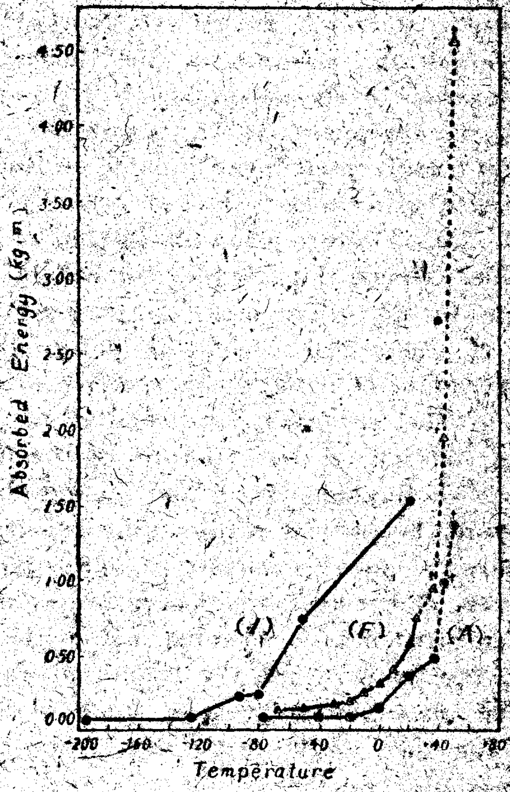

Fig. 4.

As a soft and ductile metal can sufficiently deform under a rapid testing, the difference in absorbed energy due to the difference of notch sharpness will be inconspicuous. In fact, at Flodin iron, the test-piece with the sharpest notch could not be completely broken even at the temperature of −20°, and moreover, as the absorbed energy was small, it was difficult to determine exactly the transition temperature in every case. But on the whole no difference in qualitative nature was recognized between Flodin iron and the above metals.

For aluminium no brittle failure was observed within the limits of the present experiments.

III. Discussion of the Results Obtained.

From the present experiments, it will be recognized that the transition temperature for the cold brittleness is not characteristic to a metal but widely varies with the testing conditions, rising as the sharpness of the notch of a test-piece increases. In general, under a given testing rate, the stress concentration increases and the strained volume decreases as the sharpness of the notch increases. Hence the initial velocity of deformation will increase with the sharpness of the notch and this velocity is one of the most important factors for the theoretical consideration of the deformation of a metal. Really the circumstance that a notched test-piece is usually used in an impact testing is to be seen as a means deviced to raise the initial rate of deformation above that of the machine. Hence the results obtained in the present investigation may be seen as the effect of the initial velocity of deformation on the failure of a metal irrespective of the form of the test-piece, or as that of the testing velocity on the rupture of the test-pieces with the same form and dimension. Therefore the present results may be stated as follows: As the velocity of deformation decreases, the transition temperature of ductility to brittleness is lowered and, with the fall of the temperature, the transition comes to take place abruptly. The same is also valid for the tensile tests with respect to the stretching rate.

If a slip deformation is caused by the movement of a dislocation as suggested by Taylor(4), Polanyi(5) and others, it will not happen instantaneously but may necessarily require a certain time. According to the dislocation theory, the slip for one atomic distance in the slip direction can be resulted when the dislocation travels to some misfit in the regular arrangement of atoms as mosaic or grain boundaries, where the motion is temporarily arrested. Hence, although an external stress may activate the dislocated atom and make its motion to take place somewhat easily, yet the slip will not be an instantaneous phenomenon. We may now roughly estimate the time required for the motion of a dislocation to cause an elementary slip. Let a be the atomic distance in the slip direction of a crystal, L the mean free path of a dislocation, ν the frequency of the thermal oscillation of an atom, A the potential barrier at the dislocation, T the absolute temperature, k the Boltzmann's constant. Then the required time τ will be given by the following expressin:

$$\tau = \frac{L}{a} \cdot \frac{1}{\nu} \cdot e^{\frac{A}{kT}}$$

τ may be designated as the critical time for a slip deformation. Now L may be taken as the linear dimension of a mosaic block whose magnitude is of the order of $10^{-4}cm$ in most metals.(5)(6) A is estimated to be $1 eV$ for the normal state and of about $0.3 \sim 0.4 eV$ for the dislocated point, still lowering under the action of an external force. Let $\nu = 10^{13}/sec$ and $a = 10^{-8}cm$, then $\tau \doteqdot 0.005 sec$ at ordinary temperature. If we assume $A = 0.3 eV$ under the action of an external stress, it becomes $\tau \doteqdot 10^{-4} sec$. At the vicinity of the temperature of liquid nitrogen, $\tau \doteqdot 200 h$; however, L seems to decrease with temperature, being, at this low temperature, about one-thirds of the value at ordinary temperature, and the activation due to an external force will be increased as the temperature falls. Hence, considering these circumstances, the critical time at that low temperature may possibly be smaller than the above estimated value by one order.

If an external force is very rapidly exerted, there will be no time sufficient for the propagation of a dislocation and consequently no slip will take place. That is, if we will rupture the test-piece at room temperature in the duration less than $10^{-4} sec.$, the propagation of a dislocation will be impossible. To cause any slip at the vicinity of the temperature of liquid nitrogen, a very long duration of the order of $10 \sim 100 h$ may be necessary. Therefore, when the action of an external force is sufficiently rapid, the atom at the most unfavourable position will be caused to escape the sphere of action of the neighbouring atoms by the concentrated stress alone without the aid of thermal fluctuation: there will be the generation of a crack but not of a slip. In other words, a brittle failure will be regarded as to be due to the escape of the atoms situated at a defect of crystalline structure from the field of action of their neighbours, gaining the sufficient momentum mechanically from the external force, whereas a slip or a ductile failure is caused by a thermal fluctuation of the atom at a dislocation, the rôle of the external force being merely to regulate the slip direction and the ease with which the motion of dislocation may take place. Accordingly, the resistance to slip may greatly depend on the temperature, whereas the cohesion may be almost independent of the temperature, and these relations, in fact, have hitherto been confirmed by every experiment.

In the previous experiments⁽⁷⁾ on the stress-strain relation in the impact tests, the test-piece of 0.5 per cent carbon steel with the notch of the Izod type was ruptured at room temperature with the energy of 1.8 *kgm* and the time required for the breakdown was estimated to be $6\sim9\times10^{-4}$ *sec*. As the experiments were carried out at high temperatures and brittle materials were laid aside, there was no observation which indicated the time less than the above. But the time required, for breaking ought to decrease with the decrease of the absorbed energy. Hence, in the case of the failure with the energy of the order of 0.5 *kgm* as in the present experiments, the duration may actually be of 10^{-4} *sec* or less. Thus it may be inferred that the critical time for slip is, at least at the vicinity of room temperature, consistent with the experimental evidence.

As the sharpness of the notch increases, the work done by an external force becomes to complete rapidly and the change of momentum of an atom will take place in short time, and consequently the contribution of the thermal fluctuation for a slip must be increased. That is, the transition temperature comes to rise with the sharpness of the notch in the test-piece. As the temperature rises, some slip will be accompanied and with it the inclination of the energy-temperature diagram becomes slowly; on the contrary, as the notch becomes obtuse, or as the action of an external force becomes slow, the less contribution of the thermal motion of a dislocated atom will be sufficient for a deformation and hence the transition temperature falls, causing an abrupt brittle-failure as shown in the figures.

Metals with face-centred cubic lattice generally have low elastic limits and can deform considerably even at low temperatures⁽⁸⁾. The low elastic limit may be regarded as an indication of low potential barrier between atoms. Therefore, in these metals, it may be expected that the motion of a dislocated atom will easily take place. For example, in aluminium, let $A=0.1\,eV$, then $\tau\fallingdotseq10^{-5}$ *sec* at the vicinity of the temperature of liquid nitrogen. According to the estimation of Miller and Du Mond⁽⁹⁾ from the X-ray analysis, the linear dimension of the mosaic in aluminium at room temperature is 2×10^{-5} *cm*. On considering also the circumstance that L decreases with the fall of temperature, it will be perceived that no brittle failure was observable in aluminium irrespective of the form of the notch of the test-piece in the ordinary Charpy machine*.

The transition temperature for 0.7 per cent carbon steel is higher than that for 0.3 per cent one. The reason for this will be as follows:- In general, the brittleness of carbon steel increases with the increase of carbon content. As the content of pearlite increases, the distribution of an applied force will become less homogeneous and the share of the stress to be borne by the soft ferrite ground will decrease with it. In other words, the activation of an atom in the ferrite ground caused by an external force will gradually decreases with the increase of the pearlite structure; or it may be stated that, under the action of an external force, the relative value of the potential barrier in ferrite will be seen to be raised as the carbon content increases. This may probably be a principal cause for the rise of the elastic limit of carbon steel due to the increase of carbon content. As the slip ought to start in the weak structure of ferrite ground, the critical time in a high carbon steel may be long and thus it becomes brittle.

According to the above conception, the most effective procedure for the prevention of a brittle failure is to cause the motion of dislocation as quickly as possible, that is, if the height of the potential barrier between the atoms is lowered and the transition temperature is made to fall sufficiency, a brittle failure will not occur in the limits of practical uses. On the other hand, however, a low potential barrier may result a low elastic limit which, in turn, is contrary to practical purposes in some cases. In order to obtain

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* The pendulum of the machine runs 8 mm at its lowest position in about 1.56×10^{-3} sec.

A large ductility under the given breaking strength and elastic limit, it may be necessary to make the total amount of deformation as large as possible. In the theory of dislocation the mean shear is given by

$$\gamma = aLN$$

where N is the density of dislocation. The mean free path L may somewhat vary with the treatment of the material, but be perhaps accepted to take the value for the normal state. Hence γ will be principally controlled by N. But, if N is too great, there will be a mutual action between dislocations and their movement will become difficult, resulting an over-hardening. The important procedures for increasing N may be as follows:-

(1) Fining down the crystal grains.

(2) Straining the solvent lattice by adding other elements.

(3) Unstabilizing the structure by heat treatments.

Summary.

The results of the present investigation may by summarised as follows:-

(1) Charpy impact tests were carried out with various forms of notch for Flodin iron, 0.3 and 0.7 per cent carbon steels, zinc and aluminium at temperatures ranging from that of liquid nitrogen up to about 200°.

(2) For the purpose of confirming the results, tensile tests were also carried out at low temperatures under various stretching speeds.

(3) It is confirmed that the transition temperature from a ductile to a brittle failure is not inherent to a metal as hitherto accepted but is greatly influenced by experimental conditions.

(4) Considering the time required for slipping one atomic distance caused by the movement of a dislocation at various temperatures, the cold brittleness was interpreted as the phenomenon which appears when the breaking is taken place at the given temperature within this critical time.

(5) Some suggestions for the prevention of cold brittleness are remarked.

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References

(1) E. Mauer und R. Mailaender, Stahl u. Eisen, **45** (1925), 409.
(2) F. Sauerwald, E. Schmid, und G. Kraemer, Z. Phys., **67** (1931), 179. F. Sauerwald und H. G. Sossinka, Z. Phys., **82** (1933), 634.
(3) K. Heindlhofer, Metals Tech., **1** (1934), Oct. T. P. 581.
(4) G. J. Taylor, Proc. Roy. Soc., A **145** (1934), 362.
(5) M. Polanyi, Z. Phys., **89** (1934), 660.
(6) W. G. Burgers and J. M. Burgers, First Rep. on Viscosity and Plasticity, (Amsterdam, 1935), 173. M. Kimura and R. Hasiguti, Nippon Kinzoku Gakkai-si, **7** (1943), 386.
(7) T. Sutoki, Sci. Rep., **19** (1930), 1.
(8) W. J. de Haas and R. Hadfield, Phil. Trans. Roy. Soc. **232** (1933), 297. T. Sutoki, Sci. Rep., **29** (1941), 673.
(9) P. H. Miller and J. W. M. DuMond, Phys. Rev., **57** (1940), 198.