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From: Chief, Naval Technical Mission to Japan.
To : Chief of Naval Operations.

Subject: Target Report - Metallurgy, Atomic Structure Relative to Dynamic Properties.

Reference: (a) "Intelligence Targets Japan" (DNI) of 4 Sept. 1945, Fascicle X-1, Target X-13.

1. Article 3 of the report covering Target X-13 of Fascicle X-1 of reference (a) is submitted herewith.

2. The target was investigated and the report was prepared by Lieut. J.H. Norwood, USNR, assisted by Capt. M. S. Zaslow, AUS.

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JAPANESE METALLURGY - ARTICLE 3
ATOMIC STRUCTURE
RELATIVE TO DYNAMIC PROPERTIES

"INTELLIGENCE TARGETS JAPAN" (DNI) OF 4 SEPT. 1945

FASCICLE X-1, TARGET X-13

NOVEMBER 1945

U.S. NAVAL TECHNICAL MISSION TO JAPAN

SUMMARY

MISCELLANEOUS TARGETS

JAPANESE METALLURGY - ARTICLE 3
ATOMIC STRUCTURE RELATIVE TO DYNAMIC PROPERTIES

This report deals with Japanese research on the mechanism whereby the crystal lattice performs the functions which are measured as strength, ductility, and brittleness. The usual method is to observe a certain phenomenon in a crystal structure, make observations, and attempt to explain them in terms of structure of the crystal lattice. Once the measurements have been made, all such work is theoretical and subject to considerable disagreement among scientists.

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REFERENCES

Location of Target:

Imperial University at SENDAI

Imperial University at TOKYO

Institute for Physical and Chemical Research, TOKYO

Japanese Personnel Assisting in Gathering Documents:

Dr. K. HONDA, TOHOKU Imperial University at SENDAI

Japanese Personnel Interviewed:

Dr. T. HIRONE, (Metals Research Institute, TOHOKU Imperial University at SENDAI, 15 years research experience, very capable.)

Dr. T. SUTOHI, (same as above; 14 years experience)

Dr. S. KAYA, (Head, Physics Dept., TOKYO Imperial University, very capable researcher)

Dr. Y. NISHINA, (Head, Physics Dept., Institute for Physical and Chemical Research; JAPAN's authority on the nucleus; ex pupil of BOHR; extremely capable)

LIST OF ENCLOSURES

INTRODUCTION

The following report covers Japanese research in the field of atomic or crystal structure in relation to dynamic properties such as strength and ductility. There have been very few researchers working in this theoretical field during the war years since most of the capable men were assigned projects of more practical and immediate value to the Army and Navy.

The Metals Research Institute of TOHOKU Imperial University at SENDAI was the only research activity in JAPAN, according to the best information obtainable, which was engaged in this field during the war. The work there was quite intensive and may possibly add to the theory of a highly controversial subject - the mechanism of the crystal lattice.

This report deals with the research at TOHOKU Imperial University. All the ideas presented were advanced by researchers there, principally Dr. T. SUTOKI.

THE REPORT

Part I. Scope of Experimental Work

1. To study the dynamic properties of strength and ductility in metals, tensile tests and charpy impact tests were carried out with Flodin iron, 0.3 and 0.7 percent carbon steels, zinc and aluminum, at temperatures ranging from that of liquid nitrogen to 200°C. From the experiments it was shown that the temperature at which there was a sudden drop in ductility without a corresponding loss in strength, (the cold brittleness transition temperature) was strongly influenced by experimental conditions and cannot, as commonly accepted, be regarded as an inherent characteristic of a metal.

2. The phenomenon is explained as follows--the time required for the crystal lattice to slip one atomic distance under an external force is estimated as a function of the temperature. When a specimen is broken within this critical time at a given temperature a so-called brittle failure will result. If the specimen is broken over a period of time longer than the calculated critical value, a desireable ductile failure will result. From observation of this phenomenon, suggestions for the maintenance of ductility at low temperatures or the prevention of cold brittleness can be made.

Part II. Background

1. The loss of ductility without loss of strength or brittleness of a metal is usually measured by impact testing; that is, when the absorbed energy of a notched test specimen decreases more or less abruptly at a narrow range of temperature, the material is said to be brittle below that temperature. When the phenomenon occurs below room temperature it is known as cold or low temperature brittleness, as distinguished from a relatively slow and moderate transition observable at higher temperatures up to 600°C.

2. Many experiments on cold brittleness, especially with iron and steel, have been carried out, and, although the results have been more or less influenced by testing conditions such as the capacity of the Testing machine or the dimension of the specimen, the transition temperature has usually been regarded as a characteristic of the metal and considered for all practical purposes as a mechanical constant of the metal. There are few theories for this loss of ductility which results in cold brittleness. The representative theories are briefly described in the following paragraphs.

3. MAUER and MAILANDER (note 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 in temperature until at a certain temperature brittle failure along the cleavage plane occurs more easily than failure due to 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 slip resistance change with temperature. For example, in alloy steels the impart value slowly decreases over a wide range of temperature and this shows that the change of the above mentioned ratio with time is small.

Note 1 - MAUER and R. MAILANDER, STAHL and EISEN 45(1925), 409.

4. But this interpretation is no more than an expression of the phenomenon in different words. It is certainly the observed fact that the slip resistance is more dependent on temperature than the cohesion (note 2) but unless it is indicated beforehand how each quantity varies with temperature, the above explanation will not suffice as a basic theory.

5. Based on the MAUER-MAILANDER conception, HEINDLOFER (note 3) has explained the difference of the transition temperature for cold brittleness on the basis of tensile, torsional and impact tests as follows: the ratio of the maximum normal stress to the maximum shearing stress is respectively 2:1 and 1:1 in the first two cases but far greater than 2:1 in the third case. Thus, in a tensile test a decrease in 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 occurs at about - 155°C. In a torsional test brittle failure will occur at the temperature at which the ratio falls to 1:1. In iron this temperature is below - 185°C. In the case of an impact test, where the ratio is greater than 2:1, the transition will begin at a higher temperature than in the other two cases, and in iron the brittle failure is actually observable at - 20°C in the notched bar impact test.

6. Though this explanation has endowed the MAUER-MAILANDER theory with some quantitative basis, the transition temperatures mentioned above are merely experimental results. Moreover from this point of view, loss of ductility or cold brittleness is dependent only on the type of loading, and is not affected by other test conditions such as the speed of loading. Therefore, this theory cannot satisfactorily explain the test results.

7. 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, type of specimen, velocity of testing, and the method of loading; the reason for this is that various structural defects are inherent in the preparation of the material. Taking into account the actual circumstances of the solid state, the mechanism of deformation and the failure of a crystalline substance are best explained not by mere classical elastic theory but atomisically or crystallographically. although loss of ductility or cold brittleness, especially in ferrous alloys, has been widely investigated and the transition temperature is regarded as practically inherent in a material, no satisfactory explanation has yet been given to the actual mechanism. So it is desireable to examine extensively these phenomena under various conditions and investigate their mechanism in relation to the atomistic theory of deformation.

Part III. Results of Experiments

1. Tensile tests and charpy impact tests were made with Flodin iron, 0.3 and 0.7 percent carbon steel, zinc and aluminum at temperatures ranging from that of liquid nitrogen up to 200°C. The materials were annealed in vacua. The form of the tensile test - piece was of standard type, 5 mm diameter, 60 mm gauge length. The six different types of charpy impact specimens are shown on Enclosure A, all having the same minimum section of 7 x 10 mm, the sharpness of the notch being varied.

2. As a typical example the results of impact testing for the 0.3 percent carbon steel are shown on Enclosure (B). In technical usuage the energy absorbed is related to the sectional area of the notched portion of the specimen. But this procedure has no physical significance, and since the principal object of the present investigation is to examine the nature of the phenomenon rather than to give quantitative measurements, the full energy absorbed for

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Note 2 - F. SAUERWALD, B. SCHMID, and G. KRAMER, Z. Phys. 67(1931),179.
Note 3 - K. HEINDLOFER Metals Tech. 1(1934) Oct. T.P. 581.

the breaking of the test-piece was considered the significant figure. For comparison the results of tensile tests are also plotted in the figure. Curves (1), (2), and (3) take into consideration all the work done up to the break-down point in stretching at loading speeds of 0.05, 9.0, and 29.0 mm/min respectively.

3. From the figure it will be seen at once that the transition temperature for cold brittleness is considerably influenced by the shape of the notch. As the sharpness of the notch increases brittle failure occurs at a higher temperature and the transition occurs more slowly, ranging over a wider temperature range. In the tensile tests, the phenomenon has taken place at lower temperatures than in the impact tests where the specimen is rectangular and unnotched, and the transition temperature falls as the loading speed decreases.

4. The result for the 0.7 percent C steel are similar. As shown in Enclosure (C), in the type A test piece with the sharpest notch the transition has taken place slowly at temperatures ranging from 90°C to 170°C, whereas in the case of type F, unnotched, it occurs at about - 40°C. In the other specimens the phenomenon is observable between the two temperature ranges above, in regular order dependent on the sharpness of the notch. In comparison with the results for 0.3 percent carbon steel it will be seen that the transitions are shifted to higher temperatures. The results of the tensile tests are similar to those in Enclosure (C), that is, while the 0.3 percent C material rapidly becomes brittle at about the temperature of liquid nitrogen. The same occurs in the case of the 0.7 percent C steel, at a somewhat higher temperature, -160°C.

5. In Enclosure (D) the results for zinc are shown. Only the results for specimen type A, having the sharpest notch, and specimen type F, unnotched, are shown. To avoid confusion the results for the other test pieces which would be situated in regular order according to the sharpness of the notch are not plotted. In the zinc specimens the depth of notch was two millimeters in order to obtain a large impact value.

6. Since a soft and ductile metal can deform with great rapidity the difference in absorbed energy due to the degree of sharpness of the notch will be inconspicuous. In fact, with Flodin iron, the test piece with the sharpest notch could not be completely broken even at - 20°C, and since the absorbed energy was very small, it was difficult to determine the transition temperature exactly in every case. But on the whole, no qualitative difference was observed between Flodin iron and the other metals. For aluminum no brittle failure could be obtained within the limits of the present testing equipment.

Part IV. Discussion of Results

1. From the experiments cited above it will be recognized that the transition temperature for cold brittleness is not a characteristic of the metal but varies widely with the testing conditions, rising as the sharpness of the notch increases. In general, under a given testing rate, the stress concentration increases and the 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 in the theoretical consideration of the deformation of a metal. In reality, the notching of a test-piece for impact testing is merely a device 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 the results may be considered as the effect of the testing velocity on the rupture of test-pieces of the same form and dimensions. 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 takes place more abruptly. The same deduction is valid for the tensile test with respect to stretching rate.

2. If a slip deformation is caused by the movement of a dislocation as suggested by TAYLOR (note 4), POLANYI (note 5) and others, it will not happen instantaneously but necessarily requires a certain time. According to the dislocation theory, the slip for one atomic distance in the slip direction can result when the dislocation travels to some misfit in the regular arrangement of atoms as mosaics or grain boundaries, where the motion is temporarily arrested. Hence, although an external stress may activate the dislocated atom and facilitate its motion somewhat, 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" be the mean free path of a dislocation, "Z" the frequency of the thermal oscillation of an atom, "A" the potential barrier at the dislocation, "T" the absolute temperature, "K" BOLTZMANN's-constant. Then the required time "t" will be found by the following equation:

$$t = \frac{L}{a} \frac{1}{Z} e^{\frac{A}{KT}}$$

3. The critical time for a slip deformation may be designated by "t". Now "L" may be taken as the linear dimension of a mosiac block whose magnitude is of the wider 10(-4)cm in most metals (notes 5 and 6). "A" is estimated to be 1eV for the normal state and about 0.3eV to 0.4eV for the dislocated point, still decreasing under the action of an external force. Let Z = 10(13)/sec and "a" = 10(-8) cm then "t" equals 0.005 sec for room temperature. If we assume A = 0.3eV under the action of an external force t = 10(-4)sec. At the temperature of liquid nitrogen "t" = 200 hours, however, "L" seems to decrease with temperature, being, at this low temperature, about 1/3 of the value at room temperature, and the activation due to an external force will be increased as the temperature falls. Hence, considering the above, the critical time at that low temperature may possibly be smaller than the estimated value by one order.

4. If an external force is applied very rapidly, there will be insufficient time for the propagation of a dislocation and consequently no slip will take place. That is, if we rupture the test piece at room temperature in less than 10(-4) seconds the propagation of a dislocation is impossible. To cause any slip at the temperature of liquid nitrogen a very long time, 10 to 100 hours may be necessary. Therefore, where the action of an external force is sufficiently rapid the atom at the most unfavorable position will be forced to escape from the sphere of action of the neighboring atoms by a concentrated stress alone, without the aid of thermal fluctuation--there will be a crack generated but no slip. In other words, a brittle failure will be regarded as due to the escape of atoms situated at a defect in the crystalline structure from the field of action of their neighbors, gaining sufficient momentum mechanically from the external force. Conversely, a slip or a ductile failure is caused by a thermal fluctuation of the atom at a dislocation, the role of the external force being merely to regulate the slip direction and the ease with which the motion of dislocation takes place. Accordingly, the resistance to slip may depend greatly on the temperature, whereas cohesion may be nearly in-

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Note 4 - G.I. TAYLOR, Proc. Roy Soc. (London) A145 (1934), 362.

Note 5 - M. POLANYI Z. Phys. 89(1939), 660.

Note 6 - W.G. BURGERS and J.M. BURGERS, First Report on Viscosity and Plasticity (AMSTERDAM (1935), 173.
M. KIMURA and R. HASTIGUTI, Nippon Kinzoku Gakki-Si 7(1943), 386.

dependent of temperature. These relations have been confirmed by every previous experiment.

5. In previous experiments on the stress-strain relationship in impact tests (note 7) a test piece of 0.5 percent carbon steel with an Izod notch was ruptured at room temperature with an energy absorption of 1.8 Kgm and the time required for the breakdown was estimated at 6 to 9 x 10(-4) seconds. As the experiments were carried out at high temperatures and only brittle materials were tested, no time was observed less than that above. But the time for rupture should decrease with the decrease of absorbed energy. Hence in the case of the failure with an energy absorption of 0.5 Kgm, as in the present experiments, the time duration may actually be 10 (-4) seconds or less. Thus it may be inferred that the critical time for slip, at least at room temperature, is consistent with the experimental evidence.

6. As the sharpness of the notch increases the work done by an external force comes to completion rapidly and the change in momentum of an atom will take place in a short time. Consequently the contribution of the thermal fluctuation for slip must be increased. That is, the transition temperature rises with the sharpness of the notch in the testpiece. As the temperature rises, some slip will occur and with it the slope of the energy-temperature curve becomes smaller. Conversely, as the notch becomes less sharp or as the action of the external force becomes slower, the contribution of the thermal motion of a dislocated atom becomes insufficient to cause deformation and the transition temperature falls, causing the abrupt brittle failure shown on the Enclosures.

7. Metals with face-centered cubic lattices generally have low elastic limits and can deform considerably even at low temperatures (note 8). The low elastic limits may be regarded as an indication of a lower potential barrier between atoms. Therefore, it is expected that the motion of a dislocated atom will take place easily. For example in Aluminum, let "A" equal "0.1 eV," then "t" equal 10 (-5) sec. at the temperature of liquid nitrogen. According to the estimates of MILLER and DUMOND (note 9) from X-Ray analysis, the linear dimension of the mosaic in aluminum at room temperature is 2 x 10 (-5) cm. On considering also that "L" decreases with a fall in temperature, it will be perceived that no brittle failure is possible in aluminum, irrespective of the notch of the test-piece in the ordinary Charpy machine. The pendulum traverses eight millimeter at the bottom position in about 1.56 x 10 (-3) sec.

8. The transition temperature for 0.7 percent carbon steel is higher than that for the 0.3 percent type. The reason for this is the following: In general, brittleness of carbon steel increases with the increase of carbon content. As the percentage of pearlite increases, the distribution of an applied force become less homogenous, and the share of the stress borne by the soft surrounding ferrite decreases. In other words, the activation of an atom in the ferrite ground, caused by an external force, gradually decreases with the increase of pearlite structure. 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 is probably a principal cause for the rise of the elastic limit of carbon steel with the increase of carbon content. As the slip should start in the weak structure of the ferrite ground, the critical time in a high carbon steel may be long, and thus it becomes brittle.

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Note 7 - T. SUTOKI, Sci. Rep. 19(1930)1.

Note 8 - W.J. de HAAS and R. HADFIELD, Phil. Trans. Royal Soc. 232 (1933), T. SUTOKI, Sci. Rep. 29 (1941), 673.

Note 9 - P.H. MILLER and J.W.M. du MOND, Phys. Rev., 57(1940) 198.

9. According to the above conception the most effective procedure for the prevention of brittle failure, the increase of ductility, is to cause the motion of dislocation to occur as quickly as possible, that is, if the height of the potential barrier between atoms is lowered and the transition temperature caused to be lowered sufficiently, a brittle failure will not occur within the limits of practical usuage. On the other hand, however, a low potential barrier may result in a low elastic limit, which in turn is undein some cases. In order to obtain a high ductility with a given tensile 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, "S", is given as follows:

$$S = aLN$$

"N" equals the density of dislocation. The mean free path "L" may vary somewhat with the heat treatment of the material but the value for the normal state is usually sufficiently accurate. Hence "S" is primarily a function of "N". However, if "N" is too great, there will be a mutual action between dislocations and their movement will become difficult, resulting in over-harding. The important procedures for increasing "N" are as follows:

a. Refining the crystal grains.

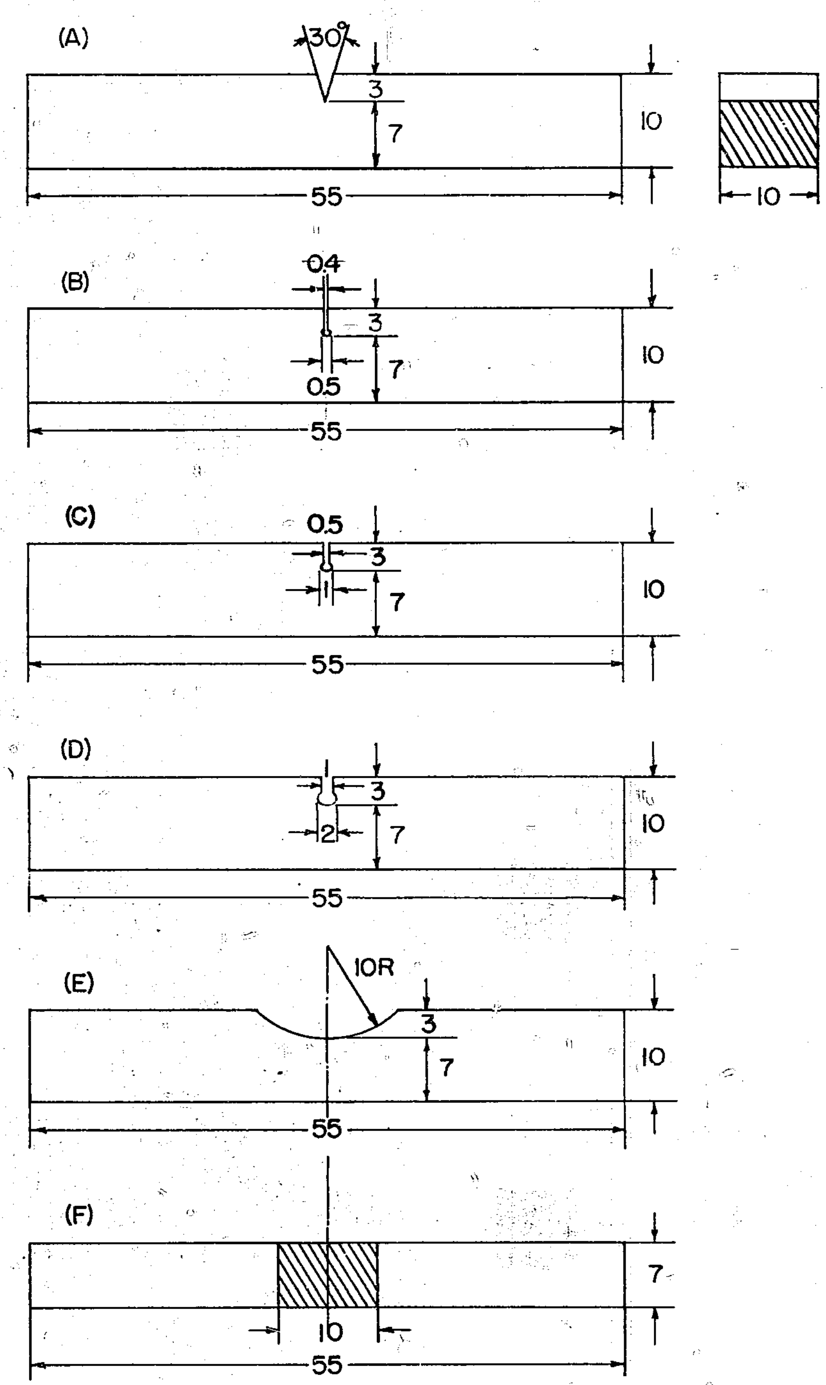
b. Straining the solvent lattice through the addition of other elements.

c. Unstabilizing the structure through heat treatment.

10. To summarize, the temperature at which sudden loss of ductility occurs, or the transition temperature, is not an inherent characteristic of a metal but is greatly influenced by test conditions. Cold brittleness is interpreted as the phenomenon which occurs when rupture takes place in a time less than the critical time required for a slip of one atomic distance, caused by the movement of a dislocation at various temperatures. Brittleness may be decreased by refining grain size, adding other elements, or heat-treatment.

ENCLOSURE (A)

CHARPY SPECIMENS - FIG. 1



ENCLOSURE (B)

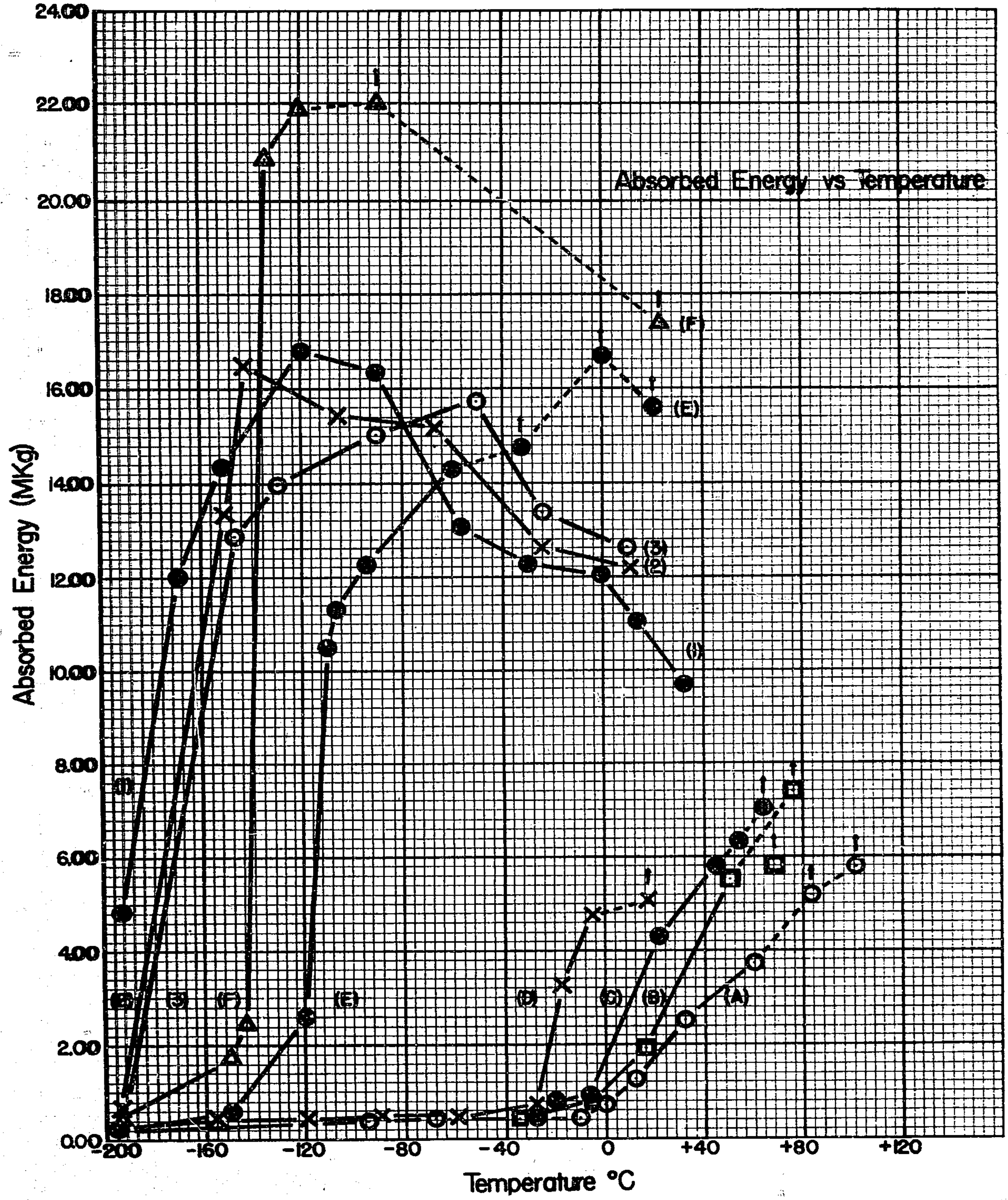


Fig 2. 0.3% Carbon steel

ENCLOSURE (C)

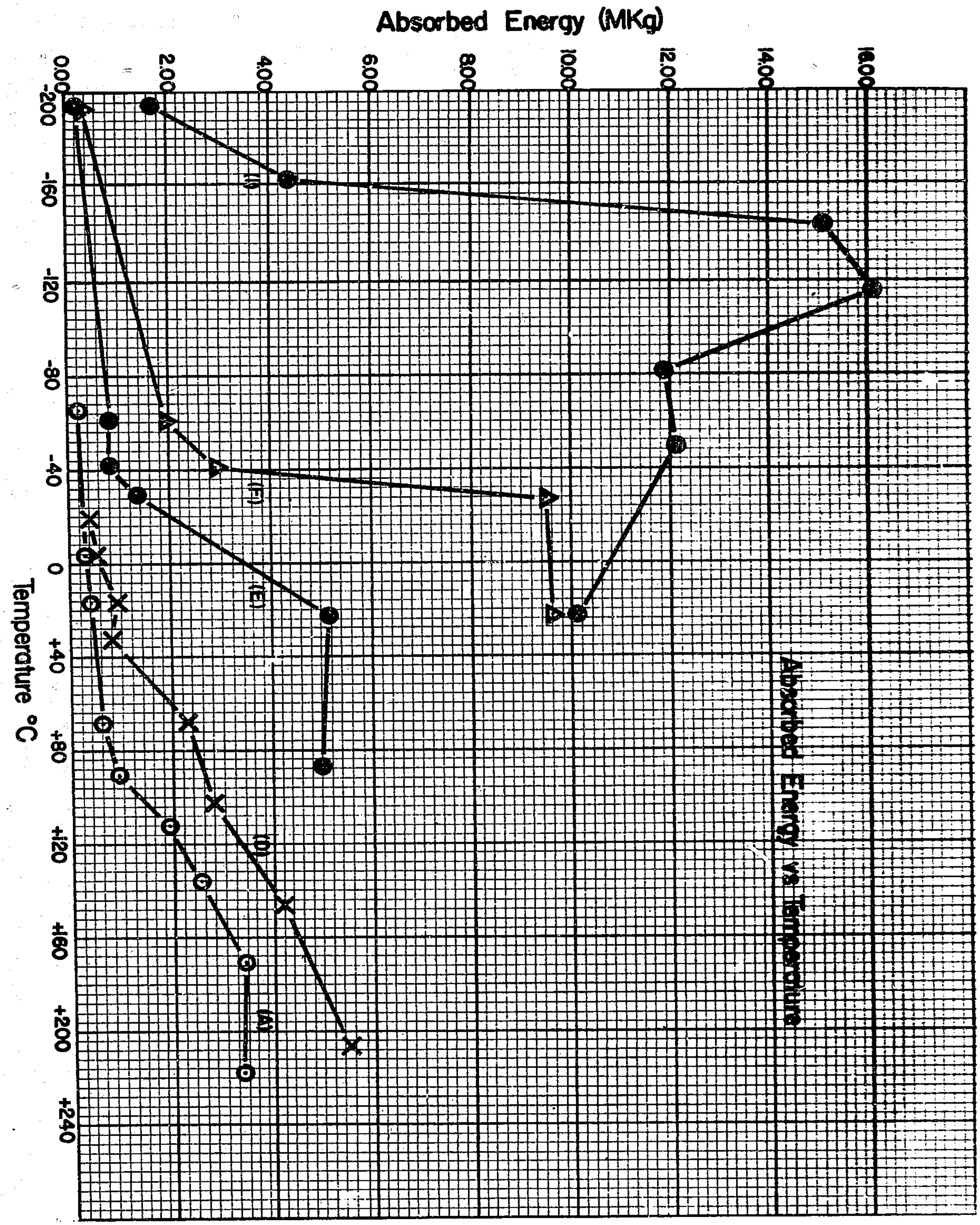


Fig. 3. 0.7% Carbon steel

ENCLOSURE (D)

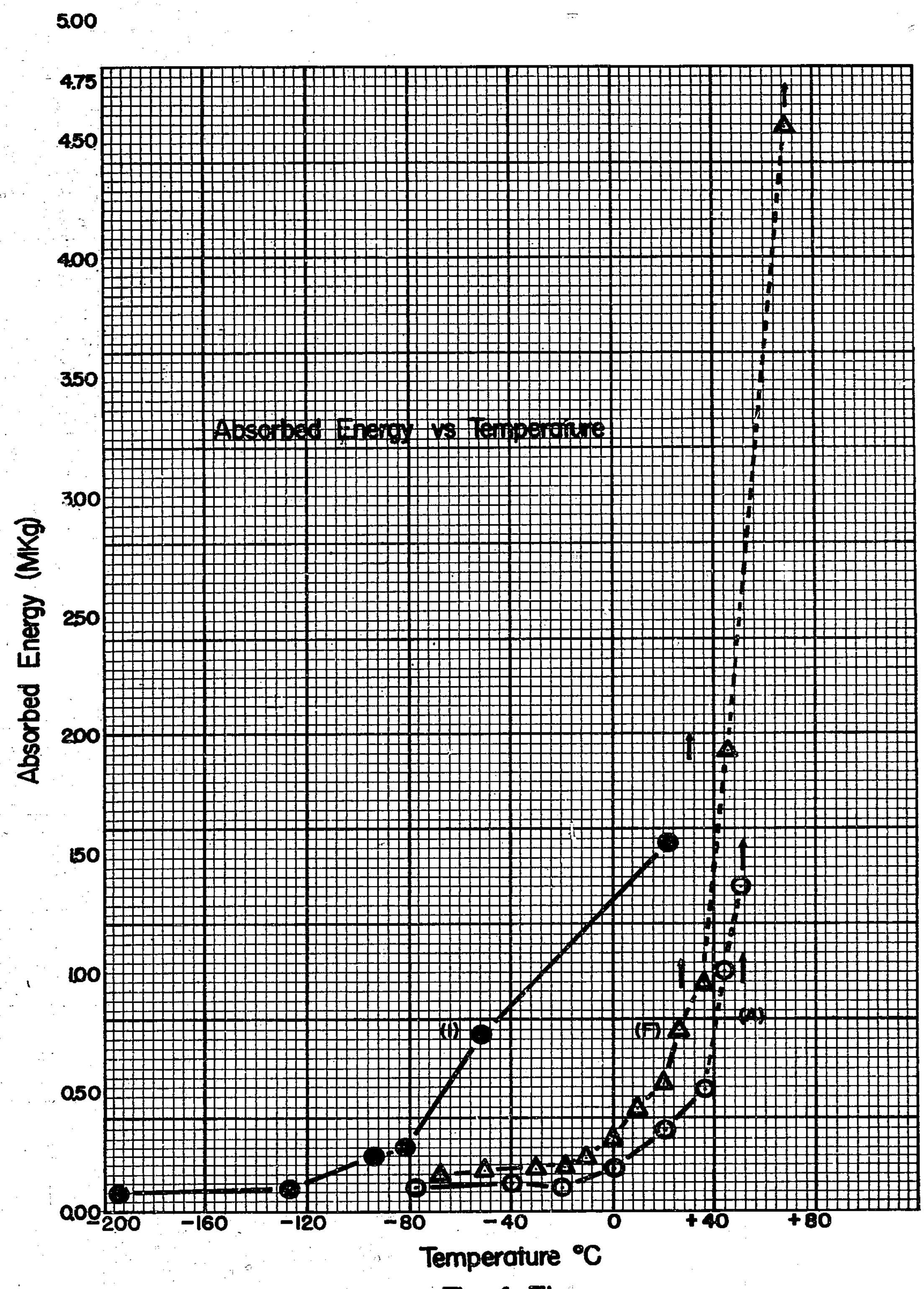


Fig 4. Zinc