Instrumented impact testing as a way to obtain further information on the behaviour of steel in welded constructions

Nielsen, A.

Publication date:
1976

Document Version
Publisher's PDF, also known as Version of record

Risø-M-1865

Risø

Risø - M - 1865

Title and author(s)	Date May, 1976
Instrumented Impact Testing as a way to obtain further information on the behaviour of steel in welded constructions Arved Nielsen	Department or group Metallurgy
	Group's own registration number(s)
18 pages + tables + 8 illustrations	

Abstract

Based on the experience gained by instrumented impact testing of ten different mild steels using test pieces of different geometrical shape (Charpy V-notch, Charpy knife-notch, DVM, Schnadt K_0, $K_{0.5}$, K_1 and K_2), some general features are seen of the fracture process during impact testing.

Steels can be divided into two main groups which are significantly different with respect to the behaviour during Charpy V-notch testing. The difference vanishes when a crack-like notch is used, and other properties of steel are revealed.

It is evident that even when modified, the impact testing bears little resemblance to what is happening in an actual steel construction. For the purpose of investigating the fracture conditions in welds, it seems more significant to relate the dynamic aspects to the speed of propagation of the crack when it starts to penetrate the volume considered at a certain stress level.

Copies to

Library
Reactor Dept.
Engineering dept.
Metallurgy dept.

Available on request from the Library of the Danish Atomic Energy Commission (Atomenergikommissionens Bibliotek), Risø, DK-4000 Roskilde, Denmark
Telephone: (03) 35 51 01, ext. 334, telex: 43116

CONTENTS

1. EQUIPMENT USED

In order to record the pressure between test piece and striker during impact testing in a common pendulum apparatus, the striker has been modified to act as a pressure transducer, by inserting a ceramic wafer between the hammer and striker as indicated in figure 1.

The ceramic wafer (PZT) has piezoelectric properties, which cause a voltage difference to appear between striker and hammer, when a pressure is exerted on the striker. The voltage, picked up and displayed on an oscilloscope screen, represents the pressures occurring.

A certain static prestressing of the ceramic wafer is preferable to cause it to operate within a linear stress - voltage range. This is obtained by the use of isolating pieces, screws and springs as shown in fig. 1.

The difference in performance of this system compared with the more generally adopted strain gage arrangement on the side faces of the striker is not significant in general, but a good transient response is readily obtainable with the described piezoelectric system. The ceramic wafer picks up the total pressure, and distorsion of the output is only caused by the deterioration of the stress wave as it travels from the edge of the striker to the wafer. The upper limit of the frequency range is for this reason higher than 100 kHz. Overall accuracy in pressure recording in N is within ± 4 per cent of maximum deflection. With unfavourable conditions, certain residual phenomena higher than +4% can pass. Precision from day to day is within 1 per cent.

The frequency range also has a lower limit due to the low capacity of the ceramic material. Therefore a capacitive attenuation has been used to extend the frequency range down to 0.1 Hz.

With the good high frequency response, this instrumentation is considered very well suited for investigating transient phenomena in particular those occurring during incidence of the striker on the test piece.

Another instrument used during the experiments has been an optical displacement recording system with a distorsionless response from 0 to over 100 kHz. The accuracy is within ± 2 per cent, or better than 1 μm. Different accelerometers have also been used to investigate the origin and nature of oscillations observed. The optical displacement system is used when stress - strain diagrams are preferred to the more easily obtained stress - time diagrams.

To present a stress - time diagram from an impact test, it is sufficient to display the voltage from the ceramic transducer as the vertical deflection on an oscilloscope screen. With a suitable triggering arrangement and sweep speed, the horizontal deflection will be proportional to time and thus the stress - time function during the test can be displayed ready for photographing.

2. BEHAVIOUR OF STEEL DURING IMPACT TESTING

With the above mentioned equipment, diagrams have been recorded during the impact testing of various types of test piece from different mild steels, some from failed steel structures.

A typical diagram, from the impact testing at ambient temperature of a Charpy V-notch test piece of a mild steel of medium quality, is shown in fig. 2.

A high energy absorption of 1650 kJ/m^2 (132 J or 13.5 kgm or 98 ftlb.)

was recorded, but still a brittle fracture area, covering 15 per cent of the total fracture surface, could be seen. The energy calculated from the area covered by the pressure curve is equal to the energy absorption recorded by the testing apparatus, if this is not found, then the equipment is defective.

Investigations have been carried out using the above mentioned optical displacement recording system and accelerometers to explain how the general features of the diagrams reflect the behaviour of the test pieces. The following explanation can be given with reference to figure 2.

At zero - time the striker hits the test piece, and instantaneously a very high pressure is recorded, followed by violent but rapidly decaying pressure oscillations.

At the time t_a (generally about 0.4 ms), a change in frequency spectrum of the oscillations seems gradually to take place. Prior to this time, pressure oscillations are caused by the oscillations of the test piece in bending centered at the vertical lines of support. However, these oscillations are rapidly damped, but a standing wave is persistent in the hammer, and since the pressure transducer can also act as an accelerometer, it picks up the standing wave and records it as the pressure oscillations seen after t_a. Unfortunately, the natural frequencies found in the hammer are rather close to that of the test piece (20-25 kHz), and the standing wave is only slightly damped. These oscillations, found after t_a, are considered insignificant with respect to the behaviour of the test piece. The initial phenomena occurring before t_a will be considered in a later chapter.

At about t_b, a maximum on the pressure curve is found. This is followed at t_c by a vertical pressure drop, which is due to brittle fracture propagation. For each steel tested, the magnitude of the pressure drop was proportional to the brittle area of the fracture surface. This was also found to be true for types of test piece other than the Charpy V-notch.

After the brittle fracture time t_c, pressure is still recorded due to tearing of the shear lips and the remaining part of the compressed zone of the test piece.

For each steel subjected to Charpy V-notch testing it was found that the recorded pressure always followed exactly the same trace. However, with some exceptions, discussed later on in this chapter, t_c usually changes from test to test as indicated by the dotted lines in fig. 2. This means that change in energy absorption from test to test is due to the change in time to brittle fracture t_c.

As the speed of the hammer is only negligibly decreasing with the time t_c, then t_c is closely proportional to the amount of bending of the test piece before brittle fracture occurs. From the bending of the test piece it should be possible to estimate the notch opening displacement, and from that the plastic zone size in accordance with the application of the COD measurement. As an approximation,however, it is simply assumed that the plastic zone size is increasing with increasing bending of the test piece previous to brittle fracture, and that the extent of the plastic zone is determined by displacement of the striker when bending the test piece.

The resulting relationship is illustrated by figs. 3 and 4 depicting for two different mild steels the energy absorption in Nm against the bending in mm of each test piece before brittle fracture occurs. In the same figures, the transition curves are given, indicating that steel 2251 (fig. 4) is of superior quality with respect to ductility as the transition temperature is -60° C. Steel 2253 (fig. 3) is poor in comparison, as the transition temperature is +35° C. However, these two are quite common mild steels, the good one is a killed steel from a ½ in. plate, the poor one obviously semi-killed, but from a heavy angle section.

Looking at the relationship shown in figs. 3 and 4 between energy absorption and bending of the test piece, it seems quite clear that there is a close correlation, and it seems reasonable to state that the energy absorption is due to the amount of bending the test piece can endure before brittle fracture occurs. According to the above described, assumption increase in energy absorption of these steels, when Charpy V-notch tested, is due to increase of the plastic zone size.

In the history of brittle fracture research, a trend has always been present to try to correlate new testing methods with Charpy V-notch testing, this is even so with respect to the COD-technique. On the basis of the above mentioned statement, that the energy absorption during Charpy V-notch testing is closely correlated to the plastic zone formation, it seems reasonable to relate COD-measurement to Charpy V-notch testing, even when no real crack is present before testing in the latter type of test. However, some conditions need to be considered, one is that slow crack growth can take place before brittle fracture, the second is that not all steels behave like those in figs. 3 and 4.

Turning to fig. 2 again, it is difficult to accept that the decrease in pressure between time t_b and t_c should not be caused by crack growth, since the lateral contraction only accounts for a very small part of the fracture area. Knowing that the pressure always follows exactly the same trace until brittle fracture, it is assumed that any trace of ductile fracture, seen after testing on the fracture surface between the notch and the brittle fracture area, has been produced before the brittle fracture. Looking at the fracture surfaces of the test pieces of the two steels, 2253 and 2251, it is obvious that ductile tearing preceded the brittle fracture in all cases where t_c appeared on the decreasing part of the pressure trace. However, this was also true when t_c appeared on the increasing part of the pressure trace near the maximum. The value of t_c, below which no ductile tearing was seen, was, for steel 2251, 0.4 ms corresponding to 40 J energy absorption; maximum pressure occurs at the time t_b 0.6 ms corresponding to 60 J. These conditions were generally confirmed when testing other steels, and the preceding ductile tearing was even more prominent when using test pieces with larger notch radii (DVM, Schnadt K_1 and K_2).

Even though ductile tearing is not as catastrophic as the brittle fracture, it must be remembered that in a bend test piece, the tensile stress is rapidly decreasing along the path of the fracture, and may even turn to compression, while in many steel constructions the stress situation is such that ductile tearing will inevitably lead to failure. For this reason, only the information gained before ductile tearing begins in the test piece is considered valid with respect to plastic zone conditions, particularly when relating to COD measurement. When impact testing is done without instrumentation, it is proposed that only test results obtained with negligible ductile tearing at the notch root should be considered and that energy absorption higher than those observed in this way should not be used for further analyses, which are based on plastic zone considerations. When using the term "work to fracture" in this connection, such as done by A. A. Wells[1], it is difficult not to consider the energy absorption during the ductile crack propagation, but it would perhaps be advisable to deduct the energy used for tearing of the shear lips and compressed zone, since such phenomena are special features of the bend-test. This energy appears on the diagram as the area below the pressure curve from time t_c until the pressure has gone to zero. This energy is not easy to estimate without instrumentation except for the case of pressing side notches on the test piece, as done by N. Christensen[2], and drilling a hole in the compression zone, as done by Schnadt[3].

It is found that the maximum pressure on the test piece is genrally proportional to the yield point of the steel. If one is looking for a good ductile steel and appreciates that this is a steel able to develop a large plastic zone, it is quite clear that the desired energy absorption at a certain temperature needs to be increased proportional to the yield stress. This is done by Det Norske Veritas and Lloyds.

Even when different steels generally behave as illustrated in figs. 3 and 4, exceptions are found. For some steels, t_c will never exceed some low value, but the increase in energy absorption will depend largely on the magnitude of the pressure drop at t_c, i.e. the extent of compressed zone remaining after brittle crack formation at t_c. These conditions are illustrated in fig. 5, which depicts the energy absorption on the bending of the test piece prior to brittle fracture in accordance with figs. 3 and 4.

Steel 2255 is a common semi-killed mild steel of medium quality as the transition temperature is 0° C. However, the maximum energy in the ductile range is remarkably low, 47 J (35 ftlb). This is not due to a low maximum pressure on the test piece, but to the short time needed for the whole fracture process to take place. Time to maximum pressure is within 0.2 ms, and within 1 ms, the pressure has again fallen to one tenth of the maximum.

Looking at fig. 5 it is seen that the test pieces are only slightly bent before brittle fracture occurs. The horizontal line at 45 J indicates that no brittle fracture area is seen on the fracture surface, and no steep drop seen on the diagrams, and consequently no estimation of t_c can be made. This steel probably does not form any significant plastic zone before either ductile tearing or brittle fracture occurs, depending on the temperature. This feature cannot easily be evaluated on the basis of the energy absorption alone. For steels behaving in this manner, there does not seem to be any basis for establishing a correlation between COD measurement and Charpy V-notch testing.

It could be assumed that the behaviour of steel 2255 indicated the ability of the steel to stop a propagating brittle fracture, but in fact a small bend test piece is not very well suited for demonstrating the damping capacity of steel, since the stress is rapidly decreasing in the path of the fracture. This behaviour only indicates that it is a poor steel in the context of modern fracture mechanics, even though the transition temperature is satisfactory.

Steels have been found which behave partly as steel 2251 or 2253 and partly as steel 2255.

Therefore, it seems advisable, with respect to the application of established correlation data based on Charpy V-notch testing, to do at least a limited number of instrumented tests, to see if the behaviour of the steel will justify the use of the data in question.

3. PRESSED KNIFE-NOTCH TEST PIECES

Some of the problems discussed in the above chapter seem to vanish when the acuity of the notch is increased. Investigations have been done using test pieces, according to M. Schnadt[4)], with a notch made by milling a conventional V-notch to the depth of 1.6 mm in the test piece and further pressing a sharp 45°-knife to the depth of 2 mm thus constituting a sort of Charpy V-notch test piece with root radius equal to zero. This test piece is referred to as Charpy-O.

Investigations have been carried out using true Schnadt-K_o pieces. They have a notch prepared as mentioned above and further the compression zone of the test piece has been drilled away, and a hardened steel pin of diameter 5 mm inserted in the hole. The Schnadt test piece has indeed advantages when doing common impact testing, but unfortunately the pin interferes with the initial bending oscillations of the test piece creating a very complicated frequency spectrum, which shows up on the pressure - time trace. This even changes from test to test, and parts of the trace are obscured. For this reason when doing instrumented testing, Charpy-O pieces are preferred, and on the trace, the part of the pressure curve, originating from the compression zone of the piece, is not considered.

The pressed knife-notch is considered as a sort of crack-like defect not only because of the acuity of the notch, but more so since the steel in the root of the knife-notch has been locally damaged by deformation. It is believed that a tiny crack is present in the damaged zone before serious deformation takes place during impact testing. A fatique crack would of course have been a better defect, but the inexpensive knife-notch provides a basis for a more extensive investigation.

Doing instrumented Charpy-O testing, it is found that the behaviour of steels of type 2255 is not basically different from their behaviour during Charpy V-notch testing, except that the transition curves are shifted to higher temperatures due to the sharper notch.

It is more interesting to see what happens to steel 2251 and 2253. This is illustrated by figs. 6 and 7, prepared in the same manner as the previous figures. In figs. 6 and 7 a remarkable bimodality in the distribution of the test results is seen. This is perhaps less pronounced in fig. 6, as unfortunately too few pieces have been tested near the ductile temperature range.

When the actual pressure diagrams are analysed, it is found that within the group of high energy absorption, the steel behaves as it does during Charpy V-notch testing. This means that if a test piece survives the first bending without brittle fracture, it develops a plastic zone, and ductile tearing takes place as it does during Charpy V-notch testing. The test pieces giving results within the group of low energy absorption behave like the steel 2255 did during Charpy V-notch testing, as seen in fig. 5. It has been explained above that such behaviour does not justify the use of the observed energy absorption data for further fracture mechanics considerations. Neither is the observed energy absorption a useful criterion for control of the fracture toughness of the steel.

The knife-notch does not seem to result in any improvement over the V-notch with respect to the application of the observed energy absorption.

But other advantages can be found. If a fracture surface criterion is applied, it is quite clear that within the temperature range over which no visible brittle area extends from the knife-notch on the fracture surface, the steel is indeed behaving in a ductile manner. When doing instrumented testing, it is an advantage to use a knife-notch, because within the low energy range, brittle fracture is not preceded by ductile tearing. In this case, the brittle fracture occurs at lower than maximum pressure and at a time t_c before the maximum pressure is reached. From the diagrams, t_c can be observed and the bending of the test piece prior to brittle fracture derived. This bending can then be more readily related to plastic zone formation, because it does not involve any ductile tearing.

Data obtained as described above are perhaps more applicable in establishing correlations to fracture mechanics data obtained with larger and more expensive test pieces. But it must be realised that his implies both a change of the test piece from the common Charpy V-notch piece and instrumentation of the impact testing equipment.

It is seen that when using Charpy-O pieces, the range of testing temperatures shifts to far higher than useful service temperatures, the shift being 30-70^{o} C for different steels. This drawback is of course due to the fact that the speed of loading during impact testing is far higher than the speed of loading during service. So using Charpy-O pieces, slow bending could just as well be applied

4. INITIAL PHENOMENA

Turning again to fig. 2, it is seen that initially a very high pressure is reached, higher than the maximum pressure reached later during bending of the test piece. The height of the initial pressure peak is dependent on the accuracy with which the striker hits the test piece. Putting a bit of soft material between striker and test piece reduces the height considerably. On the other hand hitting the test piece slightly with the hammer, to form an indentation fitting exactly to the edge of the striker, will increase the height of the initial pressure peak when the test piece is subsequently tested as normally.

A careful investigation has shown that the initial maximum pressure is generally reached within 10 μs of the incidence. Within this time range an elastic dilatational wave will be able to travel not more than 60 mm through steel, consequently the pressure between striker and test piece is building up so rapidly that the stress wave spreading from the point of incidence is only just able to arrive at the supports and be reflected back to the striker before maximum pressure is reached. Because of these facts, the initial pressure conditions recorded are caused entirely by inertia forces.

The pressure maximum is followed by a steep drop because the test piece is forced by the initial pressure to move away from the striker. As the test piece is deformed within the elastic range, it will oscillate as revealed by the pressure oscillations on the diagram. These oscillations are rapidly damped, particularly when the test piece begins to deform plastically.

Within the first 0.4 ms of incidence, the conditions within the test piece are completely unstable, and at a sufficiently low temperature it is possible to break the test piece by the inertia forces alone. This has been done by resting the test piece on horizontal supports only and kicking it away with the hammer swinging as normally.

The above mentioned conditions in the test piece have nothing to do with service conditions and ought to be avoided. This can be done by damping the impact with the effect that the initial pressure between test piece and striker is built up during at least 0.4 ms, i.e. during at least 2 mm displacement of the hammer.

Another solution is to do slow bend rather than impact testing.

5. BRADY TESTING ACCORDING TO THE SCHNADT METHOD

To try something between impact and slow bend testing, instrumented Brady testing has been investigated. This test uses a device designed by H. Schnadt[4)] and takes place as a common impact test, except that the striker moves with a speed of 100 mm/s when hitting the test piece. This speed is 1/50 of the common impact testing speed, and about 50 times as fast as the speed generally applied when bending a test piece in a universal testing machine. The device has been instrumented, and the resulting diagrams look like figure 8, which has been recorded during the Brady testing of a Charpy-0 test piece. The curve is smooth except when the brittle fracture occurs.

The temperature range of Brady testing is generally about 20-60°C lower than when impact testing similar test pieces of the same steel, thus compensating the shift to higher temperatures, mentioned in chapter 3, when using Charpy-0 instead of Charpy V-notch test pieces. Accordingly, Brady testing has its advantages.

It is often considered that a tremendous advantage of impact testing is that it is "dynamic". However, the dynamic conditions involved in the initial phenomena only confuse the process artificially, as described in the previous chapter. When, later on during the impact test, the test piece is bent, this causes a speed of deformation which is far higher than it could be during service except when explosions occur. This inconsistency is due to the difference between the big mass behind the force of loading and the small mass of the loaded part.

It seems more reasonable to relate the concept "dynamic" to the speed of crack propagation rather than to the speed of loading. In this connection it is proposed that the test piece should be embrittled locally, as it has been done by Loss and Pellini[5)], instead of cutting a notch or producing a fatique crack. Testing this type of test piece by instrumented slow bend or Brady testing, would at a certain load cause a dynamic crack to hit the steel, and the behaviour of the steel in this situation could be revealed by the recorded diagrams. This testing would reflect, in a far more satisfactory way than notch impact testing, the behaviour of welded connections. Cracks start running from defects within the weld subjected to the residual stress field and hit the base metal which is supposed to have a sufficiently high fracture toughness to arrest cracks of less than critical length. It is always assumed that these cracks are stationary and not much is known of the critical length of running cracks.

CONCLUSIONS

1) By instrumenting Charpy V-notch testing it is seen that the observed energy absorption is often proportional to the amount of bending the test piece can endure before brittle fracture occurs. Consequently a correlation between energy absorption and plastic zone formation can be assumed,

provided the reservations in par. 2) and 3) are not neglected.

2) Preliminary ductile tearing is involved in the fracturing process during Charpy V-notch testing, particularly at higher energy absorption levels. Therefore only information obtained from test pieces not displaying any ductile area between notch and brittle fracture area should be considered valid with respect to the assumption in par. 1)

3) Some steels, when Charpy V-notch tested, endure only slight bending before brittle fracture occurs. The absorbed energy is then proportional to the area which remains to be fractured in a ductile manner after the occurrence of brittle fracture and hence, no basis is found for the assumption in par. 1). Therefore, it is proposed that instrumented testing is done when required in order to check that the assumption in par. 1) is justified.

4) Test pieces with pressed knife-notches (considered as crack-like defects) do not generally exhibit ductile tearing prior to brittle fracture during impact testing. In this case energy absorption is not found to be a useful toughness criterion; a much better criterion is the bending prior to brittle fracture, which is recorded as time to brittle fracture during instrumented impact testing.

5) Impact testing knife-notch instead of Charpy V-notch test pieces shifts the testing temperature range to far higher than service temperatures. It is proposed that this be compensated for by doing bend testing at lower speeds, and to this end Brady testing according to the Schnadt method, at a loading

velocity of 0.1 m/s, has been instrumented.

6) The initial stress conditions in the test piece are found during impact testing to be complex and significantly different from service conditions due to the difference between loading and loaded mass. It is proposed that bend testing should be done at lower loading velocities in order to relate dynamic conditions to the velocity of crack propagation, e.g. by using an artificially embrittled zone instead of a notch in the test piece, thus approaching the conditions in a welded connection.

REFERENCES

1) Wells, A. A., "Notch Ductility, Design and the Specification of Permissible Defect Sizes in Welded Metal Structures". Practical Fracture Mechanics for Structural Steel. Proceedings Symposium on Fracture Toughness Concepts for Weldable Structural Steel. Risley, April 1969. IIW Doc. X-582-70.

2) Augland, B., and Christensen, N., "Bruddforplantning - praktiske erfaringer og laboratoriemessig prøvning". (Crack Propagation - Practical Experience and Testing in the Laboratory). Sveiseteknikk (1958), no. 5, p. 3-12.

3) Weck, R. Transactions of the Institute of Welding, Vol. 13, no, 2, p. 41-56.

4) Schnadt, H. M., "Einführung in die Atopieprüfung von Stählen".
(Introduction to the Atopy-Testing of Steels).
Oerlikon Schweissmitteilungen, Vol. 16 (1958), no. 31, p. 14-28.

5) Loss, F. J., and Pellini, W. S., "Dynamic Tear Test Definition of the Temperature Transition from Linear Elastic to Gross Strain Fracture Conditions".
NRL Report 6787, Nov. 29, 1968; ASME Winter Annual Meeting, Dec. 1-5, 1968, Paper 68-WA/ER-1.

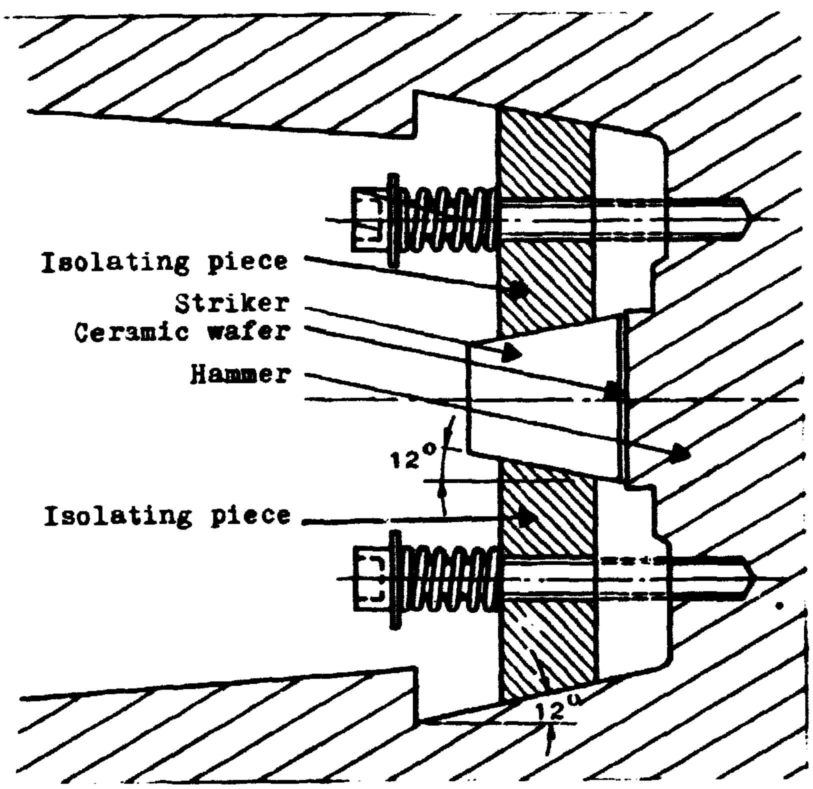

Fig. 1. Pressure transducer.
Scale: 1:1.

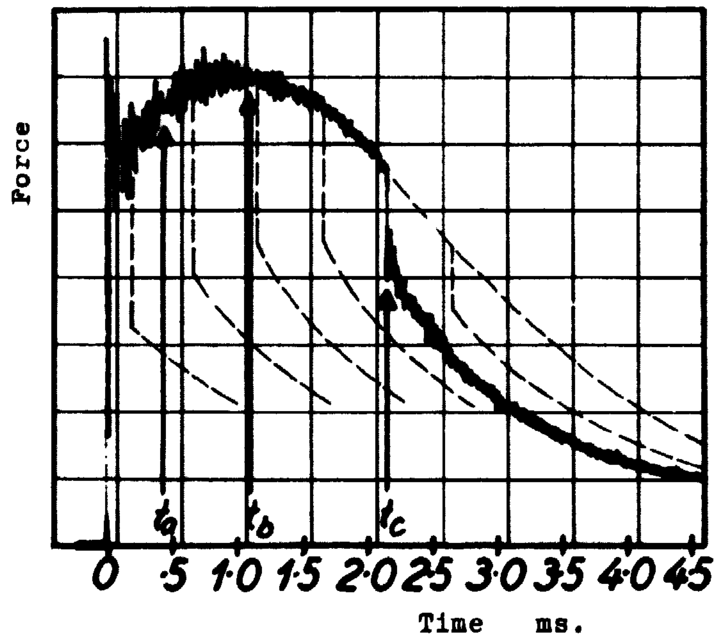

Fig. 2. Diagram recorded during Charpy V-notch testing.

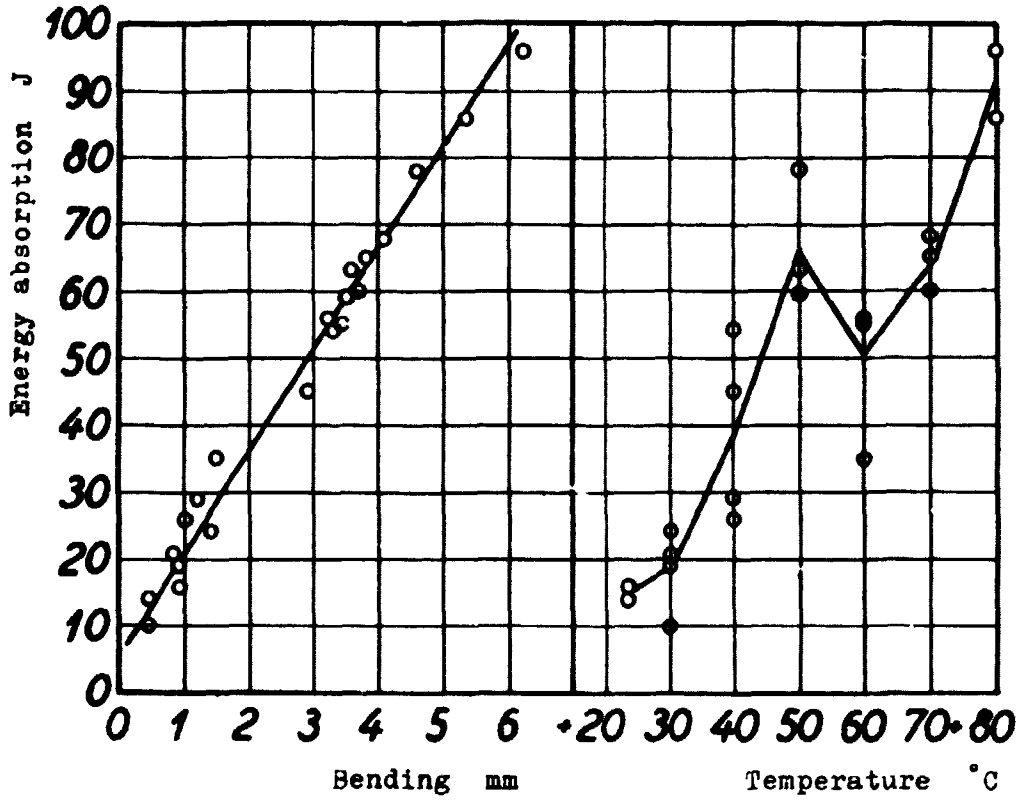

Fig. 3. Steel 2253. Charpy V-notch testing.
C.19 Si.08 Mn.61 S.014 P.032 N.005%
σ_m=465 N/mm^2(68 ksi) δ_5=30 % ψ =58 %.

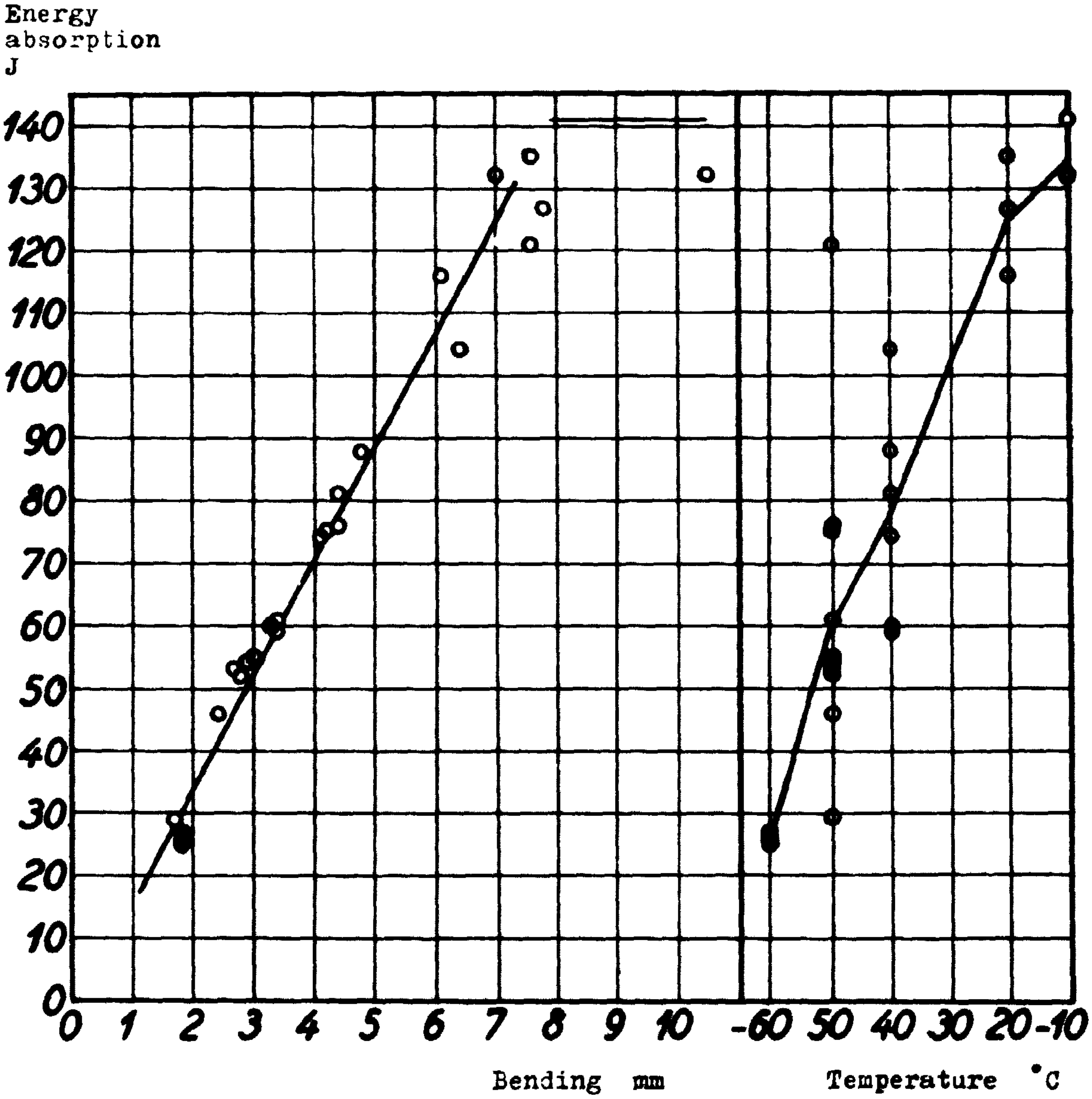

Fig. 4. Steel 2251. Charpy V-notch testing.
σ_m=464 N/mm^2(68 ksi) σ_y=304 N/mm^2(44 ksi)
δ_5=32 % ψ =69 %.

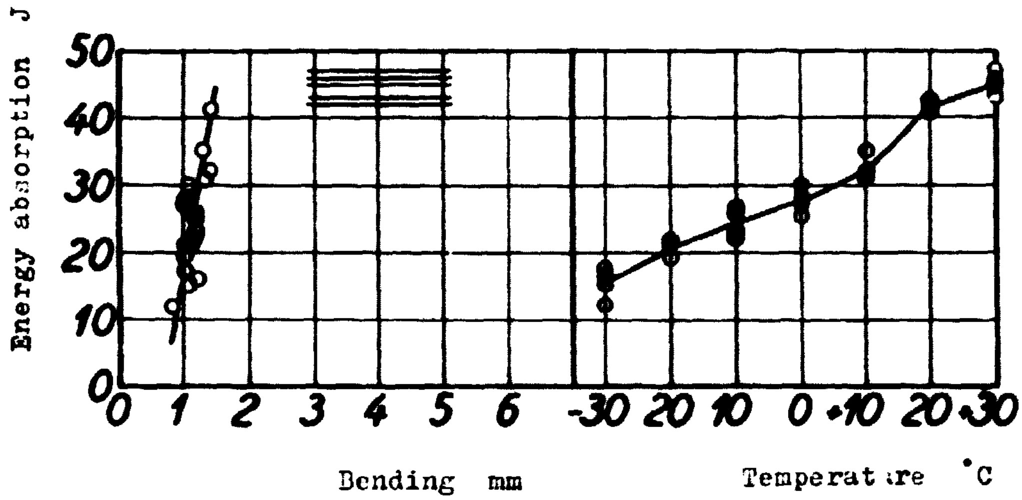

Fig. 5. Steel 2255. Charpy V-notch [illegible].
σ_m=468 N/mm^2(68 ksi) σ_{s}=[illegible] N/mm^2(4[illegible] ksi)
δ_5=3[illegible] % ψ [illegible] %.

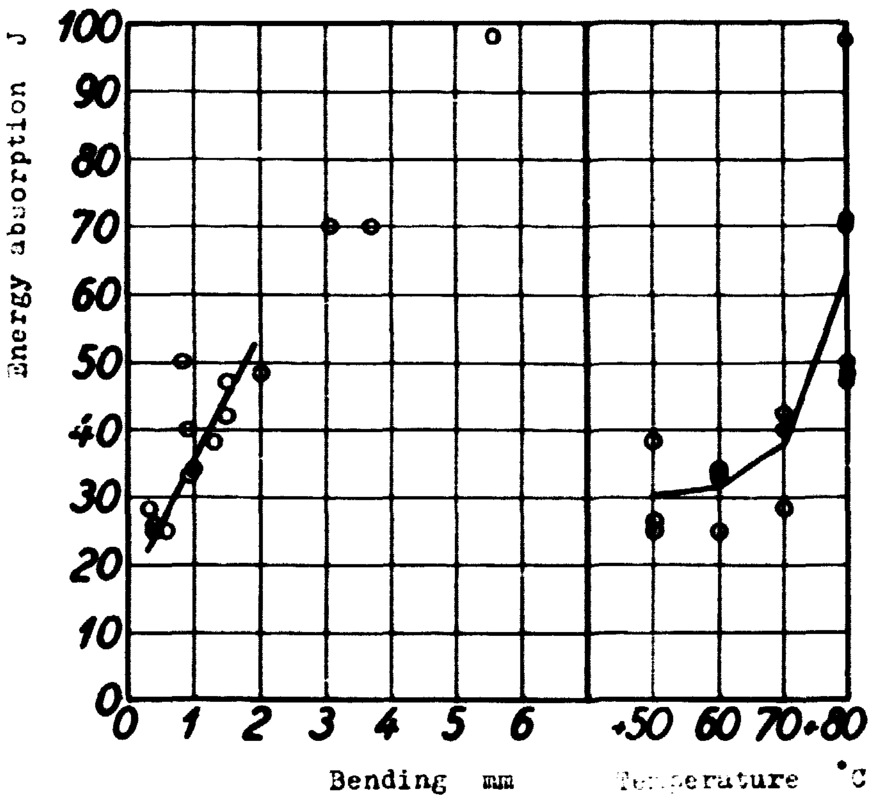

Fig. 6. Steel 2253. Charpy-C testing.

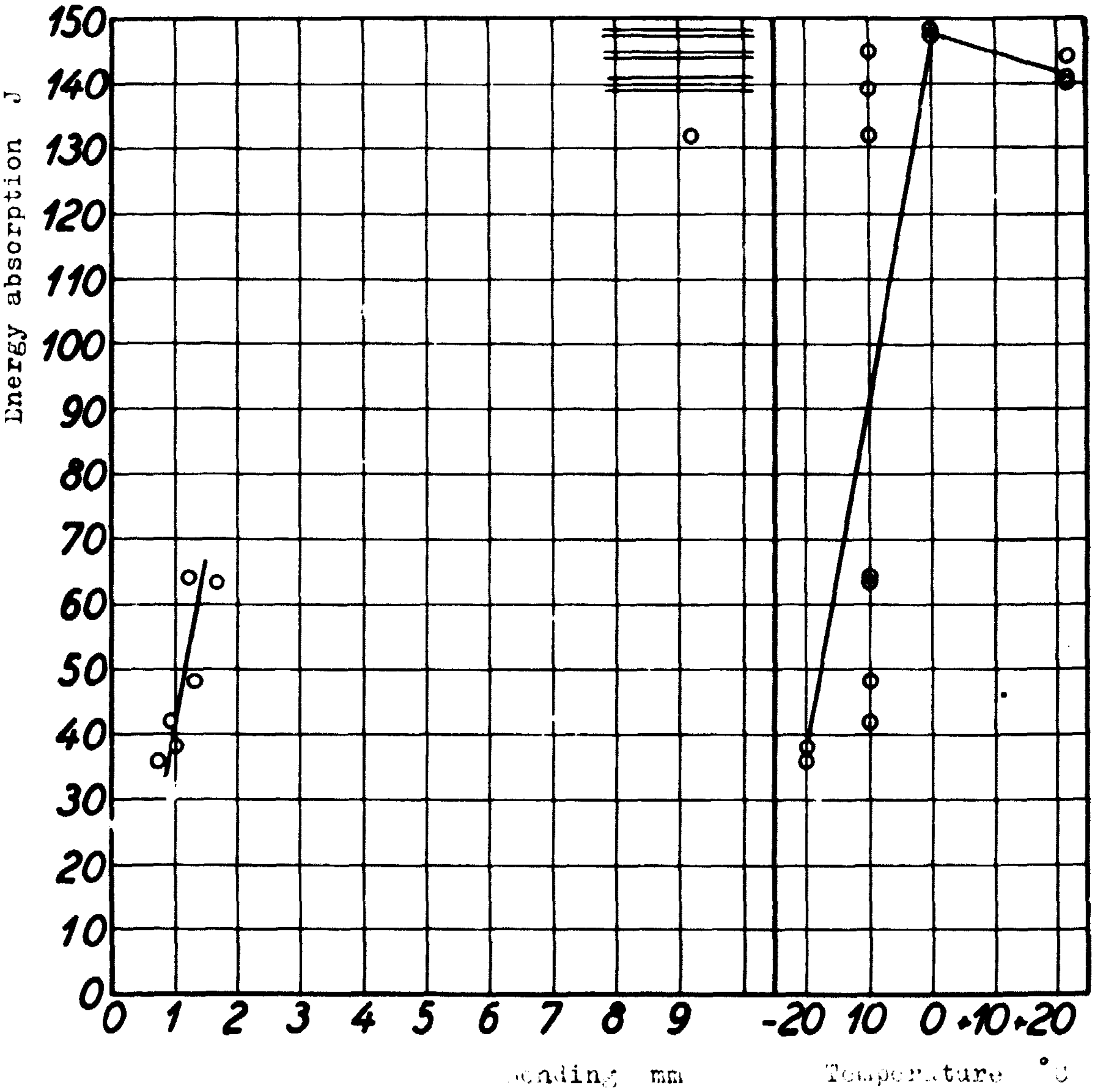

Fig. 7. Steel 2251. Charpy-C testing.

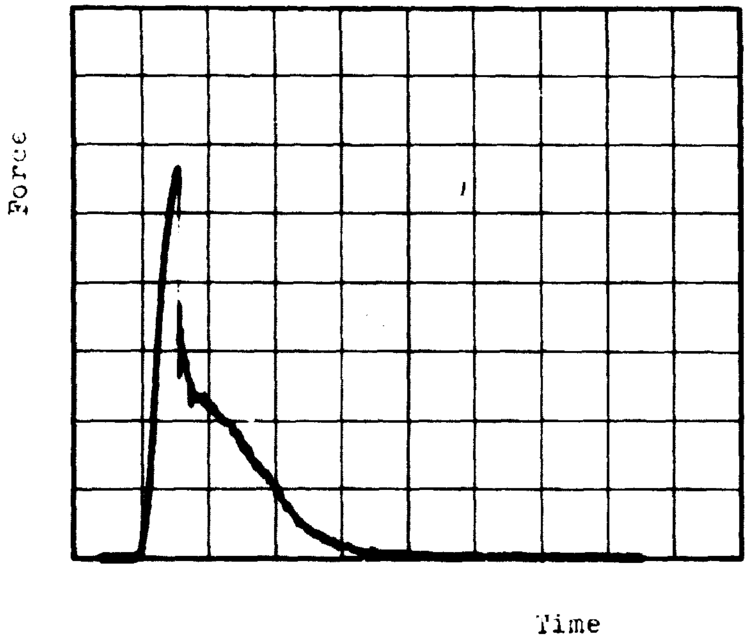

Fig. 8. Diagram recorded during Brady-testing