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THE FIBRE FRACTURE TEST

as a

CONTROL OF THE TOUGHNESS OF CAST AND ROLLED HOMOGENEOUS ARMOR.

[redacted]

25 March 1944.

WATERTOWN ARSENAL
WATERTOWN, MASS.

[redacted]

[redacted]

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The Fibre Fracture Test

Introduction

1. The Fibre Fracture Test has been developed as an inspection device to control the processing and heat treatment of armor to insure optimum ballistic properties in the steel at the respective hardnesses which may be involved. The validity of the test has been adequately investigated. It is well suited for process control because of its simplicity and its "go" or "no go" characteristic. It requires no accurately machined specimens or unusual plant equipment. It is applied to the production material after final heat treatment and to the full cross section of the armor involved. The only important difficulty encountered in its application is the problem of obtaining accurate and consistent interpretations among inspectors and producers. In the hands of an experienced person, a careful look at the fracture is all that is required. This experience is necessary, but a knowledge of the significance of the test is also helpful in arriving at a thorough understanding of its purpose and importance. This discussion is intended to assist those responsible for the application and interpretation of the test in the inspection of steel for Ordnance applications, particularly armor.

The Armor Problem

2. Armor, as contrasted to steel for ordinary commercial purposes, is a special application. Machine parts or members of other engineering structures are designed so that, for the greatest part, the stresses are not sufficient to exceed the elastic strength of the material and no

[redacted]

permanent deformation results. Armor Plate, however, is practically always plastically deformed when impacted with projectiles. The properties of the material under plastic deformation are, therefore, of primary importance.

3. To the above consideration must also be added the factor of <u>rate of deformation</u> or speed at which the plastic deformation is accomplished. Armor plate in combat is impacted at velocities varying from 1000 to 3000 or more feet per second, the lower end of the range being many fold more rapid than rates of loading involved in most commerical applications. To this factor must also be added the <u>effect of temperature</u>. Armor plate must be so processed that it will retain adequate resistance to cracking at the lower ambient temperatures which may be encountered in combat. The figure of -40°F. has been adopted as the minimum which should be anticipated in combat for ground operations, whereas -65°F. represents the minimum figure likely to be encountered in air operations. The temperature factor is of extreme importance because of the well known decrease in ductility suffered by steel as the temperature is lowered. Its effect upon the properties of the steel is similar to a change in rate of strain. The lowering of the temperature of test in the case of steel by 50°F. in any temperature range below room temperature has a similar effect on the properties as an extremely large increase in the rate of deformation.

4. From the above, it will be seen that armor is thus a unique problem. Therefore, to perform in an optimum manner, it is necessary to insure properties in the material which are infrequently required in steels utilized for most commerical applications.

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Ballistic Quality Characteristics of Armor.

5. Basically, there are three ballistic quality characteristics which are desired in armor. These are:

1 - Resistance to penetration or ballistic efficiency.

2 - Resistance to back spalling.

3 - Resistance to structural failure or cracking.

6. Resistance to penetration of armor when struck by a projectile, is largely a function of its hardness. Therefore, when the steel is sound and the heat treatment has been properly carried out, the accurate measurement of the hardness of a piece of armor can be made to provide the necessary control over the factors which affect resistance to penetration. In order to determine the optimum hardness of armor in any given thickness to best resist the combat attack anticipated, it is necessary to conduct extensive development ballistic programs. Once this information is available, it is then merely necessary to control the hardness characteristic as nearly as commercially possible to this desired value.

7. Resistance to back spalling in armor is largely a function of the soundness of the metal through the section. Obviously this characteristic is interwoven with resistance to penetration considerations. As the hardness increases, the likelihood of back spalls forming is also increased. Conversely, the inherent spalling tendency of armor caused by unsoundness will materially jeopardize the ballistic efficiency under many types of attack.

8. Whether a back spall forms or not under a given type of penetration and in armor of a given hardness, is a function of the stress necessary

[redacted]

to cause fracture of the metal in the thickness direction across the section. Therefore, discontinuities occuring through the section will materially affect the ability of the armor to resist spalling. In the case of cast armor, deficiencies appear as unsoundness at the center of the section. This condition can, and is, being controlled by radiographic examination. In the case of rolled armor, wherein back spalling occurs more often, the defects consist of non-metallic inclusions or discontinuities caused by other factors which form planes of weakness along which rupture occurs in the development of the back spall. This condition is, therefore, largely a function of steel soundness and processing methods and may be controlled by a test for steel soundness. Many tests have been suggested such as the macroetch test, tensile tests across the section and the fracture test for steel soundness. The test which appears most practical and which has been instituted is known as the fracture test for steel soundness.

9. Resistance to structural failure or cracking or, what is commonly known as Resistance to Shock, is a measure of the ability of the steel to absorb in a ductile manner, plastic deformation occuring at high rates of strain and at low temperatures. This characteristic in armor is largely determined by its metallographic structure which, in turn, is a function of chemistry and heat treated condition.

10. The Fibre Fracture Test has been developed as a control of the metallographic structure of the armor which is determined by the factors chemistry and heat treatment. It is sufficiently simple so that it may be applied in the production shop on an adequate number of samples to effectively control the quality of the armor produced. Its usefulness lies in the fact that, by a control of the characteristics of the

[redacted]

specimen, it is possible by a comparatively slow speed test conducted at ordinary temperatures to ascertain the properties of the armor which affect its ability to absorb the plastic deformation of projectile impact, involving high rates of strain, in a ductile manner and at low service temperatures.

Significance of the Test

11. For many years it has been known that tempered martensitic structures in steel provide the maximum resistance to shock loading and the optimum combination of strength and ductility. More recently this has been emphasized in the case of armor plate wherein the steel is always subject to high rates of deformation and, possibly, at low service temperatures. Numerous samples of cast and rolled armor which failed to pass the ballistic shock tests have been examined. Whenever brittle failure has occurred in the low alloy type steels, the metallographic structure has shown considerable quantities of high temperature transformation products which formed upon quenching. Such microstructures, at the hardness levels used in armor plate, have been found to be associated with poor ballistic properties under conditions encountered in the service to which armor is subjected, as will be demonstrated later. (See paragraphs 18 and 19.)

12. The detection of the presence of high temperature transformation products in sufficient quantities to have a deleterious effect upon the ballistic properties of the steel has heretofore been a problem largely involving careful laboratory techniques. The fibre fracture test, however, indirectly determines this matter by measuring the inherent ductility of the steel under severe conditions which allows a judgment to be made as to whether the microstructure is such as to produce

desirable properties in the steel under ballistic attack. With the obtainment of the ductile, fibrous fracture from a piece of steel, it is assured that its optimum properties as armor plate have been developed for the particular hardness involved. The test as applied to homogeneous armor is confined to steels within the hardness range of approximately 200 to 360 Brinell, but, fortunately, this covers the extremes in hardness involved in homogeneous armor except for the thin gauges of "hard" homogeneous rolled armor normally heat treated to 380-420 Brinell hardness.

13. The test simply determines whether or not the steel, under the testing conditions involved, fractures in a brittle or ductile manner. When the steel breaks in a ductile manner (after considerable plastic deformation has taken place), the resulting fracture has been termed fibrous. When the steel, on the other hand, breaks in a brittle manner (before appreciable plastic deformation has taken plate), the resulting fracture has been termed crystalline. The ductile fracture is characterized by high energy absorption required for breaking. During the past year the ductile fibrous fracture has been found to be associated with the following characteristics observed in the examination of numerous samples of armor:

High impact strength (as indicated by Charpy and Izod tests)

Essentially tempered martensitic structures

Satisfactory resistance to shock at normal and higher hardnesses and at low temperature as indicated by ballistic tests.

14. Reference to Figure 1 will show examples of the impact properties of cast armor as a function of the type of fracture and at a hardness of approximately 220 Brinell. It will be seen that the material which

developed a satisfactory fibrous fracture absorbs 85 foot pounds of energy in the standard V-notch Charpy impact test. This high value exceeds by ten times the impact value of a material which developed a crystalline fracture in the standard fibre test. The material which when fractured yields a mixed, or partially crystalline - partially fibrous fracture, develops an impact resistance intermediate to that of the materials developing fibrous and crystalline fractures. These are typical examples of the impact values which may be obtained. Materials which fracture in a crystalline manner will always have comparatively low impact values. If, on the other hand, the hardness of the steel is known and it fractures in a fibrous manner, the impact value can be predicted within narrow limits and will be of a high order for that particular hardness. If the fracture is fibrous, other factors such as steel quality or type analysis have a small but comparatively minor effect upon the impact properties.

15. The characteristic Charpy V-notch impact behaviors of a typical cast and rolled armor steel (of adequate hardenability for full hardening in water) as a function of temperature of test and metallographic structure are illustrated in Figure 2. Samples from each steel approximately 2" x 2" x 6" in size were quenched in (1) water, (2) oil, and (3) air cooled after proper austenitization and then tempered at a constant temperature. The hardnesses resulting after tempering and the types of fractures developed on standard fibre test specimens were as follows:

	Cast Steel		Rolled Steel	
Quenching Treatment	BHN	Type of Fracture	BHN	Type of Fracture
Water Quenched	255	Fibrous	277	Fibrous
Oil Quenched	212	Mixed, fibrous and crystalline	248	Mixed, mainly fibrous
Air Cooled	207	Crystalline	217	Crystalline

16. It will be noted that water quenching produced a desirable condition of essentially tempered martensite which resulted in a fibrous fracture in both steels whereas oil quenching produced a metallographic structure resulting in a mixed (approximately half fibrous - half crystalline) fracture in the cast armor composition and a mixed (mainly fibrous) fracture in the rolled armor steel. Pearlitic microstructures resulted from the air cooled treatments which produced completely crystalline fractures in both steels. Subsequently, duplicate impact test bars from each steel in the three heat treated conditions were broken at four different temperatures. Referring to Figure 2, it will be noted that the cast armor steel in the water quenched and tempered condition (resulting in a fibrous fracture) retains excellent impact strength at a temperature as low as -40°F (-40°C). At -94°F (-70°C) the impact value falls off considerably accompanied by a partially crystalline Charpy bar fracture. The oil quenched material is considerably less satisfactory except at room temperature. The room temperature superiority of the oil quenched material is the result of its considerably lower hardness. The inferiority at low temperatures is associated with the partially or completely crystalline impact bar fractures. The decidedly poor properties of the air cooled material even at lower hardnesses correlate with the completely crystalline fracture. In all cases the low impact values are associated with partially or completely crystalline impact bar fractures.

17. The rolled steel as water quenched retains excellent properties at -94°F (-70°C). The steel as oil quenched is also satisfactory at the higher temperatures, but the unsatisfactory condition of the steel as indicated by the slight amount of crystallinity developed in the

fracture test shows its effect upon the low temperature impact values. The comparatively poor impact performance of the air cooled material, correlating with the crystalline fracture, is indicated.

18. The best evidence obtained to date of just what the different modes of rupture observed in the fracture test signify is illustrated in Figure 3. The fibrous fracture is synonomous with a ductile fracture requiring high energy for rupture. The crystalline material fractures in a brittle manner requiring considerably less energy. A careful study of this figure will reveal the reasons for the differences in energy absorption. The photomicrographs are at the edge of fractured Charpy specimens of materials which fracture to yield typical crystalline and fibrous appearances and at the same hardness level (225 Brinell). The upper photomicrograph is typical of a steel which was incompletely hardened upon quenching and which microscopic examination shows that it contains considerable quantities of high temperature transformation products including ferrite. The lower photomicrograph is of the same steel after reheat treatment in a smaller section in which complete hardening to martensite was obtained in the quench. The structure after tempering is tempered martensite. It will be noted that the incompletely quench hardened material has fractured in a brittle manner without visible distortion of the individual grains. Rupture occurs along a regular path which changes direction at intervals. The flat crystal facets which result are responsible for the typical crystalline appearance of incompletely quench hardened steels. The absence of deformation results in the low impact energy of the material. The completely quench hardened material, on the other hand, breaks along an irregular path and produces an extremely rough and torn appearance. The grains are

considerably deformed along the path of rupture, which accounts for the high Charpy value recorded. Careful study of this figure and complete understanding of the respective modes of fracture propagation will assist materially in comprehension of the significance of the test.

19. Under the direct ballistic shock test, the superiority of the materials which fracture in a ductile manner has been repeatedly demonstrated. The most significant evidence is recorded below as Table I. The results are those obtained on cast and rolled homogeneous armor of 1½ to 2 inches in thickness tested at the Winter Proving Ground during the 1942-1943 season at temperatures varying from -10 to -35°F. The marked correlation between the results of the standard fracture tests conducted at ordinary temperatures and the performance under ballistic shock tests at low temperatures is clearly indicated.

TABLE I

Correlation between Type of Fracture and the Ballistic Shock Test Results of $1\frac{1}{2}$ and 2 inch Cast and Rolled Homogeneous Armor Tested Ballistically in a Standard Manner at Low Temperatures.

CAST ARMOR

*Type of Fracture Obtained in Standard Fibre Fracture Test	Results of Ballistic Tests for Resistance to Shock		
	Number Tested	Number Failed	% Failures
Fibrous	15	0	0
Predominantly fibrous	4	1	25
Mixed, fibrous and crystalline	10	8	80
Predominantly crystalline	22	17	78
Crystalline	28	20	83

ROLLED ARMOR

Fibrous	17	0	0
Predominantly fibrous	5	1	20
Mixed, fibrous and crystalline	11	2	18
Predominantly crystalline	7	5	71
Crystalline	-	-	-

*Samples fractured at room temperature (70°F approximately).

Such a correlation is not as evident at normal temperatures since ballistic shock tests as conducted at normal temperatures are not as severe as when conducted at low temperatures. The same general trends are evident, however, in numerous comparisons which have been made.

Preparation of Specimens

20. The fibre fracture test is conducted on the sample to be investigated by breaking the sample transversely under the impact of a freely falling weight or power driven hammer. The desired severity in the test depends upon the provision of transverse notches midway between the ends of the specimen. The notch not only locates the fracture but produces the constraint and stress concentrations which, when the sample is struck a sharp blow, will provide the restraint to deformation and rapid rate of strain or progression of the rupture which constitute the significant features of the test and the mechanism whereby a test conducted at comparatively low rates of load application at ordinary temperatures correlates well with ballistic shock test results at low temperatures. Therefore, the general features of the notching technique are important. The type of notching which has been developed and is most easily accomplished is illustrated in Figure 4. The notches may be produced by sawing, abrasive disc cutting, or flame cutting. The important consideration is uniformity.

21. It has been found by experience that the necessary severity of the test to correlate with ballistic shock tests at low temperatures is obtained when a specimen at least 2T in width (where T is thickness of armor) is notched in to a distance of at least ½T from each edge leaving an area T x T to be fractured. In the case of thick armor, the T x T area is often too large to be fractured by available equipment. In these cases the notching may be continued in to a greater depth leaving a fracture approximately ½T in width to be broken. Further reductions in the area to be fractured may be achieved by notching along one or both faces of the test sample as also indicated in Figure 4. The additional notching may provide some additional stress concentrations which in the case of

unsatisfactory material produces a greater tendency to form the crystalline fracture. The satisfactory materials will produce fractures which appear identical, however, irrespective of the type of notching utilized except for edge effects which sometimes appear adjacent to the un-notched faces of the fractured specimens.

22. In order to maintain the proper stress concentrations in the specimen and provide the desired restraint to deformation that is necessary to produce the required severity of the test, it is essential that the ratio between the width of the specimen prior to notching (W) and the distance across the throat of the specimen between the notches (Y) be 2 or greater and the width of the notch not be large. As long as the ratio exceeds 2 and the width of the notch is not excessive, maximum constraint in the width direction appears to have been achieved and further notching does not result in a more severe test.

23. In order to provide the proper constraint in the thickness direction, the width of the notch (d) in terms of the distance between the notches (Y) must be controlled. If the distance (d) were large, then necking could occur in the thickness direction and restraint in this direction would not be achieved. It would be desirable to maintain the ratio between the distance across the throat of the notched specimen (Y) and the width of the notch (d) at 10 or greater and this can be attained on thicknesses of armor greater than 5/8 inch. However, one is limited by the minimum width of the notch (d) that can be obtained by a saw or flame cutting torch. In general, the width of the notch can not be expected to be less than 1/8 inch and since the distance across the throat of the specimen (Y) must be controlled with respect to thickness, it then becomes necessary to deviate from this desired ratio in the case

of thin armor and specify that the ratio between the distance between notches (Y) and the width of the notches (d) be 5 or greater. Experience has shown that this ratio provides a satisfactory test. If the distance across the throat of the specimen (Y) were allowed to exceed the thickness (T) many times, constraint in the thickness direction would be lost in the center of the specimen. Constraint would be maintained at the roots of the notches but could not extend across the large unnotched distance. Therefore, the distance between notches (Y) must be controlled within minimum and maximum limits dictated by the relationship between this dimension and the width of the notches and the necessity for controlling the maximum width between the notches. The maximum distance between notches, expressed in terms of the thickness of the armor (T), should not exceed 2T.

24. In order to maintain the above relationships, large "U" shaped notches must be avoided. For all thicknesses above 1", it is merely necessary to use a specimen at least twice the thickness in width and notch in straight with an abrasive wheel, saw, or cutting torch an equal amount from both sides leaving an area approximately T x T in size to be fractured. In summation it may be stated that the following factors should be controlled to assure reproducibility and an accurate indication of the properties of the steel:

A. $W > 2T > Y$. From paragraphs 21 and 22, it is necessary that the width of the specimen exceed twice the thickness as one relationship governing constraint in the width direction of the specimen. A maximum dimension for Y must be specified in terms of thickness or constraint is not maintained at the center of the unnotched dimension Y.

B. W > 2Y. From paragraph 22, width of specimen must be at least twice the distance across the throat of the specimen to provide the desired stress concentration and constraint.

C. Y > 10d for thicknesses over 5/8 inch.

Y > 5d for thicknesses under 5/8 inch.

From paragraph 22, the relationship between the distance across the throat of the specimen and the width of the notch must be controlled to provide the desired constraint in the thickness direction of the specimen. The limitation on width of notch indirectly places a maximum on the radius at the root of the notch and, in so doing, assists in providing the desired stress concentrations.

D. Temperature of sample at time of breaking.

E. Application of impact in fracturing.

The importance of temperature has been indicated. Care should be taken that all samples are at a fairly constant temperature at the time of fracture. The temperature of 70°F has been selected as desirable. Lower temperatures, of course, provide a more severe test. Materials which break to give a fibrous fracture, however, will not alter in fracture appearance over a considerable temperature range such as +30° to +70°F. Specifications control the upper limit on temperature at 100°F.

25. The rate at which the impact blow is delivered has not been found of great importance as long as adequate constraint and concentration of stresses have been provided by notching. The speeds obtained by falling weight mechanisms, steam and air hammers are satisfactory. Breaking of samples in a hydraulic press is not considered satisfactory, however, since erroneous results have been obtained on borderline materials at low

hardnesses when this method of fracturing has been used.

26. Figure 5 shows schematically a typical arrangement for fracturing specimens. It is important that the striking object have a narrow striking edge so that essentially line contact is obtained which can be positioned directly in the plane of the notches in the specimen. In the case where the falling weight has a large contact area, the impact may be concentrated at the notched region by placing a small bar across the surface of the fracture specimen along the plane of the notch. The span of the specimen, or the distance between the bottom supports, for heavier thicknesses of armor (above 1-1/4") may be adjusted for convenience as long as the span length is not excessive. On thin armor, however, such as up to 1 inch in thickness, the span should be progressively reduced with decreasing thickness so that rigidity of the specimen is maintained and bending prior to fracture does not result to an appreciable extent. Severe bending of the specimen may result in partial shear failure which promotes a "smeared" fracture surface which is difficult to interpret.

27. The dimensions of specimens which have been found to be most satisfactory for the several thickness ranges are recorded in Table II. The concept of a fracture area approximately T x T in size with adequate notching has been adhered to except on thin and extremely heavy gauges. In the case of thin armor, an area in excess of T x T in size is desirable for ease in interpretation.

TABLE II

Standard Dimensions for Fibre Fracture Test Samples

Desirable Notch Characteristics and Span Distances

Armor Thicknesses Inches	Span of Specimen	*Width of Specimen	Width of Notch, Maximum	Area to be Fractured
3/16 - 1/2	4 - 6"	2 - 3"	1/8"	Up to 2T width x T
5/8 - 1	6 - 8"	2 - 4"	1/8"	Up to 2T width x T
1-1/8 - 1-3/4	7 - 9"	4 - 6"	3/16"	Up to 2T width x T
1-7/8 - 2-1/2	8 - 10"	4 - 7"	1/4"	Up to 2T width x T
2-5/8 - 4	9 - 12"	5 - 9"	1/4"	Up to 2T width x T **Up to 2T width x 3/4T
4-1/4 - 6	12 - 18"	10 - 12"	3/8"	Up to 2T width x T **Up to 2T width x 3/4T

* Greater widths of specimens may be used as long as notching is deeper to conform to maximum area to be fractured.

** Notching also along each face of sample to a depth of 1/8T may be accomplished to facilitate fracture.

Finally, with respect to the fracturing of specimens, best results are obtained with a single blow which causes complete fracture with one application. The necessity for using repeated impacts tends to promote bending and consequent "smearing" of the edges of the fracture and difficulty in interpretation of the results. It is important that the fractured halves of the samples separate completely upon rupture in order that damage to the surfaces may not result.

Type of Fractures

28. Armor is desired which under the standard test conditions will fracture in a ductile manner to produce a fibrous appearance. The crystalline or brittle fracture indicates extremely unsatisfactory properties in the hardness ranges to which armor is normally heat treated.

Between these extremes of the completely crystalline and fibrous fracture are the mixed fractures or borderline cases which are most often encountered in the inspection of production armor. Only materials which fracture in a fibrous manner are satisfactory. The completely fibrous fractures are easily recognized; the same is true of the completely crystalline fractures. Once the typical appearance of the fibrous fracture has become mastered, it then becomes a comparatively easy matter to recognize deviations from this appearance. The main difficulties in this connection are caused by local defects uncovered in the fracture surface such as shrinkage or porosity in cast sections and nonmetallic inclusion streaks in rolled armor.

29. The difference in appearance of the fibrous and non-fibrous fractures is a function of the light-reflecting characteristics of the surfaces of fractures produced by the two modes of rupture as indicated in Figure 3. Thus the light source under which specimens are examined is important. A spot source of light would be ideal; a practical substitute is an unfrosted electric light bulb the rays of which strike the fracture surface normally. The eye then is sighted parallel to the light rays and the specimen is tilted slightly while being examined. Specimens are most easily examined when approximately 6 to 12 inches from the eye.

30. The fibrous fracture is characterized by a dull grey, uniform, non-reflecting appearance. The surface exhibits a "torn" aspect.

31. The completely crystalline fracture caused by incomplete quench hardening will be seldom encountered in practice. However, mixed fractures, with fibrous rims and crystalline areas in the center or near one edge due to incomplete quench hardening are common and will be

frequently encountered. The crystalline material exhibits the typical bright, shiny, granular appearance caused by light reflections from the individual crystal facets, as pictured in Figure 3. The lack of ductility is definitely indicated by the fracture being unusually flat with little or no plastic deformation having occurred at the edges of the sample.

32. The mixed fracture, containing crystalline patches near the center surrounded by a fibrous rim, is most easily recognized because of the contrast in color and texture of adjacent areas on the same surface. The fracture, of course, may be predominantly crystalline, or, in the borderline condition, may exhibit only small crystalline patches. Crystallinity is a characteristic of the matrix and as such must necessarily involve a group of grains. Therefore, isolated speckles seen in a fracture, even though bright in appearance, cannot be construed as crystallinity, but may often be caused by local defects in the steel such as inclusions or shrinkage voids.

33. The brittle fracture obtained in high hardenability steels is not caused by incomplete quench hardening. Therefore, the fracture is uniform in appearance across the section. The poor properties of these steels are a function of the type analysis and heat treatments utilized. In some cases the difficulty is probably associated with the retention of austenite upon quenching which subsequently may transform upon tempering to yield high temperature transformation products and resulting poor properties. The non-fibrous fracture encountered in these types of steels may be described as follows:

1. The fracture appearance is uniform throughout the section.
2. Little ductility is evidenced at the edges of the fractured specimen.

3. The color of the fracture as a whole is intermediate between the fibrous fracture and the bright, crystalline fracture associated with incomplete quench hardening.

4. The surface presents a mottled, grey appearance.

5. Close inspection visually or with the use of a $1\frac{1}{2}$ - 3 magnification reading glass will show crystalline patches intermixed in a fibrous background.

Once this typical fracture has been seen a few times, it can be readily recognized. Comparison with a fibrous fracture will immediately illustrate the considerable difference in appearance.

Local Defects in Steel and Appearance on Fractures

34. As the heat treated condition of a steel is improved so that upon fracturing it approaches or becomes completely fibrous, the steel acquires ductility which causes rupture to occur through local defects in the steel since these constitute the path of minimum resistance. Such defects in cast specimens are usually caused by nonmetallic inclusions, or, more often, shrinkage voids. These shrinkage voids are usually lined or partially filled with a bright, shiny material which in most cases has a dendritic or "tree-like" aspect. The distinction between these bright spots and true crystallinity in a borderline material must be recognized. Careful examination of these shrinkage defects and surrounding area will reveal that they appear to be depressed under or superimposed upon the fibrous matrix and are not a part <u>of</u> the matrix. The use of a reading glass which produces a stereoptic effect is useful in recognizing this material. Under the reading glass it will appear to stand out in relief. In contrast, the crystalline patches of an unsatisfactory material are a part of the matrix and do not present the relief effect. Obviously, the presence of bright

spots due to local defects is not caused by undesirable metallographic structure which would produce true crystalline fractures and hence does not indicate unsatisfactory toughness. Efforts should be exerted by those responsible for the interpretation of fractures to initially distinguish between local casting defects and crystallinity so that false interpretations will not arise because of such conditions.

35. In rolled armor, local defects such as small nonmetallic inclusion stringers appear as bright streaks on a fibrous or nearly fibrous fracture. These streaks, which are parallel to the plate surfaces, are caused by small splits in the material perpendicular to the plane of the fracture and extending along the inclusion. Such splits may range in depth from .001 to .05 inches. Where the interface between the inclusion plate and the steel matrix has so ruptured, a bright surface results. The bright streaks seen visually, therefore, are occasioned by looking along this bright surface at an acute angle. In some steels this effect may be concentrated towards the center of the section; in others it may be uniformly distributed throughout the section.

Application of Test to Production Inspection

36. The use of the test in inspection is covered by the applicable armor specifications. However, some of the factors involved in the processing and heat treatment of armor which affect its ballistic and fracture characteristics will be discussed. The ballistic test, when it approaches as nearly as practicable actual service conditions, in the ultimate criterion of armor quality. However, a satisfactory ballistic test performance at normal temperatures offers little guarantee as to the performance of that material at low temperatures or when incorporated in a vehicle, and restrained by adjoining armor. Furthermore, ballistic test sampling

necessarily is far from adequate. The fracture test allows more thorough sampling and, hence, more adequate inspection of the production material and checks the characteristic which inherently determines whether or not the armor will be satisfactory ballistically from the standpoint of ability to withstand plastic deformation in a ductile manner. The following factors determine whether or not a fibrous fracture is obtained:

A. Hardenability of steel for the section involved and quenching practice in use.

B. Inherent characteristics of heat of steel. Some steels, because of inherent chemistry or quality factors, cannot be made to fracture in a ductile manner with normal treatments.

C. In armor steels, heating and quenching practices are important. The following are some of the deficiencies which have been noted:

1. Improper austenitizing treatment involving incomplete carbide solution.
2. Excessive scaling of armor prior to quenching.
3. Lack of agitation of quenching medium.
4. Elevated temperature of quenching medium.
5. Stopping the quench at too high a temperature, with resultant partial transformation to products other than martensite.
6. Transformation of austenite retained upon quenching at high temperatures during subsequent tempering.
7. Inadequate tempering cycles.
8. Rate of cooling from tempering temperature.

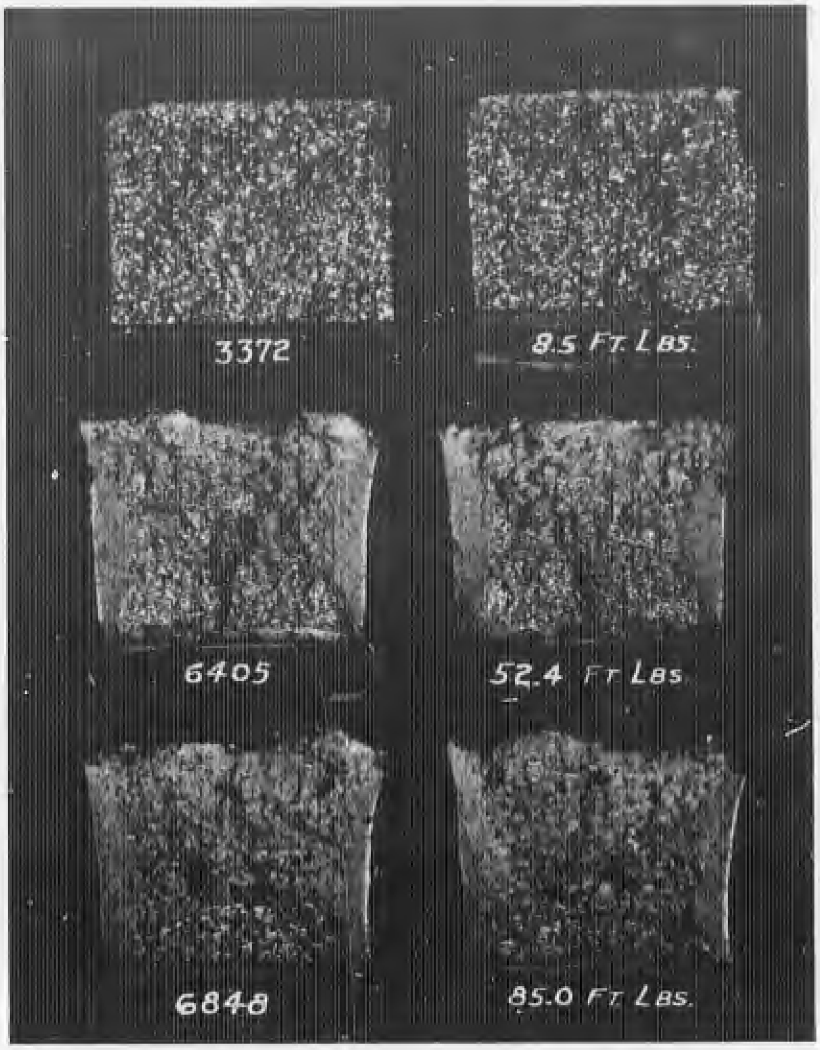
All of the above factors are important and must be controlled to insure uniformly satisfactory fractures.

37. The fibre fracture test is sensitive and, therefore, if properly applied, should insure a high degree of uniformity and satisfactoriness in armor with respect to its ability to deform without cracking. It, of course, has no connection with the soundness of castings or the freedom from laminations of the steel in the case of rolled armor, factors which affect the back spalling tendencies of armor. The test does, however, provide a non-ballistic method for determining the toughness characteristic of armor. In the case of armor castings, the fibre test, hardness measurements and a control of soundness are the factors which need to be regulated to insure satisfactory ballistic behavior. In the case of rolled armor, the fibre test, a control of steel soundness, and hardness tests will provide the same assurance. Irrespective of the reasons underlying the development of a crystalline or brittle fracture in armor, it has been found by experience that the same steel heat treated to produce the fibrous fracture and at the same hardness level will be more satisfactory for the purposes intended. Armor plate as utilized on most armored vehicles serves the dual purpose of defeating projectiles and constituting the framework of the vehicle. When one considers the likelihood of impacts with overmatching armor piercing projectiles at high obliquities or high explosive projectiles at any obliquity, all of which produce considerable shock effect on the armor, then it is at once apparent that resistance to shock is important. Brittle failure of the armor not only will allow admittance of these projectiles but will probably prevent the further use of the vehicle because of the impairment of its strength as an engineering structure.

38. The foregoing discussions are based upon experience obtained at this arsenal during the past year in the development and investigation of the fibre fracture test. The data included herein have been abstracted from the following Watertown Arsenal Laboratory reports which, among others, have been written on the subject or which have involved the use of the test in the determination of the factors responsible for the observed ballistic performance of armor:

Number	Title	Date
710/500	"Metallurgical Examination of Cast Gun Shield Armor Four to Six Inches in Thickness".	17 May 1943
710/532	"Development of a Fracture Test to Indicate the Degree of Hardening of Armor Steels upon Quenching".	1 August 1943
710/534	"Correlation of Metallurgical Properties with the Low Temperature Ballistic Shock Characteristics of 1" to 2" Low Alloy Cast Armor Tested at Camp Shilo".	16 August 1943

39. Standard fracture test samples, illustrating the various types of fractures which may be encountered, are desired to simplify the interpretation of fractures encountered in the inspection of production armor. These may be accumulated by the individual inspector and used by him in the training of subordinates. The Ordnance Department is arranging to provide standard fracture specimens for the cast armor industry. Similar standards will be provided for the rolled armor industry if necessary. Standard specimens should be studied carefully so that the significant features of the test and the appearances of the various types of fracture can be fully appreciated. It is felt that, with an understanding of the purpose and significance of the test and by reference to the standard samples, the inspector should be able to arrive at accurate and just interpretations of fractures presented to him for decision.



Mag. 4X

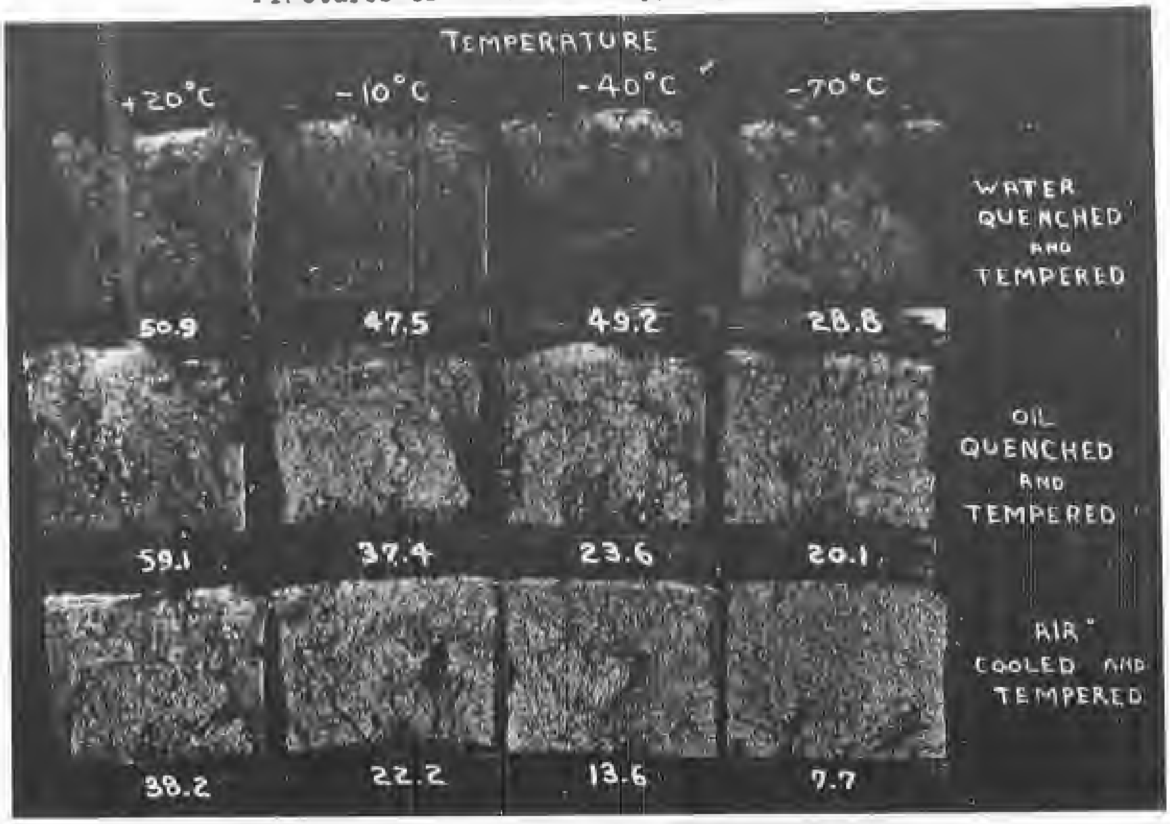
Fractures of V-notch Charpy Bars Illustrating Comparative Impact Strengths of Material Breaking with Fibrous, Crystalline, and Mixed Fractures.

Plate	Heat	Fracture	Charpy, Ft.Lbs.
1-13-3372	3372	Crystalline	8.5
1	6405	Mixed	52.4
GSC-26	6848	Fibrous	85.0

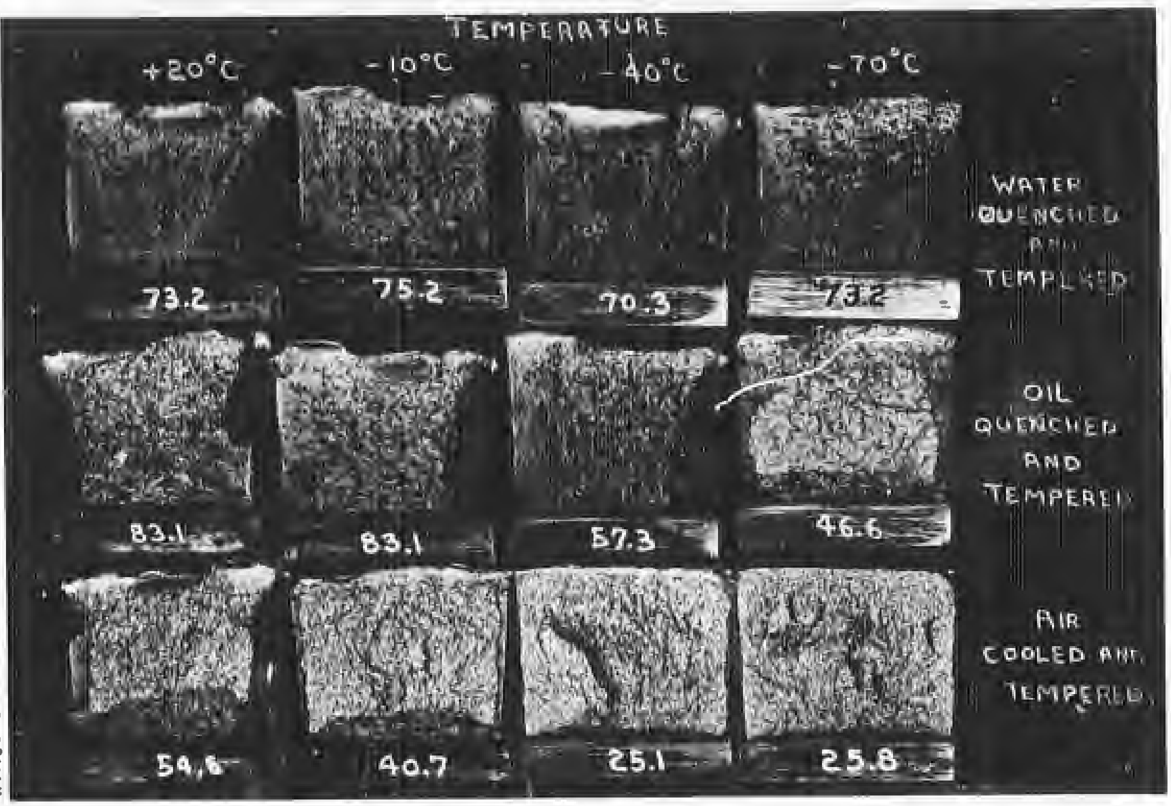
WTN.639-5138

FIGURE I

Fractures of V-Notch Charpy Impact Bars



2" Cast Armor



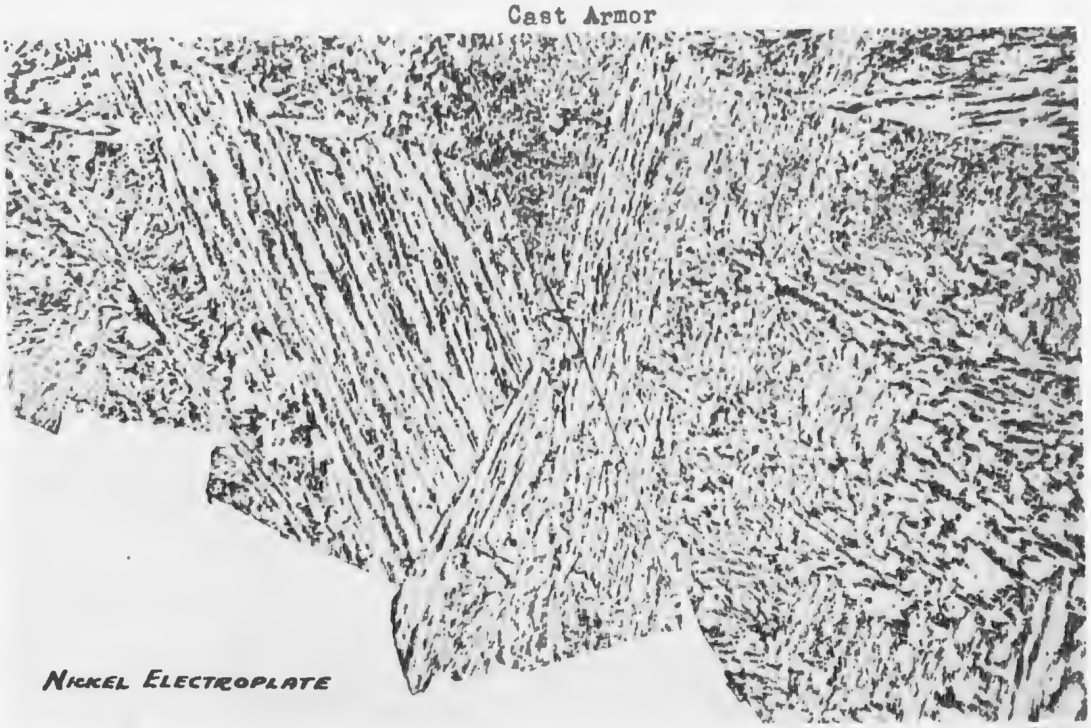
WTN.639-5376

2" Rolled Armor

FIGURE 2

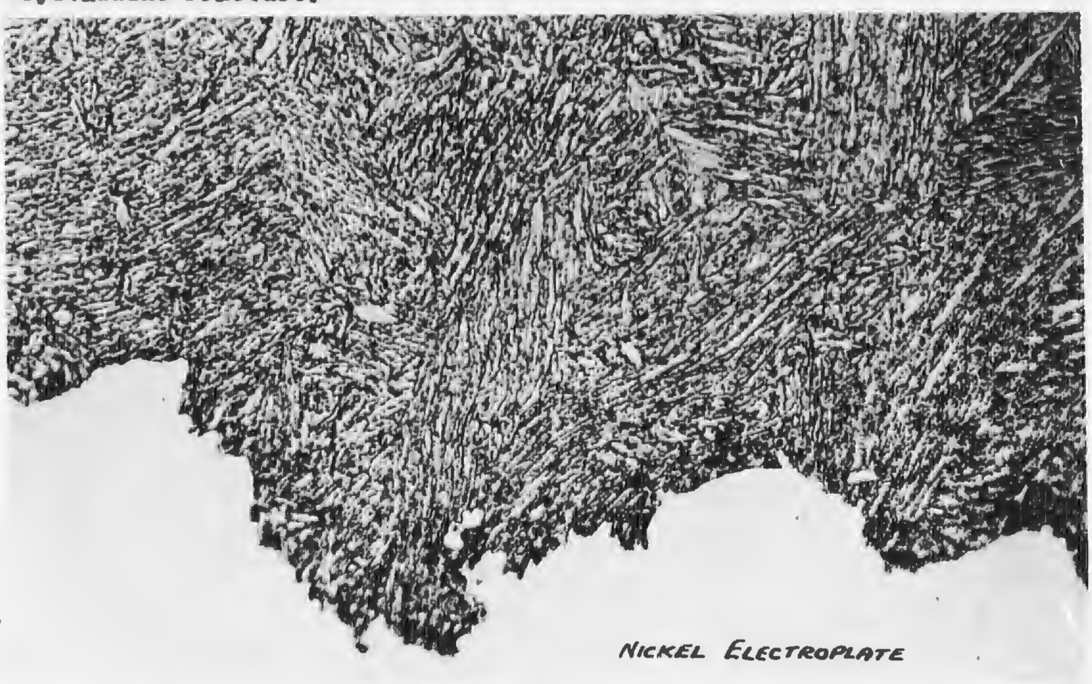
Fractures of V-Notch Charpy Bars

Cast Armor



Picral Etch -A- X750

Heat 3245. As received. Average Charpy impact - 12.3 ft. lbs. 220 Brinell. Section perpendicular to fractured surface of Charpy bar. Crystalline fracture.



WTN.639-5378

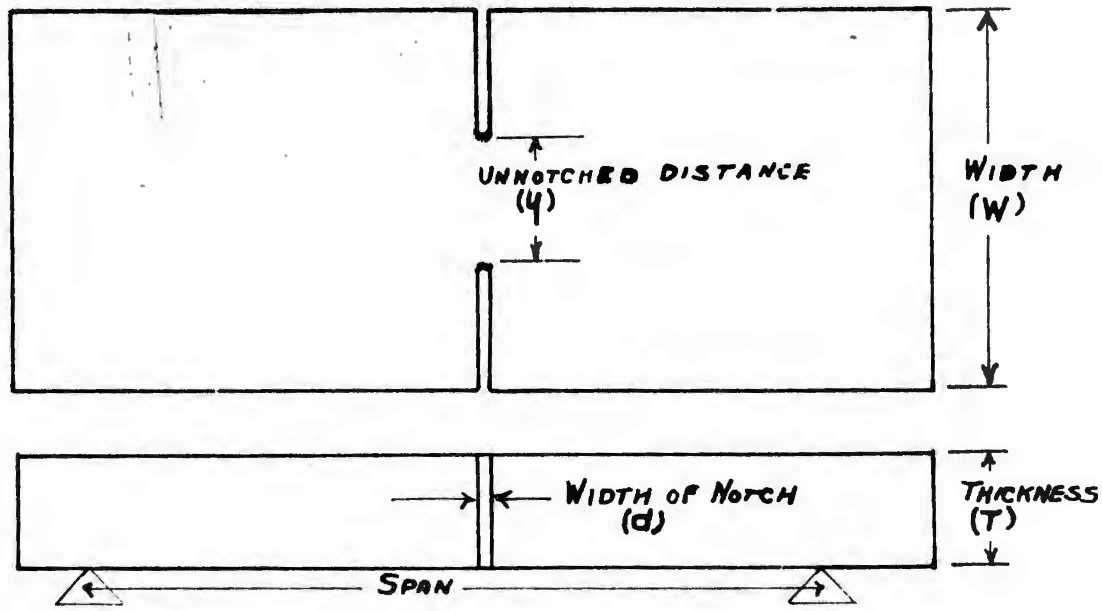
Picral Etch -B- X750

Heat 3245. Reheat-treated. Average Charpy impact - 82.7 ft. lbs. 229 Brinell. Fibrous fracture.

FIGURE 3

STANDARD FIBRE TEST SPECIMEN

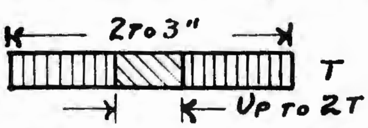
Relationships to be Controlled



(A). W > 2T > y
(B). W > 2y
(C). y > 10d, for thicknesses above 5/8", and
y > 5d, for thicknesses less than 5/8".

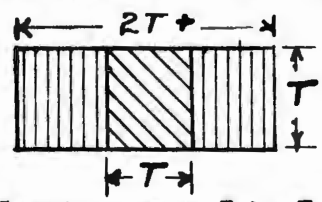
TYPICAL FRACTURE SPECIMEN RELATIONSHIPS

For thin plate up to 1".



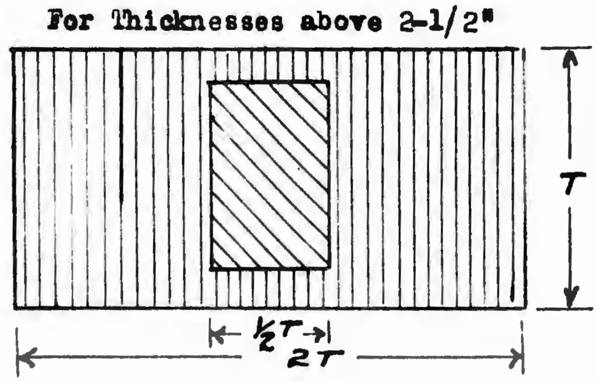
Fracture area up to 2T byT.

For thicknesses 1"--2-1/2".



Fracture area T by T.

For Thicknesses above 2-1/2"



Fracture area reduced to approximately 1/2T by 3/4T for increased ease in breaking

FIGURE 4

METHOD OF FRACTURING SPECIMENS

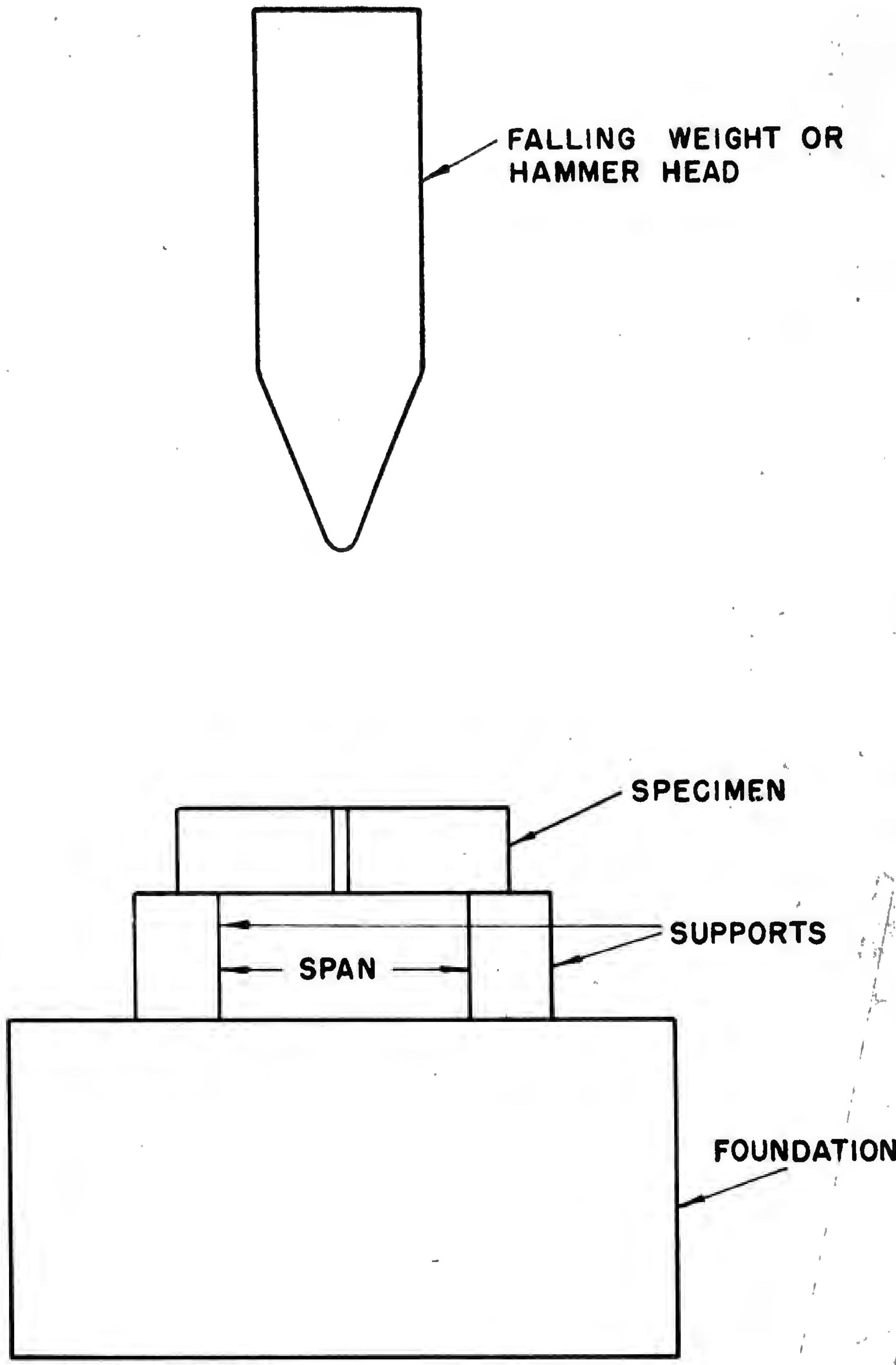


FIGURE 5