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Hardness Test	Metallurgical Tests	Tension Test
Impact Test	Microscopic Examination	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Describes methods of evaluating the physical properties of components and causes of failures. Describes equipment required and procedures for chemical analysis (wet method, spectrographic, and X-ray emission spectrographic analysis); macroscopic examination (gross structure and fracture area); microscopic examination; and mechanical testing including tension tests, hardness tests (Rockwell, Brinell, Knoop, scleroscope, and Vickers), notched bar impact tests (Charpy and Izod), fracture toughness tests, and fatigue tests.

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US ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

DRSTE-RP-702-102
*Test Operations Procedure 3-2-806 20 December 1983
AD No.

METALLURGICAL AND MECHANICAL TESTS OF MATERIALS

1. SCOPE. This TOP describes methods of laboratory destructive testing used in failed parts analysis. Rather than attempt to describe the many standard and special tests for analyzing materials, this TOP is confined to those test methods normally used by Army proving grounds.

To analyze a failed part, specific physical and mechanical properties of the part must be determined. Many of these properties can best be determined by laboratory destructive testing. After the properties of interest have been determined, they are studied for deviations from applicable specifications and drawings. Conclusions about the cause of failure can then be based upon the results of the tests as illustrated in Appendix A.

*This TOP supersedes TOP 3-2-806 dated 10 January 1973, Change 1 dated 30 January 1974, and Change 2 dated 13 November 1975.

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2. FACILITIES AND INSTRUMENTATION.

2.1 Facilities.

ITEM	REQUIREMENT
Metallurgical laboratory	Macrography, micrography, electron microscopy, and microprobe analysis
Mechanical test equipment	Tensile, fatigue, impact, hardness and fracture toughness tests

2.2 Instrumentation.

ITEM	MAXIMUM PERMISSIBLE ERROR OF MEASUREMENT*
Metallograph	±1% magnification and linear measurements
Tensile/fatigue tester	±1%
Scanning electron microscope	±1% magnification and linear measurements
Hardness tester	±2 points for Rockwell hardness; ±3% for Vickers and Brinell hardness; and ±4% for Knoop hardness
Impact tester	±1 joule or ±5%, whichever is greater
X-ray spectrometer	±1% of indicated amount
Electron microprobe	±1% of indicated amount

3. REQUIRED TEST CONDITIONS.

Not applicable.

4. TEST PROCEDURES.

4.1 Chemical Analysis. The properties of metals depend largely on their chemical composition. For this reason, it is often necessary to determine the exact percentages of the metal's constituents (quantitative analysis) and whether they represent the required percentages for a specified grade or composition.

4.1.1 Wet Method. This method is used extensively in the metals industry. It connotes the application of chemicals to weighted amounts of material in order to combine the desired elements in a chemical solution. In this manner, the concentration of the element of interest is determined as a percentage by weight.

4.1.2 Spectrographic Analysis. This method requires the use of a spectrometer. The radiation that is created by causing an electrical arc to pass between the material sample and an electrode is separated into component lines/wavelengths or a spectrum through the use of a diffraction grating system. The spectrum may be photographed but can also be read directly. In either case, the data are then compared directly with standards of known composition. This method can be used to perform either qualitative or quantitative analysis of material.

*Values may be assumed to represent ± 2 standard deviations; thus, the stated tolerances should not be exceeded in more than 1 measurement of 20.

4.1.3 X-Ray Emission Spectrographic Analysis. When a test specimen is bombarded with high-intensity X-rays, it emits X-rays that exhibit a spectrum characteristic of its chemical composition. These X-rays are collimated by lead shields and directed toward a crystal that acts as a diffraction grating. The resultant separated spectrum is analyzed by measuring the angles of diffraction. The X-ray intensity, a function of the element concentration, is plotted versus the angle of diffraction. Wave length, λ , is determined from Bragg's Law, $\lambda = 2d \sin \theta$, when d is the atomic spacing of the diffracting crystal and θ is the angle of diffraction. The elemental identification of the constituents of the test specimen can be determined from this relationship. Since the intensity of the X-rays is a measure of the proportional quantity of the elements present, quantitative analysis can be performed. Detection of elements of low atomic number (less than 12) is limited by absorption of the radiation by any gases present between the sample and the detector.

4.1.4 Examples. Two of the principal metals that are analyzed by spectrochemical means are alloys of aluminum and stainless steel. Table 1 shows the accuracy of the measurements of alloying elements when these alloys are analyzed by an XRD 6000 X-ray spectrometer These data were derived from comparisons made (ref 2, App B) with NBS standards for stainless steel alloys and aluminum company standards for aluminum alloys.

4.1.5 Chemical Analysis. Chemical analysis of test items less than 2.5 cm in cross section can be performed using either energy or wavelength dispersive X-ray emission spectrographic equipment in the scanning electron microscope (SEM). Microscopic areas can also be analyzed to determine the degree of chemical segregation in test pieces. An accuracy of 0.01% by weight is achievable with this method, under ideal conditions.

TABLE 1. POTENTIAL ERRORS FROM X-RAY SPECTROCHEMICAL ANALYSIS

Aluminum Alloys			Stainless Steel Alloys		
Alloying Element	Weight, %		Alloying Element	Weight, %	
	Measurement Error*	Range		Measurement Error*	Range
Zn	0.0558	0.036 to 6.09	Mo	0.0118	0.059 to 2.01
Zn	.0016	0.036 to 0.20	Nb	.0070	0.001 to 0.60
Cu	.0093	0.02 to 1.97	W	.0029	0.04 to 1.39
Ni	.0008	0.002 to 0.38	Ta	.0069	0.001 to 0.08
Fe	.0106	0.051 to 0.53	Cu	.0090	0.065 to 0.56
Mn	.0054	0.023 to 0.82	Ni	.1224	0.28 to 24.8
Cr	.0093	0.001 to 0.31	Mn	.0320	0.23 to 2.13
Ti	.0025	0.012 to 0.16	Cr	.4200	2.99 to 23.72
Si	.3925	6.47 to 7.24	V	.0023	0.006 to 0.061
Si	.0220	0.07 to 0.29	Ti	.0150	0.001 to 0.48
Mg	.1074	0.18 to 5.04	Sn	.0008	0.004 to 0.09
Mg	.0137	0.18 to 0.45	S	.0096	0.012 to 0.033
			P	.0129	0.015 to 0.038
			Si	.0200	0.12 to 1.25

*One standard deviation.

4.2 Macroscopic Examination. This is performed by inspecting the material with the naked eye or under low magnification (to about 64X). This technique is used to determine the fracture features of the test item, to identify its method of manufacture, and to reveal certain characteristics of the test item that may indicate the cause and nature of a particular failure (see figs. 1, 2, and 3 for macro-etch examples).

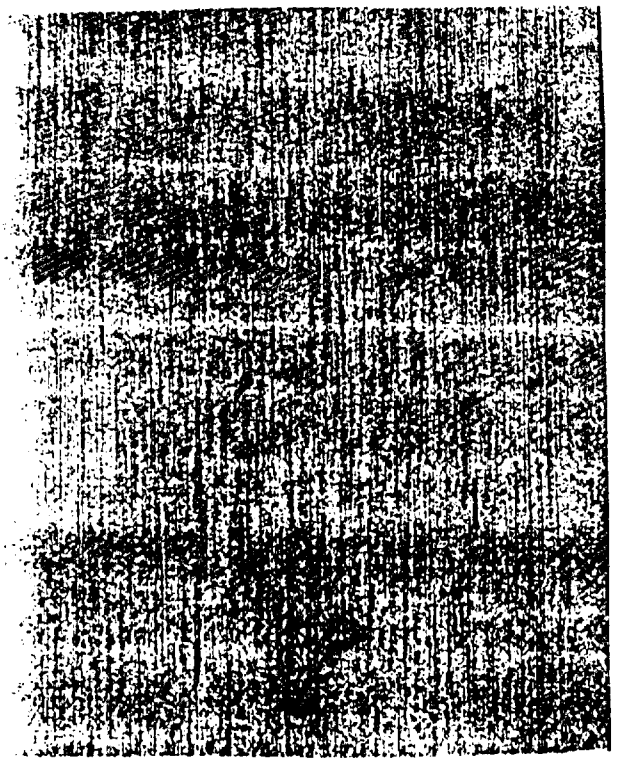

Figure 1. Macro-etch of rolled bar stock - longitudinal - 1x.

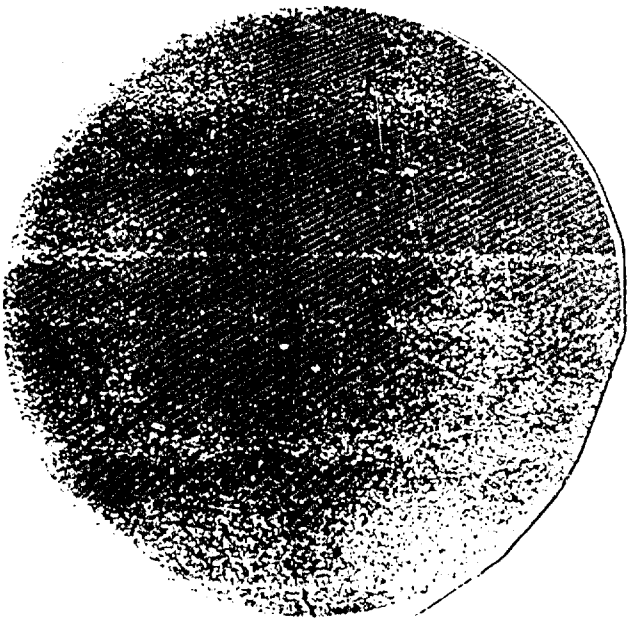

Figure 2. Macro-etch of rolled bar stock - cross section - 1x.

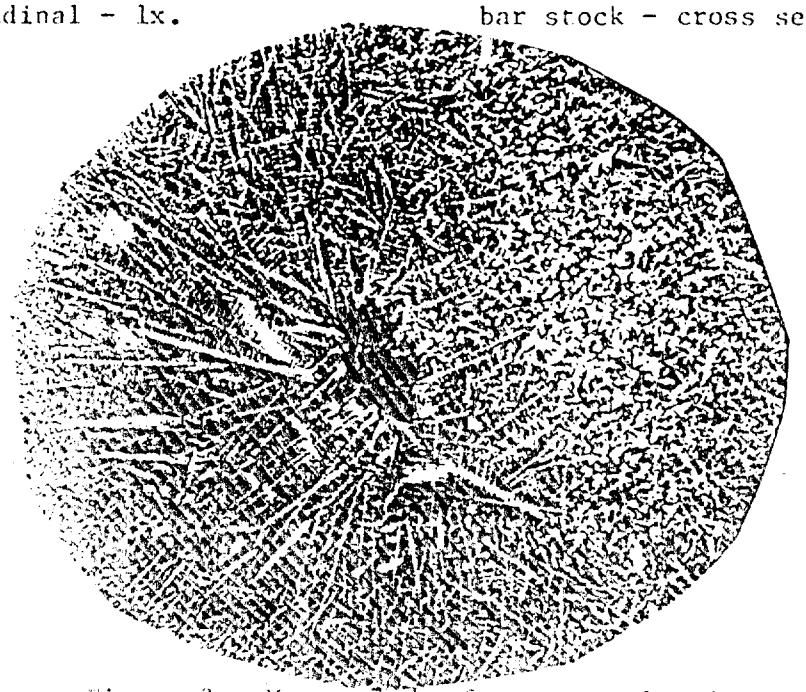

Figure 3. Macro-etch of cast steel - 1x.

4.2.1 Examination of Macrostructure. This method requires the use of a prepared specimen cut in the direction of interest. The cut surfaces are polished, and the polished area is etched in an appropriate acid solution. After suitable etching has taken place, the macrostructure of the surface will be revealed. This structure is governed by the solidification and subsequent working of the material. For instance, a hot-rolled bar-stock sample will reveal parallel flow lines in the direction of working. A cast steel component will reveal crystal growths called dendrites caused by the manner in which the steel solidified. Thus, by examination, the method of manufacture and the general soundness of the material are determined.

4.2.2 Examination of Fracture Area. A second method of macroscopic examination involves the investigation of fracture features of specimens that have failed in service or have been tested to failure. Under macroexamination, fractures often reveal certain characteristics pertaining to the properties of the materials that indicate the cause and nature of the particular failure. Photographs or macrographs are widely used to identify features with descriptive captions such as fibrous, crystalline, coarse, fine and silky, woody fiber, or laminated.

a. The appearance of a fracture that results from a service failure is often evidence that the component was subjected to vibration or alternating stress. This generates a type of progressive failure known as "fatigue". This type of failure originates at some nucleus on or near the surface of the material such as a surface pit, scratch, toolmark, or sharp fillet. These imperfections act as localized stress raisers. Alternating stresses may cause microscopic cracks to form at the local stress points. These small cracks propagate into the interior and weaken the component. Failure may then occur abruptly and without any warning. Fracture surfaces usually reveal a "beachmark" pattern, smooth at the beginning, then with concentric rings of increasing size, with the surface becoming progressively rougher (see fig. 4). Final failure is usually in shear.

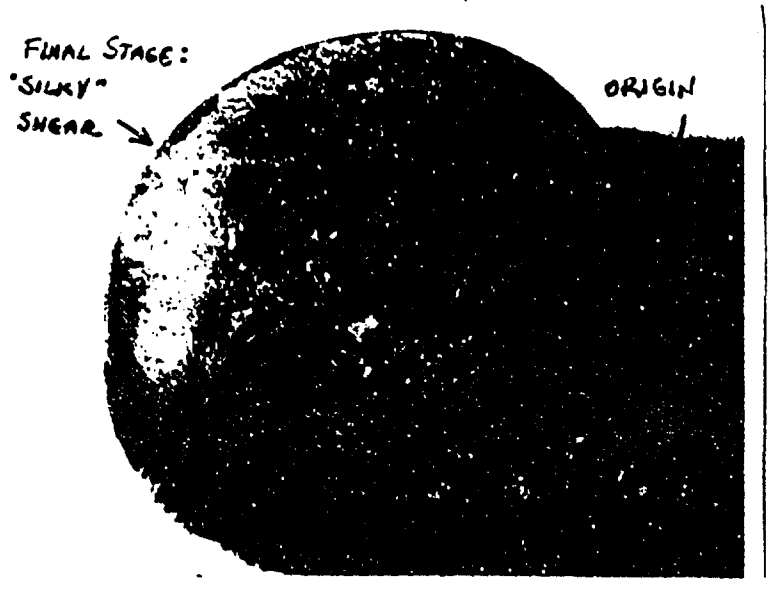

Figure 4. Fracture area examination of a failed part.

b. The appearance of fractures that result from failure due to impact or tension loads depends largely upon the structural condition of the material.

This again is associated with the solidification and heat treatment during manufacture. These fractures may vary from a coarse, crystalline type, reflecting inadequate heat treatment or poor toughness characteristics, to a fine silky appearance indicative of a hard brittle condition. In impact fractures, the degree of toughness and durability can be estimated by the appearance of fracture faces. The tougher the material, the more fibrous the appearance of the fracture; the less tough the material, the more crystalline the appearance.

c. If the failure is brittle or catastrophic, it can usually be traced to its origin by following the "chevron" or "herringbone" pattern characteristics as shown in Figure 5. The tip of the "V" points toward the source of the crack surface. By reassembling the shattered pieces in the manner of a jigsaw puzzle (without contact between fracture surfaces) and then noting the direction of fracture propagation, one can identify the point of failure origin. A careful examination can then be made in the vicinity of this point to determine cause of failure.

Figure 5. Chevron/herringbone pattern on brittle fracture surface resulting from catastrophic failure of gun tube. White lines indicate pattern, pointing to origin toward the right.

4.3 Microscopic Examination. A microscopic examination is much broader in scope than a macroscopic examination, and consequently, much additional information can be obtained by this type of examination. The microscopic examination of metals requires the use of special metallurgical microscopes because of the opacity of the metallic subjects. Metallographs are metallurgical microscopes with camera attachments capable of producing magnifications in the range of 25 to 2000X. Photographs of structures at high magnifications are called photomicrographs, and the structure itself is called a microstructure (see figs. 6, 7, 8, and 9).

Figure 6. Microstructure of gray cast iron - 100x; dark flake-like shapes are graphite.

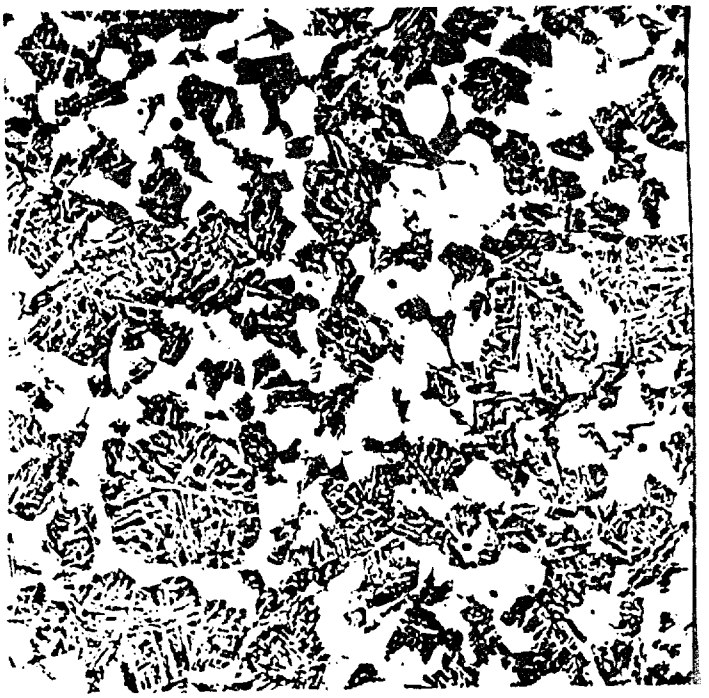

Figure 7. Microstructure of cast steel - 500x; dark areas are pearlite; light areas are ferrite.

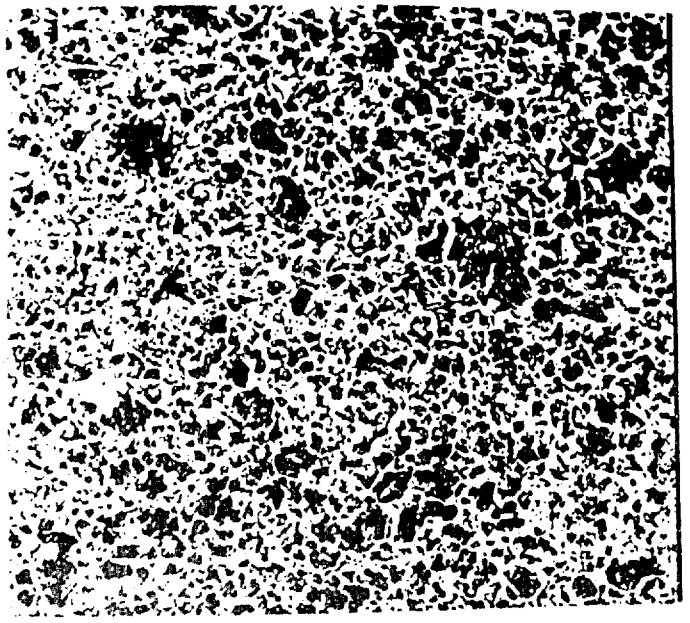

Figure 8. Microstructure of rolled SAE 1045 bar stock - 100x; dark areas are pearlite; light areas are ferrite.

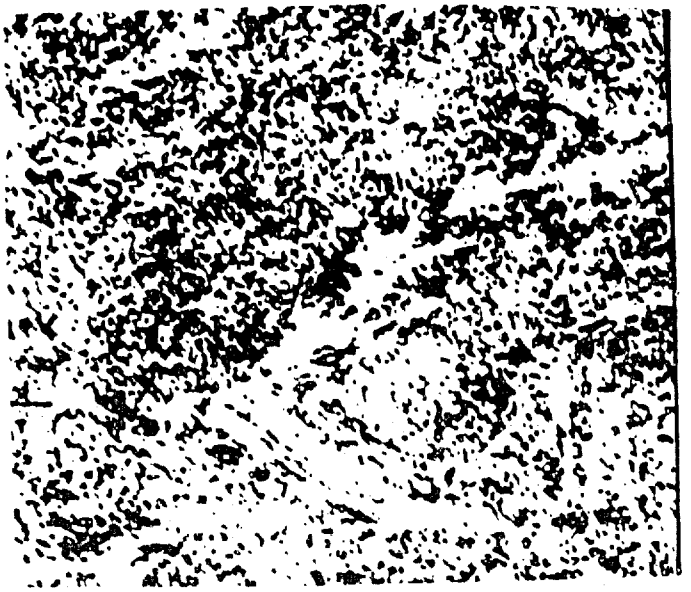

Figure 9. Microstructure of tempered Martensite in rolled armor plate - 100x; light areas are ferrite.

The importance of this type of examination lies in the fact that the microscopically visible characteristics of the material have a considerable influence on its mechanical properties. A metallurgist can determine by microscopic examination some of the mechanical properties, the manufacturing process, and more importantly, the thermal treatment that the material has received. In order to conduct microscopic examination, the material must be specially prepared.

a. A sample specimen representative of the parent metal in chemical composition and physical condition must be obtained. In a fracture examination, the specimen should be cut from the metal adjacent to the origin of failure in such a manner as to aid the examiner in determining the cause of failure.

b. The surface to be examined must be ground and polished to obtain a scratch-free surface area. Precautions are to be taken to preserve critical edges. Caution, cleanliness, and skill are required to produce good results in polished specimens for microscopic examination. The data obtained depend upon the quality of surface preparation.

c. Revelation of the microstructure is generally obtained by using etching reagents. The polished specimen is treated in one of several reagents to etch the constituents by chemical attack. The reagent must be selective and, by differential attack, must reveal differences in the constituents and the grain structures.

Correct observation and interpretation of the etched structures depend upon the ability of the examiner to interpret what is revealed. For this examination, employ a metallograph. This instrument has a lens assembly capable of magnifying and resolving fine detail such as the appearance of metallic formations. Grain structure in steel can reveal ferrite, pearlite, austenite, bainite, or other constituents, depending on the chemical composition and thermal treatment of the material. The examiner's interpretation of the characteristics and his knowledge of the properties imparted to the material by these structural forms enables him to determine the nature of the material and, in a failure, the possible cause.

In certain situations, even greater magnifications are useful. This capability is provided by the SEM which can magnify to 10,000X. The great depth of field of this instrument has made it particularly useful in examining rough fracture surfaces to determine whether the fracture mode was cleavage (brittle) or shear (ductile). The SEM is also useful in determining other modes of fracture such as transgranular cleavage, intergranular cleavage, and fatigue. This instrument provides the only method by which hydrogen embrittlement can be proven after the failure occurs. The SEM can also be used to accurately determine chemical analysis of small areas.

4.4 Mechanical Testing. The mechanical behavior of metals is characterized by relations between the stresses and strains imparted to the material under service conditions as well as in structural applications. A component subjected to external loads is strained or deformed, depending on the stress per unit area derived from the force. Stresses that exceed the elastic range of a material result in permanent deformation or rupture. To determine the causes of component failures, detailed knowledge of the fundamental properties of the material of the component is required. Standardized tests for obtaining specific information on

the mechanical properties are discussed in paragraphs 4.5 through 4.9. These tests are: tension, hardness, impact fracture toughness, and fatigue.

4.5 Tension Test. This is a procedure by which a suitable standard test specimen is fixed in a tensile test machine and is slowly pulled apart by measured loads. The information thus obtained describes the tensile properties of the material. These include the following:

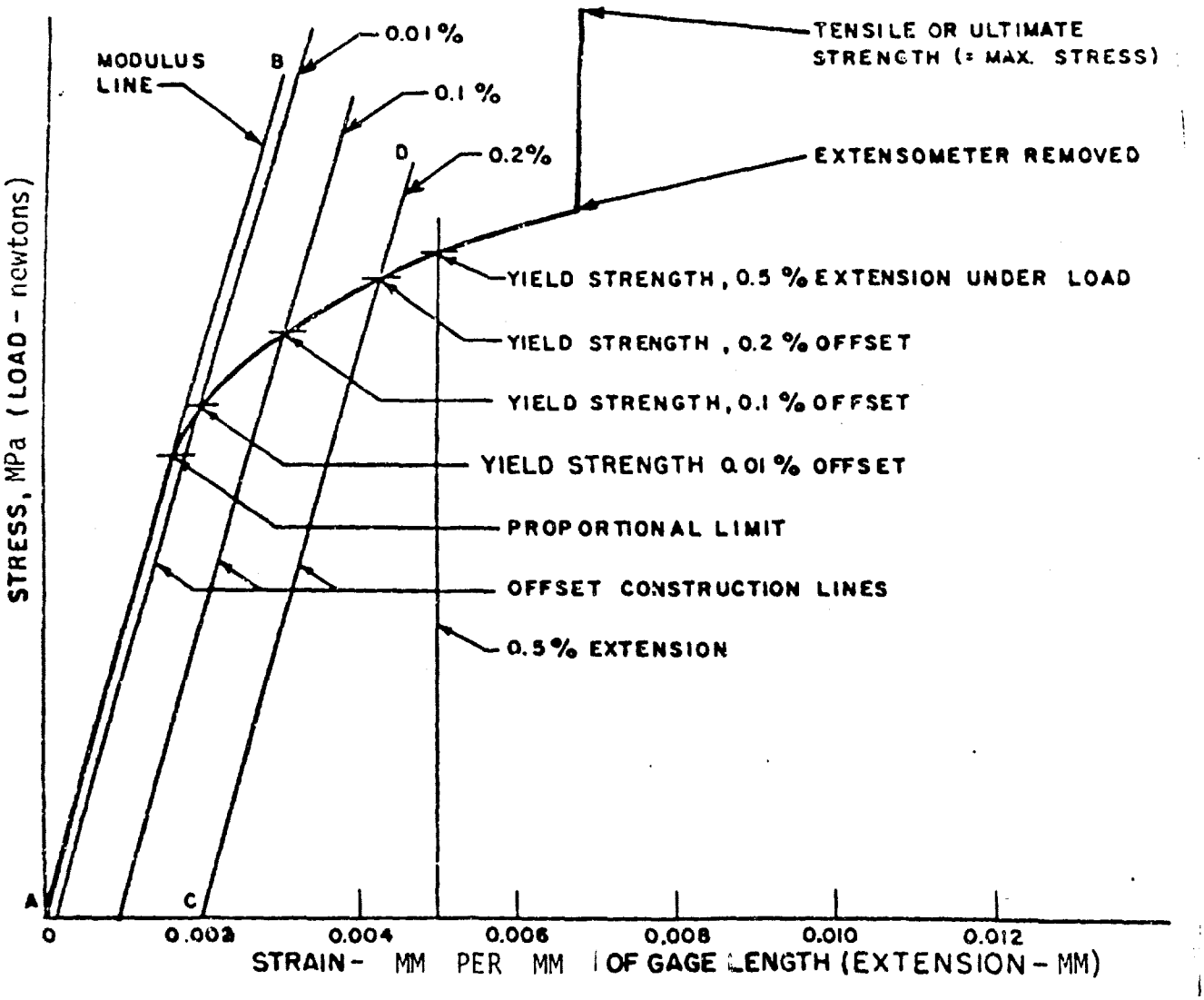

Figure 10. Stress-strain diagram with construction lines for determination of properties.

4.5.1 Tensile or Ultimate Strength. This is defined as the maximum stress that the material is capable of developing for a particular cross-sectional area. This stress in MPa is computed by dividing the load in newtons that was required to complete failure by the original cross-sectional area in square millimeters.

4.5.2 Proportional Limit. This is defined as the greatest stress a material is capable of developing without deviating from Hooke's Law (proportionality of stress to strain). This property can be determined through the use of an automatic recording test instrument to plot the stress developed per increment of

loading. While the specimen behaves in an elastic manner, the stress (MPa) is proportional to strain (i.e., Δ l/l or increased length beyond original length, or mm per mm); the plot will be a straight line. The slope of this line is defined as the modulus of elasticity of the material. At some load, the plotted line will begin to curve (stress is no longer proportional to strain) as permanent deformation begins to occur in the material. Beyond this point, the material is no longer in the elastic range. The proportional limit is determined from test results by finding the point of tangency of the curve and the straight line. The stress corresponding to this point is the proportional limit.

4.5.3 Yield Strength. This is the stress (load per square centimeter of original cross-sectional area) at which a material exhibits a specified permanent elongation. A test for determining this property must be adaptable to the properties of both hard and soft specimens. This can be accomplished by defining a specified amount of permanent elongation as the criterion for yield strength. Generally, 0.2% of the 50-mm gage length is specified as the strain offset. The specified strain offset is outlined on the stress-strain diagram parallel to the stress-strain plot in the proportional region. The intercept of this offset plot with the curved portion of the stress-strain curve defines the yield point (see fig. 10). The yield point in newtons is divided by the original cross-sectional area in square millimeters to give the yield strength in MPa.

4.5.4 Elongation and Reduction of Area. These are the amounts of deformation produced in a complete fracture of the specimen. They are a measure of the ductility of the material in tension. Measurements are based on the change in length and cross-sectional area. After the specimens are broken, the fractured parts are rejoined in a device that allows measurement of the extension of gage length and cross-sectional deformation. The values are then expressed as percentages of the original dimensions.

4.6 Hardness Test. Among mechanical testing devices, none is comparable in diversity to this test. The concept of hardness as a property of material dealing with resistance to penetration is easily understood, but no single measurement of hardness has yet been devised to be applicable to all materials. The fundamental concept of hardness as resistance to penetration is the principle on which a wide variety of testing machines operate. There are, however, other concepts of hardness if one can judge hardness by the methods employed to measure it. Hardness is measured by indentations, scratching, resilience, machinability, magnetic properties, and other related physical properties of the material. This TOP presents only the more common tests and their specific uses in the field of metallurgy.

4.6.1 Basic Applications. There are two fields in which hardness measurements are particularly important: in establishing standards and in maintaining product uniformity. In the first area, a determination can be made of the suitability of a material for a specific purpose. Once a suitable material whose behavior in actual service has been proven is found, its hardness rating can be used as a standard. Other pieces to be used for the same purpose can be accepted or rejected on the basis of a comparative hardness test. In the second area, a relatively simple check of hardness can serve as a control of the maintenance of uniformity of a product. For example, inspect the uniformity of some particular treatment such as a forming operation, a heat-treating cycle, or one of a series of various surface-hardening processes.

4.6.2 Rockwell Hardness Test.

a. Testing Machines. The most widely used hardness-measuring devices are the two Rockwell machines: normal and superficial. The normal tester is used to determine hardness of materials when the test specimens have sufficient cross-sectional area to withstand the heavy loads applied by the indenting device. The superficial tester is used primarily to determine hardness at the surface of a material without respect to the hardness of the "core" beneath the surface. The superficial tester can be used for surveying an area for surface softness due to decarburization or for determining hardness of a carburized or nitrided surface layer in a thin case.

b. Method. The two types of machines are similar in operating principle. A minor load is applied to the material by the appropriate indenting device. A major load is then applied by the same device at the same location, and the difference in depth of penetration is determined. The hardness is an inverse function of this difference. Both types of Rockwell indentations are quite small; tested items are normally still usable after the test is completed. Portable machines are available for use in Rockwell hardness determinations when the item to be tested is unsuitable for laboratory handling. In using the Rockwell test, apply different loads to the penetrator, depending on the hardness of the metal. This leads to the use of different scales designated by letters such as A, B, or C for the normal tester. Stainless steel, for example, may have a hardness of Rockwell B 80.

4.6.3 Brinell Hardness Test. The tester used in this method consists of a hand-operated or motor-driven vertical hydraulic press that forces a hardened steel or carbide ball into a test specimen. Measure the diameter of the impression, and read the hardness value from conversion tables. The standard tester can be used for both ferrous and nonferrous materials. The usefulness of this test is limited by the size of the specimen to be tested. Thin sections of material can give erroneous readings because of the effect of underlying material of the support plate. For large items, however, the Brinell hardness test is advantageous because small surface irregularities do not have much effect on the penetration of the relatively large ball. Brinell hardnesses are usually used for armor plate which is characteristically thick and not subject to damage by such a test.

4.6.4 Knoop Hardness Test.

a. Procedure for using tester. The Knoop hardness tester is one of several types of microhardness testing instruments in which the indentations are so minute that a microscope is required to measure the impression. The instrument is designed with a "Knoop" pyramid-type indenter capable of carrying loads of 10 to 3,600 grams. The test material is clamped onto the mechanical stage, an area of a few thousandths of a square millimeter, accurately located under the indenter, and the indentation is made. The specimen is then placed under the microscope. The length of the long diagonal of the diamond-shaped indentation is measured through the calibrated eyepiece of the microscope. Using this value, the "Knoop" hardness number can be calculated. This hardness number can be converted to comparable Rockwell or Brinell values with the standardized conversion charts.

b. Applications and limitations. The Knoop hardness tester is particularly adaptable to measuring the hardness of small precision parts such as

watch gears, hairsprings, and hypodermic needles; of superficially hardened surfaces such as carburized, cyanided, induction hardened, and nitrided steels, and of electroplated deposits; of thin sheet metal and small diameters such as bimetallic strips and fine heat-treated or galvanized wire; and of various components of microstructure. Readings can be obtained not only on ferrous and nonferrous materials, but also on nonmetallic materials such as porcelain, glass, plastics, ceramics, and minerals. Two limitations in using this test are that the surface on which the readings are taken must be highly polished and the specimen must be small enough to be rigidly clamped on the mechanical stage.

4.6.5 Scleroscope Hardness Test. This tester is mainly used as a portable hardness tester for shop inspection. A diamond-tipped hammer encased in a glass tube is dropped from a fixed height onto the specimen. The distance that the hammer rebounds from the test specimen is a measure of the hardness of the material (the harder the material, the higher the rebound). The height of the rebound is read on a graduated scale. Readings can be taken visually or mechanically through the use of an indicator. Correct operation of the scleroscope requires close contact between the glass tube and the test specimen which should be flat, smooth, and free from any dirt. The instrument is extremely useful because of its ability to determine the hardness of all metals from the softest to the hardest without any changes in the setup. The scleroscope also provides the convenience of the superficial hardness tester. It can be used to determine the hardness of specimens as thin as 0.006 in.

4.6.6 Vickers Hardness Test. This test is similar to the Knoop test. The tester employs a square-based diamond pyramid penetrator that can be selectively loaded with dead weights. The indentation made in the test specimen by this penetrator is measured with the aid of a microscope. The Vickers hardness number is then read from the appropriate table. The limitations to the use of the Vickers hardness test are related to surface conditions and size of the test specimen. A smooth, level surface without scratches, scale, or other surface discontinuities is required in order to see the indentation. The specimen must be limited to a size compatible with the anvil supporting the specimen during test.

4.7 Impact Tests. The most commonly used type of impact test is the notched bar test. Tests of this type are used to evaluate the "fracture toughness" of a material or its ability to absorb energy before fracture in the presence of a notch and a rapid rate of loading. The test is usually conducted at low temperatures because these represent the most severe conditions for toughness. The impact test indicates the metal's toughness. Great differences are found in the amounts of energy absorbed before rupture for materials of different structures even though these materials exhibit similar static tensile properties. Some materials show a complete reversal from ductile to brittle behavior when conditioned to low temperature. The notched bar tests cannot be used exclusively to predict the actual service behavior of a material under impact loads. The importance of the test lies in the fact that it can provide a method of ranking materials according to susceptibility to brittle fracture.

The following are some of the causes of the energy variations exhibited by materials in a notched bar impact test: heat-treatment deficiencies, chemical composition, interrupted quenching, and incomplete quenching through the cross section in thicker materials. Although the latter two deficiencies can also be detected microscopically, the notched bar impact test is the most convenient

method for identifying brittleness in steel. Impact tests also have the advantage of providing a quantitative measure.

Steels have a tendency toward brittle behavior which varies from steel to steel. To determine the extent to which a specific material exhibits this tendency, it is often necessary to conduct the impact tests at various temperatures down through at least -40° C (-40° F). The energy transition temperature is the temperature at which a sudden drop occurs in the energy required to fracture the material. For many heat-treated steels, however, there is no clearly defined transition point; rather, a steady decline in energy values occurs as the temperature is decreased. Two other criteria have been used to describe the loss of impact strength with decreasing temperature: percent fibrosity (estimated by visually inspecting the broken specimen) versus temperature, and second, lateral expansion (measured at the surface opposite the notch) versus temperature.

To conduct a notched bar test, test standards have been developed in which a specimen containing a machined notch is fractured by a blow received in a single impact. The standard tests are the Charpy and Izod V-notch tests, with the latter seldom being used except in England. Both tests are conducted in impact machines designed to deliver a blow through the use of a pendulum which is allowed to swing from a known angle, hit the specimen at the low point of its swing, and rise in the remainder of its swing to a lesser height. The energy absorbed by the specimen is calculated in joules from the angle to which the pendulum rises after rupture. The two tests are quite similar; the main difference is the manner in which the specimen is broken. In the Charpy test, the specimen is broken by transverse bending. In the Izod test, it is broken by cantilever action. The Charpy test is especially useful for low-temperature tests because the specimen can be placed in the machine quickly with little temperature loss. Specifications for gun barrels and steel armor always specify a certain minimum Charpy value (in joules) at -40° C for material of a certain thickness and hardness.

In the Charpy V-notch impact test, the test specimen is a bar, 10 mm square in cross section, with a 2-mm-deep 45° V-notch with a 0.25-mm root radius machined in the center of the bar. In the test machine, the specimen rests against rigid supports as a simple beam with the notch centered and opposite the side receiving the striking hammer. The specimen is then broken by transverse bending, with the notch acting as the crack starter. In low temperature tests, the Charpy V-notch specimen becomes quite adaptable because it can be placed in the machine quickly with no temperature loss. An alternate type of notch used in the same manner is a keyhole notch. This is obtained by drilling a 2-mm hole through the center of the specimen and cutting through to it from one side. The specimen is then tested the same as in the V-notch test.

4.8 Fracture Toughness Test. Fracture toughness, K_{IC}, is a measure of the ability of a material to arrest a crack that could cause sudden failure below its yield strength. There is a critical crack depth for each material and a system of operating stresses at which unstable crack growth occurs and catastrophic failure results. K_{IC} usually decreases as the strength of a material increases because of accompanying brittleness.

If the K_{IC} value of the material and the stress at which a structure will operate are known, the critical crack depth can be determined. To avoid catastrophic failure, nondestructive techniques of measuring crack depths (e.g., ultrasonics,

X-ray, eddy currents, magnetic recording, borescope) can be used to monitor the cracks. When the critical crack depth is approached, the item should be removed from service to avoid sudden failure. K_{IC} values and critical crack depths were found for two category II 175-mm gun tubes by a study described in reference 3 of Appendix B. In this case, critical crack depth criteria for the gun tubes were obtained so that the tube inspectors could make sound decisions on serviceability. The pertinent results are presented in Table 2.

TABLE 2. MECHANICAL PROPERTIES COMPARISON DATA

Gun Tube	A	B
Tensile strength, psi	200,000	208,000
Yield strength, psi	180,000	188,000
Charpy V, ft-lb at -40° F.	10	10
K_{IC}, psi in.	103,340	99,290
Critical crack depth, in.		
Zone 3, 145° F., 58,000 psi	0.805	0.744
Zone 3, 75° F., 48,000 psi	1.084	1.000

The effective toughness of a material is not expected to be less than its K_{IC} level under any practical conditions. It has been established that the K_{IC} levels of a number of structural materials are essentially independent of specimen design and dimensions when the specifications for valid K_{IC} testing are met. It was necessary to develop specifications for valid K_{IC} testing since real materials do not deform in the elastic brittle manner assumed in linear elastic fracture mechanics. When a sufficiently large crack-notched specimen is tested, however, the behavior is sufficiently close to elastic brittle because the crack tip plastic region remains small relative to the significant specimen dimensions.

The fracture toughness method can serve the following purposes:

a. In research and development, to establish the effects of metallurgical variables (such as composition or heat treatment) or of fabricating operations (such as welding or forming) on the fracture toughness of new or existing materials.

b. In service evaluation, to establish the suitability of a material for a specific application for which the stress conditions are prescribed and for which maximum flaw sizes can be established with confidence.

c. For information and for specifications of acceptance and manufacturing quality control when there is a sound basis for specifying minimum plane strain fracture values.

The method for conducting the test involves tension or three-point bending of notched specimens that have been pre-cracked in fatigue. Load versus displacement across the notch at the specimen edge is recorded autographically. The load corresponding to a 2% increment of crack extension is established by a specified deviation from the linear portion of the record. The K_{IC} value is calculated from this load by equations established on the basis of elastic stress analysis. The validity of the K_{IC} value obtained by this method depends on establishing a "sharp crack" condition at the tip of the fatigue crack in a specimen of adequate

size. For more detail on the test method pertaining to fracture toughness, see references 4 and 8.

4.9 Fatigue Tests. This consists of applying repeated loads of the same magnitude to a specimen or component. In tests involving the use of a standardized specimen removed from the material being investigated, several test items are subjected to cycles of the stress being studied. The stress is varied to enable the examiner to study the behavior or the material at different stress levels. By plotting the number of cycles to failure against the various stress levels, an "S-N" curve is obtained (see fig. 11). From this curve, the endurance life of the material being tested can be predicted. In fatigue testing complete components, actual service conditions are simulated. The expected stress levels are introduced to the specimen in repeated cycles until failure. The number of cycles to failure is a measure of the endurance of the component.

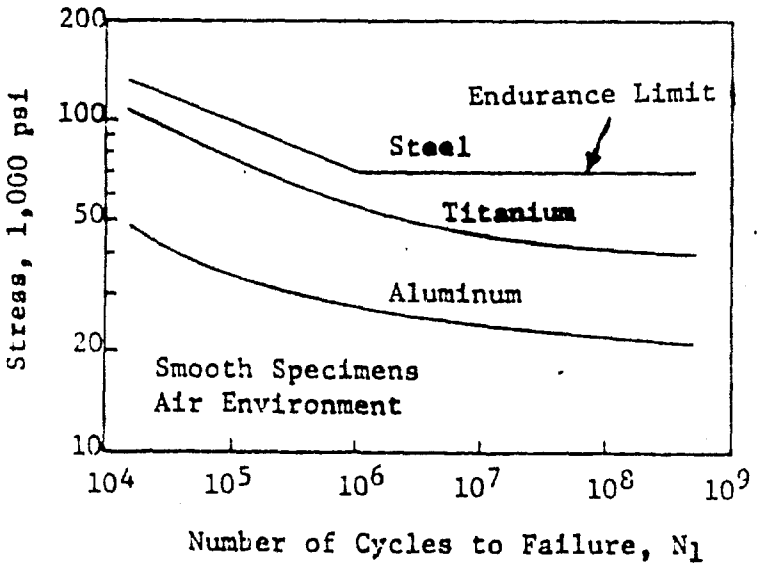

Figure 11. Typical S-N fatigue curves for several high-strength alloys.

Several types of test units available employ one of two major principles of cyclic load application: that of stress to the surface of the material as a bend, torsion, or impact test, and that of stress to the entire cross section of the material for tension and compression tests.

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APPENDIX A

METALLURGICAL TECHNIQUES FOR ANALYZING PROJECTILE PREMATURES

Occasionally during the course of testing ammunition and weapons, a high-explosive projectile detonates before emerging from the gun tube. Such an in-bore premature usually destroys the weapon. Clues must be examined to determine the reason for the premature functioning so that corrective action can be taken. Sometimes the premature is related to the weapon; at other times, it is related to some component of the round. In any event, it is necessary to try to determine the exact location in the gun tube at which the detonation occurred, whether it began at the base or the nose of the projectile, and whether the projectile detonated low or high order.

1. Steps in Examining Results of an In-bore Projectile Premature. The following steps are taken to analyze an in-bore premature:

a. Determine all pertinent firing conditions and data such as temperatures of tube and projectile, chamber pressure, readings from any strain gages, and high-speed photographic results. Record any deviations from normal procedures or observations. Examine all nondestructive test data for both tube and projectile.

b. Examine tube and projectile fragments. Reassemble both as completely as possible. An intact or sectional projectile placed alongside the assembly area is often useful in reconstructing the fragments and matching signature marks with parts of the projectile.

c. Trace chevron/herringbone patterns on fracture surfaces to the point of origin by moving in the direction to which the pattern points. This helps determine whether the tube or the ammunition caused the failure.

d. Look for the burnished circumferential area that locates the rotating band. Once the probable location of the projectile has been established, other bore signature markings can usually be matched to confirm the location, e.g.:

(1) The nose fragment ring of varying size, locates the ogive of a projectile.

(2) Smears of copper (from the shaped charge liner that forms a jet) on portions of the steel barrel are usually apparent down-bore from a HEAT projectile, and aluminum smears are left by fuze parts in most projectiles.

e. Observe the fracture mode in the detonation area. Heavy shear is usually prevalent, but the presence of a fracture in the brittle mode indicates a lower order of projectile functioning.

f. Note fragment size, both tube and projectile. Smaller sizes indicate higher orders. The symmetry of the fracture pattern should be noted. A central initiation (such as from the fuze) will cause a symmetrical pattern. For HEAT rounds, a symmetrical nose ring indicates jet formation and thus may indicate fuze action.

g. Observe any spalling of the tube, indicative of high-order functioning.

h. Examine tube fragments from the detonation area for evidence of transfer of toolmarks from the outside surface of the projectile and for land flattening which indicates high-order functioning.

i. Examine projectile fragments for rifling engraving; higher orders of functioning cause more extensive engraving. Examine the inside surface of projectile fragments for pitting caused by "jetting" of HE during high-order detonation.

j. Examine all fracture surfaces for evidence of previous fatigue cracks. Such a crack may be evidenced by a stained or discolored surface or a mismatched mode (fatigue beachmarks or a flat radial crack surface with chevrons radiating outward). Such evidence, especially when accompanied by a nonsymmetrical breakup in a tube, may indicate a premature due to initial failure of the tube.

k. Mount microspecimens of tube from the detonation area and from a place far away from the detonation area for comparison of structure. Martensite streaks caused by adiabatic shear indicate intense shear loading but cannot be used to differentiate between high and low order detonations since they have been observed for both conditions. The presence of an unusually large quantity of microvoids or microcracks is considered evidence of shock loading from a high order detonation. A "transformed" severely altered surface layer on both tube and shell fragments is another unique feature for weapon failures that occurs for both high and low order functions. Such a layer observed in cracks leading to a gas-washed surface is <u>not</u> evidence of a previous fatigue crack.

l. Conduct microhardness surveys of tube fragments from both the detonation and nondetonation zones. High order functions cause an increase in Rockwell C hardness of four points or more in detonation area fragments. Low order events cause a lesser increase. Similar hardness surveys of projectile fragments should be compared with values from an undetonated projectile. If a sufficient fit of these fragments can be made to determine nose and base directions, longitudinal surveys should be made. Some investigators have reported a change in longitudinal hardness values as an indicator of propagation direction. The usual lack of baseline data from undetonated projectiles has prevented confirmation of this finding.

m. It may be advisable to run chemical and mechanical specification checks on the material from both tube and projectile (in the case of an exploded projectile, mechanical property specification checks may not be possible, however). In any type metallurgical failure analysis, it is customary to check these properties. While results are usually negative, it is often necessary to prove that the materials meet specifications.

2. <u>Analysis and Presentation of Results</u>. All of the data are assembled and analyzed to develop a best deduction of the cause and location of the premature. If necessary to corroborate the conclusions, a firing is conducted with a similar projectile and weapon tube, and appropriate modifications made to induce a premature in accordance with the conclusions. The occurrence of a similar breakup of tube and projectile, together with similar metallurgical results, would constitute corroboration of the deduced failure analysis.

Computer calculations with numerical codes such as HEMP2D and HEMP3D are an additional tool for analyzing an in-bore. The value of the codes is presently

limited to describing the deformation but not the fragmentation part of the failure. In low-order prematures accompanied by minimal destruction of the gun, the pattern of deformation of the tube can be analyzed to reveal the origin of the explosion in the HE filler. Calculations with the codes can be used to better define the effect of various parameters when contemplating an in-bore simulation test, or in some cases, eliminate their need.

The summarized results of the premature analysis should include:

a. Factual:

Caliber of weapon and projectile
Nomenclature of tube, projectile, and fuze
Type round (HE, HEP, HEAT)
Type explosive
Propellant charge and zone when applicable
Temperatures of weapon and projectile
Past history of projectile and tube (e.g., newly developed)
Mechanical and chemical properties of projectile and tube as compared with specifications
Photographs of assembled fragments
Photographs of damaged weapon
Photographs of chevron patterns, etc.
Photomicrographs as appropriate
Fractograph sketches showing fragments and arrows indicating direction of origin of fracture

b. Deduced:

Exact location of projectile at time of detonation
Order of function
Where detonation began (i.e., at base or nose of projectile)
Description of event
Known or probable cause

APPENDIX B

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