NRL REPORT 4034

USE AND INTERPRETATION OF THE NRL EXPLOSION BULGE TEST

W. S. Pellini

Metal Processing Branch
Metallurgy Division

September 4, 1952

NAVAL RESEARCH LABORATORY

WASHINGTON, D.C.

ABSTRACT

A method has been developed for the investigation of structural performance of weldments on a model scale. The method entails bulging plates in diaphragm fashion by means of explosion gas pressure. Two types of tests are performed by means of this method; (1) Tests of plates which contain a synthetic cleavage crack, aimed at determining the brittle fracture characteristics of the base plates; (2) Tests of weldments, aimed at determining the relative resistance to the initiation of failure and the possible development of brittle fractures in either the weld or the heat-affected-zone. Extensive series of tests of the two types have been performed for mild steel and armor materials used in the fabrication of merchant and combattant vessels. The factors which determine the proper service performance, or failures, of such weldments have been established and integrated into a generalized design theory. Details of the use of the test method and of the significance of the findings are presented in simplified form for general information.

PROBLEM STATUS

This is an interim report on the problem; work is continuing.

AUTHORIZATION

NRL Problem M03-16
RDB Projects NR 443-160 and NS 021-200

Manuscript submitted July 24, 1952

CONTENTS

UNCLASSIFIED

USE AND INTERPRETATION OF THE NRL EXPLOSION BULGE TEST

INTRODUCTION

This report is aimed at summarizing the principal features of the development and application of the explosion bulge test method which represents a procedure of testing rather than a "test." The method is designed for the investigation of structural performance on a model scale. By proper size and geometry adjustment of the bulge it is possible to reproduce the features of combined loads which are characteristic of complex structures. The nature and extent of deformation which precedes fracture as well as fracture characteristics may be investigated under conditions of controlled loading. The primary feature of the method lies in the use of full-thickness plate and conventional full-size welds.

The bulge feature of the test represents a practical solution to the problem of developing controlled stress and strain conditions in a model structure of the simplest possible initial geometry. The model structure, represented by a plate, is loaded in simple fashion by the application of uniform pressure while supported by a die of appropriate geometry. The applied uniform gas pressure, developed by explosion, clamps the plate to the die support and produces controlled deformation over the unsupported region. Figure 1 illustrates the simple equipment which is required for bulge tests. Dimensional details of the dies and associated equipment are described in the Appendix to this discussion.

Bulging produces a biaxial stress condition (Figure 2) the balance of which depends on the geometry of the bulge. A circular die produces bulges involving balanced biaxial loading while elliptical dies produce bulges involving unbalanced biaxial loading. Thus, combined loads which could be obtained only with great practical difficulty by multiple, directional loading are obtained indirectly by means of the expedient of applying a uniform pressure.

The feature of uniform biaxial loading is of basic significance to bulge tests inasmuch as a means is provided to load weldments in such a fashion that all regions are subjected to the same load condition, balanced or unbalanced as is desired. For example, all directions of the weld, heat affected zone (HAZ), and base plate may thus be loaded in exactly the same manner by means of the circular bulge. The critical element of the weldment which provides the site of initial failure may thus be determined and the resultant path of fracture observed. Preferential loading in either the weld-transverse or weld-longitudinal direction may be developed by the use of elliptical bulges (Figure 3). The use of bulges of fixed geometry permits control of the loading conditions and an accurate determination of the strain and stress systems developed during the test.

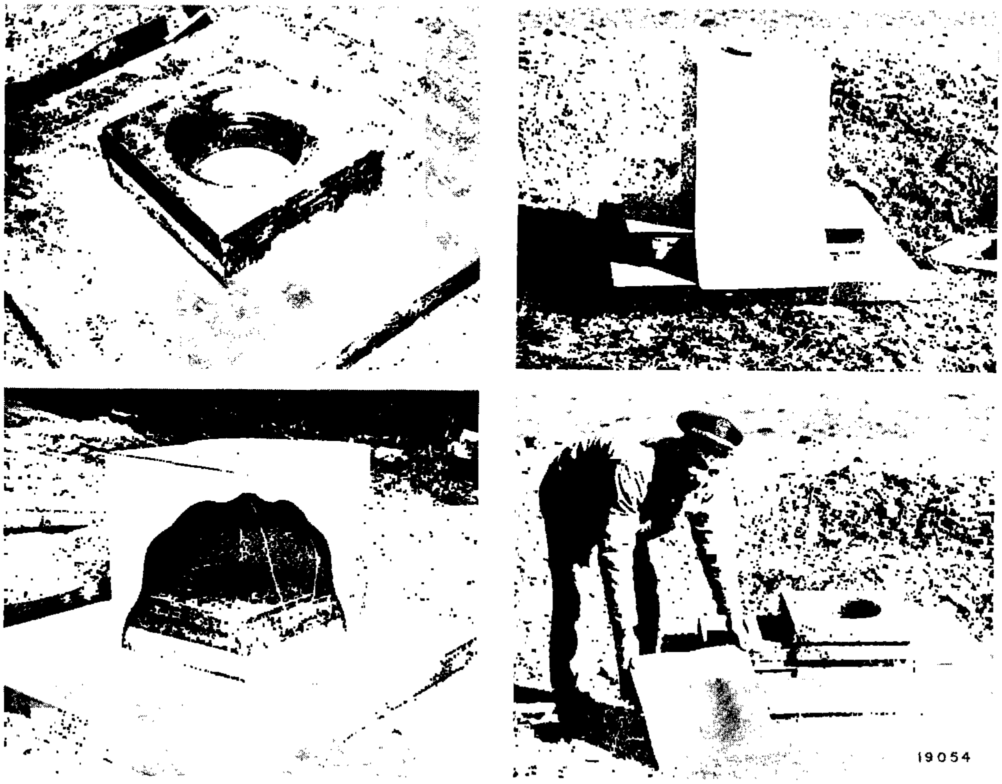


Figure 1 - Explosion bulge test equipment

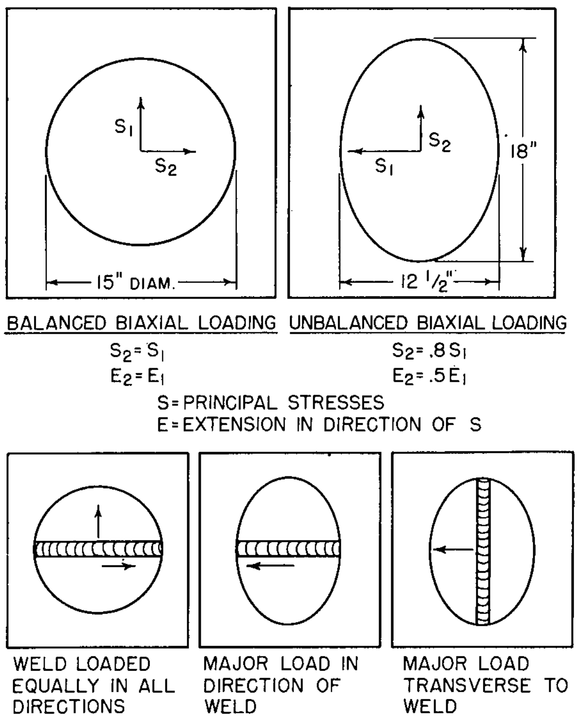


Figure 2 - Loading and deformation characteristics of circular and elliptical bulges

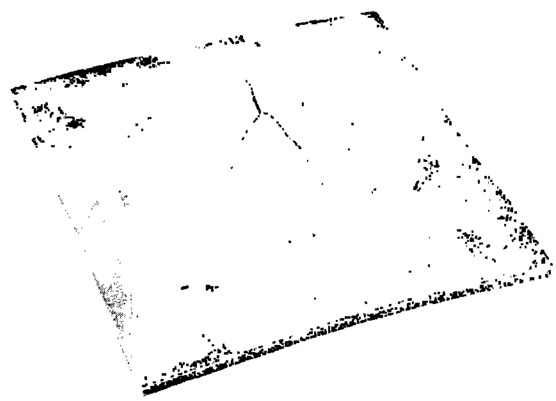


Figure 3 - Fracture of elliptical bulge (major load transverse to E6010 butt weld of 3/4-inch-mild steel plate)

Photogrids applied to the surface of the test plate (Figure 4) are used to determine the strain system from which the stress system is then calculated by means of appropriate formulae. Strain studies are particularly important for research investigations requiring exact knowledge of weld deformations. It has been demonstrated that the stress and strain states imposed by the loading conditions of the bulge are not accepted as such by the weld joint (1). Depending on the relative flow strength characteristics of the plate and weld and the nature of the weld reinforcement, a system of stress and strain foreign to the remainder of the plate may be developed in the weld and near-weld regions. This behavior is general to all weldments and must be understood to properly interpret the fracture direction of various weld-plate combinations.* Sufficient information is now available (Figure 5) to permit qualitative, prior evaluation of the deformation of specific weld-plate combinations, hence, strain studies are not required for conventional test-use of bulge methods.

The use of explosives is considered primarily as a means of obtaining the high forces required to develop bulges in thick plate—with this view point the explosive is used in a simple fashion, i.e., not as a variable but as a fixed condition of the test. The use of explosives as a variable compounds the difficulty of interpreting the already complex picture of weld performance. In keeping with the aim of simplest possible use of explosive it was deemed essential that a fixed charge be used and that it be offset from the test piece. The following considerations may be cited:

(1) Offset is required to provide uniform loading of the test piece which is necessary to develop true bulges of controlled geometry, hence of controlled loading.

(2) By means of offset the pressure is distributed evenly over the entire unsupported test area; a large bulge is developed providing a region, defined as "pole," which is essentially in uniform strain (Figure 6). The bulge size is adjusted to provide a pole area sufficient to enclose weld, HAZ, and an equal width of base plate. Smaller bulges produce a steep, radial strain gradient with the plate at a considerably lower strain level than the weld and HAZ.

* For example, the transverse weld failure shown in Figure 4 is predicted by deformation studies. This prediction follows from the fact that the major-stress - major-strain direction in overmatching welds lies in the direction of the weld. See Reference (2) for a discussion of the conditions which determine fracture direction.

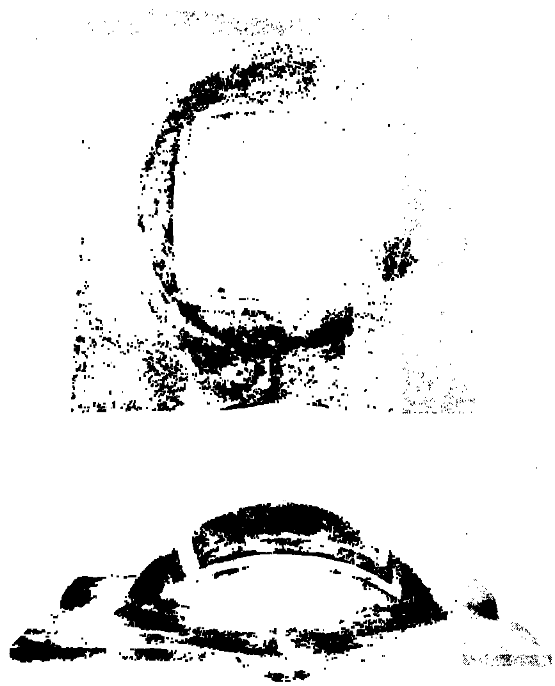


Figure 4 - Circular bulges illustrating the use of photogrid for deformation studies (15-inch diameter bulge of 3/4-inch plate)

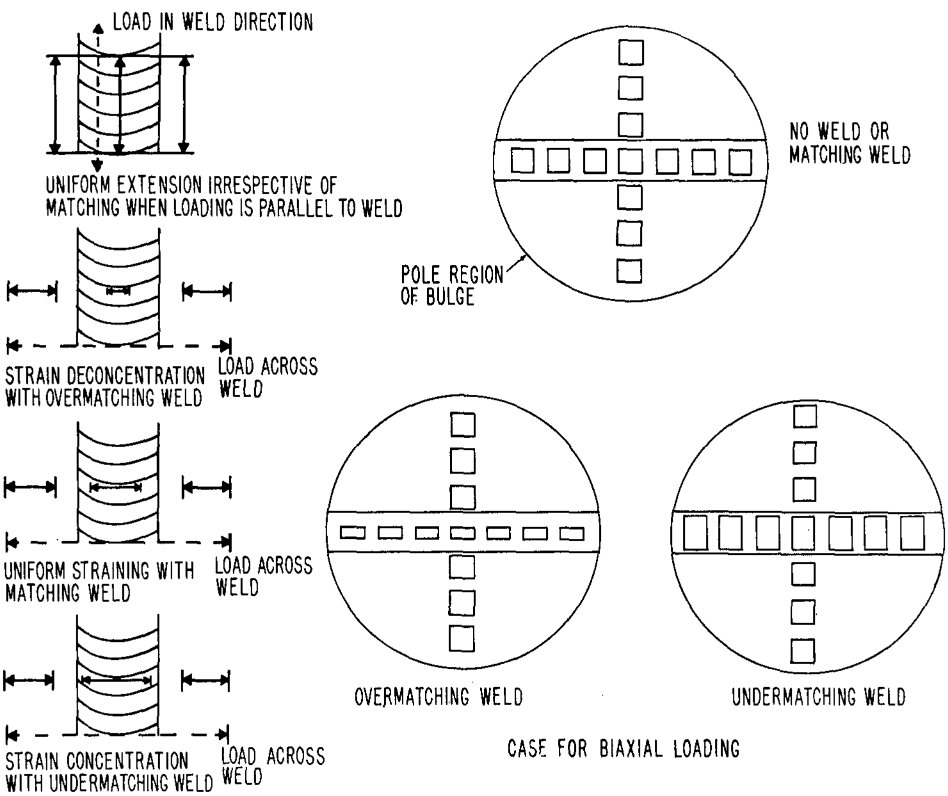


Figure 5 - Effect of matching (relative flow strength of weld compared to plate) in parallel and transverse loading of weld

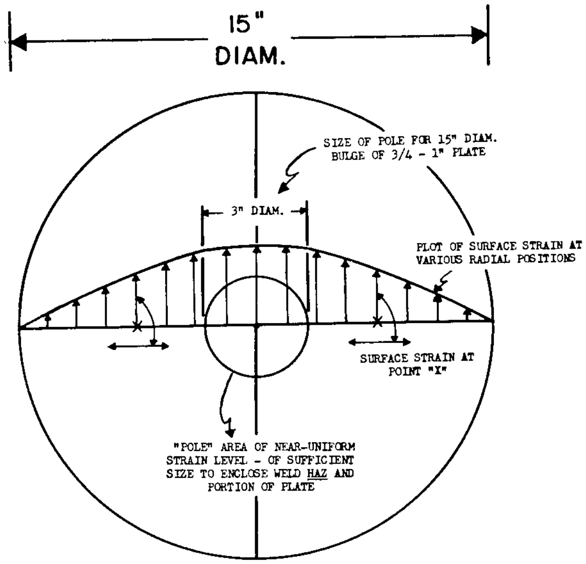


Figure 6 - Pole concept

(3) By the use of offset the "slap effects" (brisance) of explosion which are difficult to control with standard explosives are minimized. With offset only the gas pressure phase of the explosion which is inherently reproducible with standard explosives is utilized.

In keeping with the engineering approach of controlling loading conditions it was deemed desirable that the performance of the test plate or weldment be expressed in conventional engineering terms. The deformation level required to develop failure provides a convenient means of denoting performance.* This approach eliminates the difficulty of interpretation as to the engineering significance of a performance index based on weight of explosive. Furthermore, the use of a terminal ductility index eliminates the need of varying the weight of the explosive and permits the further simplification of using a fixed charge with a repetition of shots to develop the level of deformation required to produce failure. It is apparent that the choice of a deformation index relegates considerations of explosive weight, etc., to minor importance.

The general method of establishing offset conditions is based on the premise that the energy release should be such as to develop the bulge in moderate increments varying in the range of $\frac{1}{2}$ to 1 inch of bulge per shot (Figure 7). The use of moderate strain increments serves to (a) decreased the tendency towards adiabatic heating of the test piece due to the deformation and (b) prevent excessive tearing apart of the bulge on fracture, thus permitting a finer distinction in the relative cracking tendencies of the various regions of the weldment. The offset used depends on the tensile strength level of the test material and its thickness; the following offset distances which have been used in various investigations illustrate the method:

* It should be noted that such a single index defines performance only in terms of the energy required to develop rupture. Additional data relative to the nature of the rupture are needed to fully describe the performance characteristics of a weldment. This subject is discussed in detail in later sections. The discussion at this point is limited to the relative advisability of denoting energy absorption by a deformation term as compared to an explosive weight term.

Material	Thickness (inches)	T. S. (psi)	Offset of Pentolite Wafer (inches)
Steel	3/4	60,000	15 (4-lb charge)
Steel	5/8	125,000	15 (4-lb charge)
Steel	1	125,000	15 (8-lb charge)
Aluminum	3/4	60,000	36 (4-lb charge)

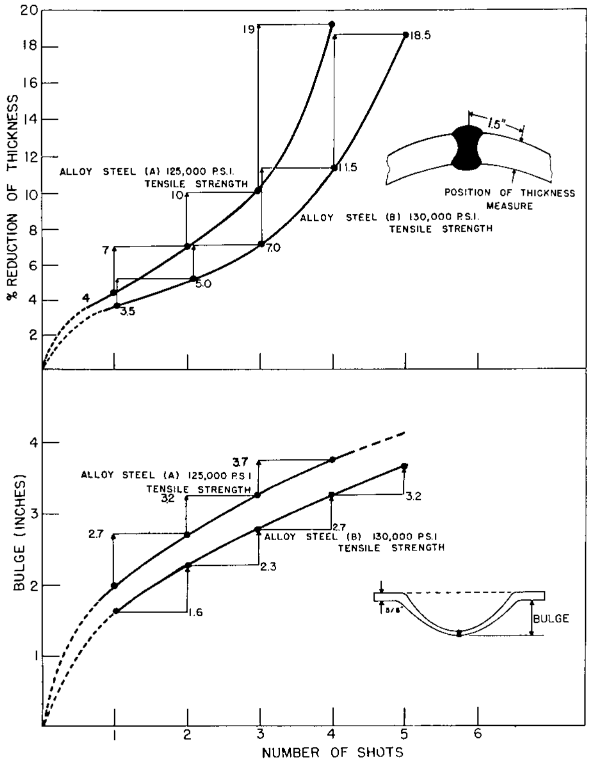


Figure 7 - Relation of number of 4-lb Pentolite shots to thickness reduction (top) and to resulting bulge (bottom)

Temperature control is easily achieved by soaking the test piece in a refrigerated or heated cabinet, removing as required and placing over the die for the test. The cardboard box used to establish the offset is then positioned, the explosive is placed and the detonating cap is inserted. The total time elapsed from the time of removal from the box to the time of firing averages 1½ to 2 minutes. Checks have shown that the temperature rise during this time interval is approximately 10°F at -100°F and 5°F at -40°F; compensation may be made by undercooling the test piece sufficiently to correct for the described temperature rise. After each shot the plate is returned to the cabinet and soaked for a minimum time of 1½ hours to ensure renewed temperature equalization.

The level of bulge deformation (measured as surface strain, thickness reduction or bulge depth) developed at the various shot levels prior to fracture is highly reproducible on repeat tests. The reliability of the explosion loading technique has been demonstrated repeatedly; Figure 8 provides an example. The level of strain at fracture varies, particularly in a fracture transition range, in a fashion similar to the scatter of Charpy specimens. This variance is the result of the normal variability of the test materials and is not related

to the use of explosives. The scatter of strain at fracture depends on the type of material tested, being least for rolled plates, intermediate for weldments and severe for certain castings.

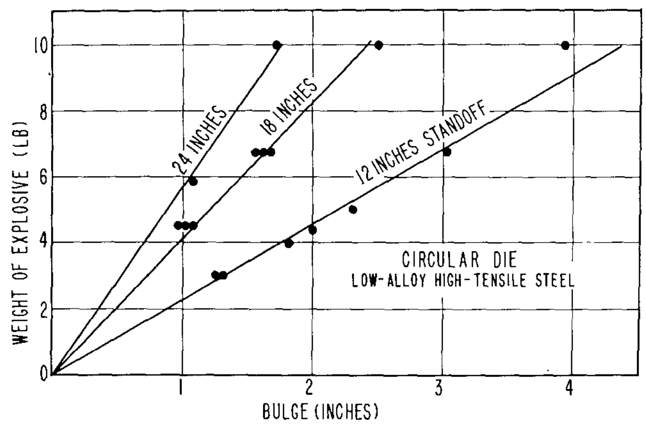


Figure 8 - Control of bulge deformation by varying weight of explosive and standoff distance

PHILOSOPHY OF THE BULGE TEST APPROACH TO PERFORMANCE EVALUATION OF WELDMENTS

The primary aspect of the bulge-test approach lies in the acceptance of the fact that the performance of weldments cannot be represented as a single parameter. The factors of resistance to deformation, deformation limits and fracturing characteristics of weldments have individual significance to engineering evaluation of performance.

Conventional design theory affords adequate guidance for design of structures which do not feature discontinuities of metallurgical and mechanical properties. If the metal part is homogeneous the presence of corners, etc., may be designed for by the allowance for stress concentration factors. Welding results in the introduction of zones of distinctly different properties from the base material. In general these zones are considered points of impairment of the mechanical properties of the base material—moreover, a high probability exists that flaws of various types may be present in the impaired zones.

Any test of weldment performance should be based on obtaining information which will permit engineering design with a reasonable assurance that the properties of the weld region are adequate for the service intended. Various factors enter into the making of such an evaluation including the following:

(1) Nature of the performance of the weld zone when located at points of triaxial stress such as sharp corners or in the presence of severe flaws. Is the weld zone capable of deforming in preference to cracking when deformation is forced into these regions?

(2) Nature of fracture which follows the development of initial failure. Is the result a brittle crack which may be propagated to the collapse of the structure or short shear tears of minor consequence?

The requirements obviously vary with the design and use of the structure—highly complex structures used in critical service require higher level performance than simple and noncritical structures. Likewise, the requirements for service entailing essentially elastic loading are considerably less demanding than for military service entailing resistance to extensive deformation such as results from explosions against ship hulls.

Testing of highly complex weldments can only be accomplished on prototype scale. Such tests, for example, are conducted on full- or reduced-scale ship hull structures. The expense of such investigations is prohibitive for extensive development or evaluation. The bulge test is aimed at obtaining information of significance to the case of complex weldments by a process of interpretation of the significant aspects of performance observed on simple weldments. A simple butt weld is used so as to permit inexpensive testing of a great number of weld variables under conditions of known and reproducible loading. The basic interpretations include:

(1) Determination of the development of brittle crack paths in the weld, HAZ, or parent material following rupture. This is perhaps the most significant aspect, for the propagation of cracks is not a function of the complexity of the structure but of the intrinsic mechanical properties of the various zones at the temperature of test. This information is directly translatable to service at the same temperature.

(2) Determination of the extent of deformation developed prior to failure of the simple butt weld. This information may be applied directly only to the case of simple butt welds in a structure operating at the same temperature. Interpretation to the case of a weld at a point of restraint (corners, etc.) may be made only qualitatively. If extensive deformation is not developed in the case of the butt weld the weld is obviously unsuited for use at a point of restraint. In the place of the restraint developed by multiaxial stress conditions recourse may be made to testing at temperatures below the service range to introduce a qualitatively equivalent embrittling effect of temperature. The weldment which is capable of developing deformation to lower temperatures is deemed more suitable for resisting restraint due to mechanical action at service temperature—again the comparison between welds is on a relative basis only.

The question of the development of extensive deformation prior to the initiation of failure is of special significance to structures which are expected to withstand such service conditions. Ship hull design for naval vessels necessarily requires such performance considerations. For the case of structures which are expected to operate under essentially elastic loading, such as merchant vessels, the problem appears to be basically one of the initiation of brittle cracks from positions of extreme stress concentration due to design or flaws. The primary concern is with the inability of the weld, HAZ, or parent metal to withstand minute amounts of flow without either developing a crack or triggering an existing flaw.

To be realistic, there is little security in the knowledge that a specific weldment will develop extensive deformation before failure and that brittle cracks will not run in the weld and HAZ if the plate itself will carry a brittle crack with ease. This, for example, is the problem of the merchant ship constructed with conventional structural steel. Arc strikes and other defects on the plate itself may trigger a brittle crack in the plate even in the absence of extensive deformation. For such a structure the greatest immediate benefit may be derived from improvement of the plate material. A similar analysis of the importance of base metal properties may be applied to armor weldments expected to withstand extensive deformation-pecularily, in either case the first weldment problem to be solved is that of the base material.

Testing of the base material for susceptibility to brittle cracking does not require the use of a conventional weldment. The answer may be obtained directly by introducing a material crack which may be considered the most serious possible flaw condition. A specialized version of the bulge test featuring the development of such a flaw condition is used for this evaluation.

THE CRACK-STARTER TEST

The crack-starter test is considered a test for the cracking susceptibilities of the material to be welded. The assumption is made that brittle cracks originate from critical flaws in the structure—the origin of the crack may be a defect such as an arc strike, a fatigue crack, a crack in the heat affected zone, a crack developed due to a defect in the weld, or simply a crack developed due to failure of the weld at a position of high constraint. The source of the crack is not important—the question to be resolved is simply one of the acceptance and progression of the crack in the base material element of the weldment.

The test is performed by bulging a plate 14 by 14 inches over a die 9 inches in diameter. The plate is prepared for testing by deposition of a short bead of a brittle hard surfacing weld metal which is then notched to half thickness of the deposit (Figure 9) by means of a disc abrasive wheel. It has been determined by static tests that on loading to the yield point of the plate the hard surfacing weld bead cracks in a completely brittle manner. Thus, the metal plate is presented with a sharp material crack at the instant it is loaded to the yield point. The explosive charge (standard 4-lb Pentolite) is used at the high standoff of 24 inches (for 3/4- and 1-inch plates) inasmuch as the determination of cracking tendencies does not require the development of extensive deformation. A standoff and explosive combination which provides a 1-inch deep bulge on a prime plate has been determined to be adequate for this test. It will be shown in discussions to follow that increasing the energy directed at the plate serves no useful purpose.

Figure 9 - Center portion of crack-starter test plate showing lead-on-plate of hard surfacing weld deposit (actual size)

In order to properly assess the significance of this test it should be noted that brittle cracks propagate by release of elastic strain stored in the material undergoing cracking. The upper limiting rate of this release is equal to speeds of the propagation of elastic strain waves, which approximate the speed of sound in metal. Cracks do not always propagate at this limiting speed inasmuch as "brittle" cracks are not always completely brittle. Minute amounts of surface shearing and variations in the nature of the cleavage fracture itself will influence the speed of crack propagation in direct proportion to the variations in the energy required to feed the advancing crack. As a result, brittle cracks may travel at speeds varying roughly from 1000 to 8000 ft/sec. The importance of these facts lies in the realization that large amounts of elastic strain energy must be available to feed rapidly moving cracks, particularly the variety having lower rates of travel. Large structures by virtue of the extensive lengths which can store elastic strain have a high potential of elastic energy—small specimens do not and therein lies the principal difficulty of correlating crack running tendencies between laboratory tests and structures. The bulge specimen is unique in that the extremely soft loading provided by gas pressure and the rapid transmittal of load results in maintaining elastic load on the specimen during the progression of cracks. In essence, the elastic strain is replaced as rapidly as it is lost in feeding the advancing crack—the conditions may be considered equal to those of a structure of extremely great length. The above concepts are presented schematically in Figure 10.

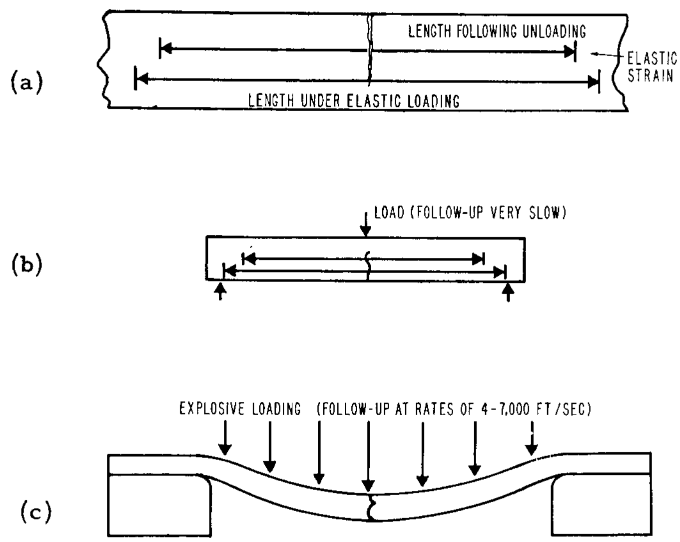


Figure 10 - Diagram showing that bulge test duplicates the elastic strain conditions of long sections in structures. In (a), representing case of structures, high speed cracks are propagated by release of elastic strain energy; in (b), representing case of small test specimen, there is insufficient elastic energy for propagation; in (c), representing explosion loading, the load follow-up is sufficiently rapid to maintain elastic loading during cracking

Figure 11 illustrates the results (mild steel ship plate) of a series of crack-starter tests conducted over a range of temperatures in 20°F temperature steps. This series is typical, except for the exact range of temperatures, for all steels tested. At the highest temperatures heavy surface shear is developed which prevents running of the crack inasmuch as high energy absorption is required to shear the surface metal. Figure 12 illustrates that the use of an ultra-high energy blast at the temperature of crack refusal results in bulging and shear tears but does not extend the range of brittle cracking to higher temperatures. As the temperature is lowered the amount of surface shear (percent of the total cross section) decreases thus permitting running of the crack to greater distances.

21716

Figure 11 - Crack-starter test series for typical ship plate steel (numbers refer to test temperature °F)

Figure 12 - Use of extra high energy blast at temperature of crack refusal (140°F above) results only in the development of shear fracture

It has been observed that in ship fractures the greatest amount of surface shear on the fractured surface is on the order of .010 to .020 inch or 1 to 2% for 1-inch plates. The absence of cracks having more than this amount of surface shear indicates that ship structures do not have sufficient elastic strain energy to feed cracks of this high energy consumption type. The rapid replacement of strain energy in the bulge tests allows propagation of cracks featuring surface shear of approximately .050 inch maximum. Such cracks are confined to the bulge region as shown by the 80° and 100°F tests of Figure 11, thus indicating difficult running. Figure 13 illustrates the surface shear lip developed in bulge fractures which show partial running in the bulge area.

The range of .010- to .020-inch surface shear has been taken as the critical limit of crack running in ship structures. Figure 14 illustrates a test series of a mild steel equivalent to the steel shown in Figure 11; the relation of the fracture to Charpy properties and surface shear is denoted by the various plots. The temperature range, at which the limit of surface shear (.010- to .020-inch) is developed, is defined as the highest temperatures of possible propagation of brittle cracks in structures or as the temperature of "fracture transition." Above this temperature the amount of shear is too great to permit free-running cracks in nonexplosive loaded structures while below this temperature crack running is possible with very little energy absorption inasmuch as the amount of surface shear gradually approaches zero with lowered temperature. It has been noted in the testing of approximately 40 structural grade steels that the .010-inch shear temperature differs from the .020-inch-shear temperature by 10^0-20^0F which illustrates the critical nature of the temperature effect on brittle crack propagation.

Figure 13 - Surface shear lip in excess of the maximum amount developed in ship fractures (approximately .050 inch)

It is also noted that in the crack-starting test the depth of bulge developed decreases with decreasing temperature, as may be observed from Figure 11. At the fracture transition temperature, plastic deformation is required to initiate the travel of the crack. At a lower temperature defined as the "ductility transition" plastic deformation is not required to initiate the travel of the crack as evidenced by the flatness of the fractured plate. Since at the ductility transition temperature the amount of surface shear is essentially zero, extensive crack-up occurs. Inasmuch as the brittle weld fractures at the yield point of the plate, it may be concluded that the sharp crack created by the brittle weld is immediately accepted at the ductility transition temperature, hence further straining into the plastic range is not required. Above the ductility transition the sharp crack of the brittle weld is not propagated into the plate until further straining into the plastic range is developed as indicated by bulging of the plate.

The two transitions are of fundamental importance in the interpretation of the test results for structural design purposes. It is essential to recognize that structures which operate entirely in elastic loading do not develop the level of deformation required to trigger a brittle crack at temperatures above the ductility transition. Such a structure therefore would remain safe even in the presence of extreme flaws as long as service temperatures remained above the ductility transition. On the other hand if plastic deformation may result from service, the structure would not be safe at service temperatures below the maximum temperature of crack propagation.

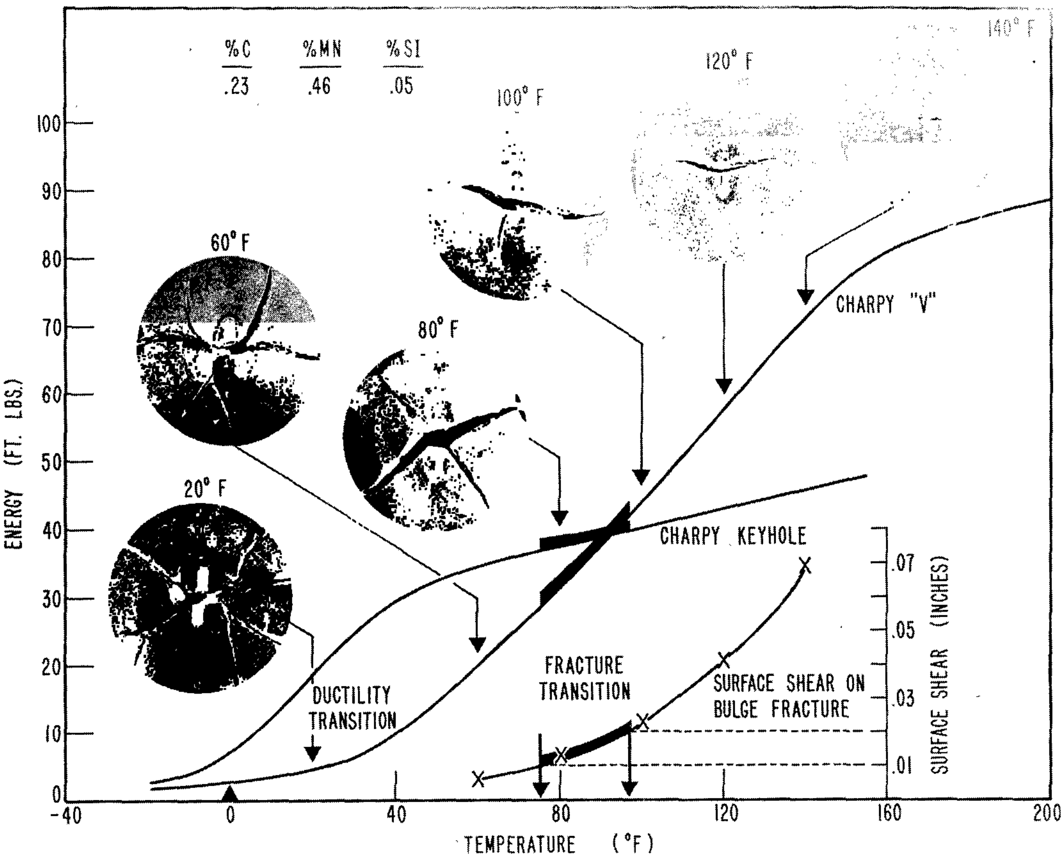


Figure 14 - Typical crack-starter test series illustrating method of determining fracture transition and its relation to Charpy "V" and Keyhole transition curves

Investigations of ship steels have shown that the ductility transitions of a large number of representative mild steels fall in the range of 0° to 40°F and the fracture transitions in the range of 50° to 100°F. The records of ship failures show that the greatest frequency of fractures occurred in the service temperature range of 30° to 50°F—the highest fracture temperature recorded is 90°F. Inasmuch as ship design, to be functional, must permit regions of localized deformation, the temperatures of possible crack starting for the steels should lie somewhat above the temperature range of the ductility transitions as shown by the bulge. The predictions of the test in this respect have been demonstrated to be accurate. It is also known from the NBS investigation (3) that, at the temperature at which fracture occurred, the plates which provided the starting point of ship fracture have a lower notch toughness as determined by the Charpy "V" test than the majority of plates which continued the fracture. The poorer plates containing flaws were "selected" as starting points and the remaining plates being below their fracture transitions supported the continuation of fracture. Briefly, the bulge test predicts that 90 to 95% of the steels used in ship construction are capable of conducting brittle cracks at temperatures up to 70°F while only 5 to 10% are capable of this up to 90° to 100°F. This is corroborated by ship failure history, in that major fractures entailing cracking of a large number of plates in line have occurred to 60°F. Minor failures entailing single plates have occurred to 90°F.

In the case of structures which are expected to withstand extensive deformation in service without brittle fracturing (such as ship bulkheads, etc.) it is essential that the highest temperature at which crack propagation is developed in the crack-starter test be below the lowest service temperature.

It is recognized that the above considerations for the case of elastically loaded structures are based on the assumption of the presence of an extreme flaw condition. Such an assumption is highly realistic and is substantiated by the numerous failures of ships traced to minute imperfections. Welding a large complex structure unavoidably produces minute, dangerous flaws beyond the possibility of elimination by even the most rigorous inspection procedure.

Correlation with Charpy "V" and Keyhole transition characteristics of the steel permits direct interpretation of the significance of conventional notched tests. It has been determined that the ductility transition shown by the bulge tests occurs at temperatures 20°F above the 15 ft-lb energy temperature of the Keyhole specimen and at approximately the 5-10 ft-lb temperature of the "V" specimen. It is significant, in this respect, that the fracture-source plates of ship fractures developed an average of 5-8 ft-lb "V" energy at fracture temperature. The bulge fracture transition occurs on the plateau region of the Keyhole specimen and on the rising portion of "V" specimen curve. The exact positions of the bulge fracture transition with respect to the Charpy "V" transition curves vary somewhat with the nature of the deoxidation used, being at higher curve positions for killed steels and at lower positions for rimmed and semi-killed steels. This indicates a serious limitation to the use of Charpy transition data for accurate predictions of crack running.

The differences in the transition range for the Charpy "V" and Keyhole specimens indicate the importance of notch sharpness in determining the temperature range of transition to brittle behavior. The same effects should be expected for natural notches of varying severity in structures. Structures in which the sharpest flaw is of lesser severity than the sharp material crack of the brittle weld in the crack-starter bulge test would be expected to require general plastic deformation at the ductility transition temperature indicated by this test before running cracks would occur. In other words the ductility transition temperature is lowered in proportion to the lesser acuity of the crack-starting flaw. The presence of flaws equivalent to the crack starter is demonstrated by the bulge predictions relative to the performance of ships and also, by the demonstration that arc strikes are equal to the crack starter in triggering failure in the bulge tests. At temperatures below the fracture transition, the fracture, once started, gravitates to a brittle crack with consequent catastrophic failure regardless of the nature of the starting notch. This fact will become more evident in later discussion of the break-up characteristics of unnotched bulges. It is, moreover, highly significant in the case of the structure which is expected to withstand plastic deformation for it predicts that tears will gravitate to brittle cracks, if a brittle crack path is available. A sharp crack condition is not necessary to produce brittle fracture—it merely helps in starting the failure.

On the basis of the above information it is concluded that a welded structure, with due consideration of the elastic and plastic loading cases, would be potentially unsafe at service temperatures below the crack-running temperature of the plate regardless of the weld type or HAZ quality. At temperatures above the crack-running temperature a brittle failure may be considered possible only if an alternate brittle path exists in either the weld or the HAZ.

It does not follow from the above considerations that the quality of welding or of the welds should be ignored. The welds and the HAZ are potential origins of failure; moreover, these elements are usually placed at positions of stress and strain concentrations. At these positions plastic flow may occur at loads which may be considered within the nominal elastic range of the structure as a whole. It is imperative that the resistance to crack initiation of welds and HAZ be of the highest possible order consistent with economic considerations. The need for high quality welds is greatest if the plate material is expected to operate below its fracture transition temperature. The aim in this case is to prevent as much as possible the starting of a failure.

Theoretically it should be possible to use the brittle crack starting technique to determine crack-running temperatures for the weld, and HAZ, however, in practice this is feasible only in the case of the weld. These tests may be performed by directing a brittle crack through the plate material in the direction transverse to the weld, as shown in Figure 15. On traversing the weld the crack may stop due to heavy shearing, propagate across the weld with difficulty due to partial shearing, or continue through in a completely brittle fashion. The partial-penetration weld of Figure 15 is shown to be more resistant to crack propagation inasmuch as the gap at the region of highest triaxiality at the center of the plate prevents crack progression more effectively than the continuous weld metal condition of the full penetration weld.

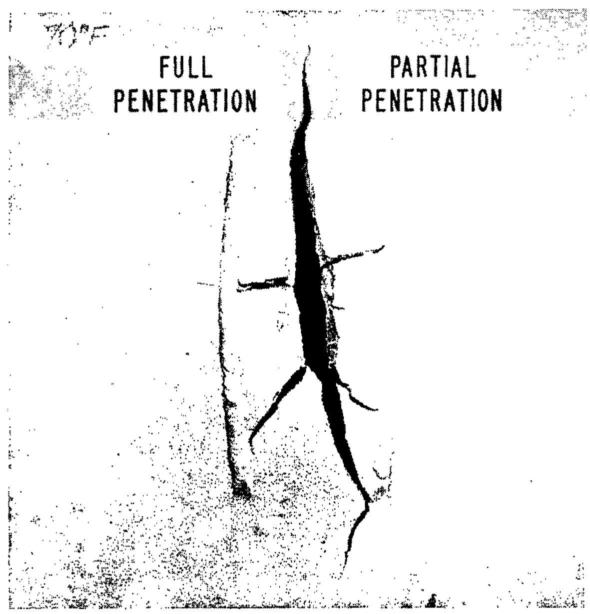
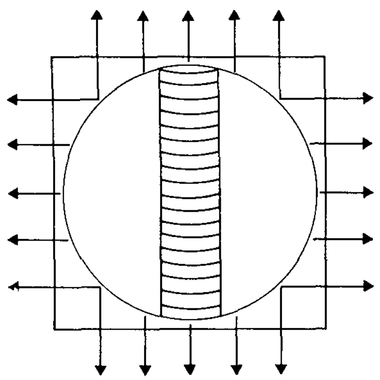


Figure 15 - Relative crack stoppage in a 1-inch ship plate at 70°F by full- and partial-penetration VV butt weld of E12016 (grade 260) deposit

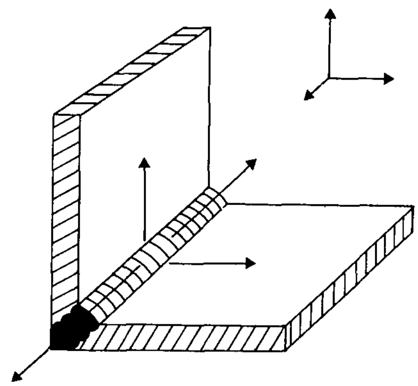
In the case of alloy steels which do not permit brittle cracking at the lowest service temperature contemplated and which are joined by the use of welds of similar desired characteristics there remains a final potential crack path in the HAZ. The crack-starting technique has not as yet been successfully applied to HAZ crack-propagation testing. The only method of determining if a brittle crack path is possible in the HAZ entails bulging of the test weldment to failure at the temperature of service and observing if brittle cracks are developed.

BULGE TESTS OF WELDMENTS

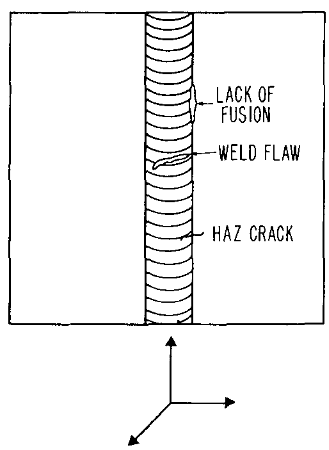
The crack-starter test may be recognized as a triaxial tension test inasmuch as the sharp cleavage crack developed by the brittle weld provides a triaxial tension condition. A weldment or prime plate bulged in the absence of the crack starter (or of severe incidental flaws) may be recognized as a biaxial tension test. In keeping with the nature of the test, extensive deformation precedes fracture even at temperatures at which freely running cracks will occur after failure is initiated. Weldments which contain flaws such as cracks or concentrated porosity show failures at low levels of deformation, inasmuch as the triaxiality conditions of the crack-starter test are approached (Figure 16).



(a) Biaxial stress condition in bulge (or at simple butt welds in structures) permits extensive deformation prior to cracking.



(b) Moderate triaxiality which decreases pre-crack deformation is developed in welds at unfavorable positions in structures



(c) Defects which develop high triaxiality resulting in low pre-crack deformation

Figure 16 - Stress conditions affecting pre-crack deformation

The level of strain reached by the bulge prior to failure may be measured either as surface strain, or thickness reduction; the depth of bulge method cannot be employed directly to denote strain at fracture. Surface strain measurements require the application of a photogrid—this method is useful in the case of plastic deformation studies involving evaluation of the nature of deformation in the weld and HAZ as compared to the plate. For general performance test purposes it is much more convenient to measure the thickness reduction by means of micrometer calipers. The measurement is both accurate and expeditious and may be made on fractured pieces as well as on unfractured bulges. The location of the measurement has been standardized as a point $1\frac{1}{2}$ inches from the apex of the bulge. This position, while removed from the weld, remains within the pole region and hence provides an accurate index off the maximum strain level reached in the test area of interest.

In order to evaluate the significance of bulge tests it is necessary to recognize the several aspects of performance as described previously. The following discussion is intended to demonstrate that the process of analysis must consider also the materials which are being tested and the service for which these are intended.

Case I. Evaluating the Performance of Various Weld Types in Structural Mild Steel Intended for Service in Structures Entailing Essentially Elastic Loading

Bulge tests of this type of weldment have demonstrated (2) that the weld proper is the site of initial failure and that the level of deformation prior to failure is determined by the notch toughness of the weld and the temperature of test. If high notch toughness of the weld is retained at low temperatures extensive deformation prior to fracture will also be developed at low temperatures. Figure 17 illustrates the fact that an E12016 (grade 260) weld having a 15 ft-lb "V" transition of -100°F will maintain high deformation to lower temperatures than an E6010 weld having a 15 ft-lb "V" transition of -50°F. These welds were tested with the reinforcement ground flush with the surface of the prime plate. If the reinforcement with its attendant ripple is retained the temperature range of bulge transition to near zero deformation will occur at higher temperature for both weldments, thus illustrating the potency of even the mild notch condition developed by the ripple.

The break-up characteristics of mild steel weldments (E6010, E7016, G260) is such that, while the failure starts in the weld, propagation is entirely in the base plate (Figure 18). Brittle fracture of the plate occurs at temperatures as high as 60°-70°F for mild steel of average quality as predicted by the crack-starter test. With such performance on the part of the plate element it is impossible to develop a welding procedure which will assure absolute safety of the structure at ordinary service temperatures. Danger will always exist that a flaw will be present in the form of fabrication crack or arc strikes which will promote failure despite proper performance on the part of the weld. Such pessimism, however, should not serve as a deterrent to determining the best possible weld; in fact, with such a critical plate material, all possible effort should be expended in developing a weld which would have minimum tendencies to fail and thus transmit a crack source to the plate. In this special test aimed at determining resistance to fracture initiation in the weld proper using plate material in which cracks propagate easily following weld failure, evaluation is made by testing at sub-service temperatures. This evaluates the welds in terms of their relative resistance to the embrittling effect of low temperature and can be translated to mean a similar ranking of quality in terms of resistance to stress concentration at service temperatures.

The peculiar behavior of failure starting in welds but not propagating in welds for the case of mild steel weldments has been observed also in structural failures of ships, pipe lines, pressure vessels, etc. The answer to this anomaly appears to lie in the differences in performance of cast and rolled materials, inasmuch as the rolled plate is joined by a weld which represents a cast material. It has been shown that for similar notch toughness as indicated by equal Charpy "V" transitions based on 10-15 ft-lb criteria, (toe of transition rather than level of upper shelf), the fracture transition temperature is the same for cast and rolled steels. Figure 19 presents a direct comparison of cast and rolled mild steels, performed by joining the two materials and testing in combination, utilizing the crack-starter technique. It is also true that if the cast material has higher notch toughness as indicated by a 10-15 ft-lb transition occurring at lower temperature, the maximum temperature of crack running will be lower for the cast steel. Thus, if the weld (casting) is of higher notch toughness than the plate, cracks will run preferentially in the plate.

Comparison of prime cast and rolled steels (no weld or crack starter) shows clearly that the level of deformation which is developed prior to fracture initiation is drastically decreased in the cast steel. This should be expected inasmuch as the cast steel inherently contains defects which are eliminated in the case of the rolled plate during the consolidation process which accompanies forging. This information concerning cast and rolled steels provides the clue as to why it is possible to start a crack in a weld which has higher notch toughness than that plate, as indicated in Figure 20. The pertinent consideration is that the weld (casting) is always tested in a notched condition because of inherent macroscopic and microscopic flaws while the rolled plate is in a purely unnotched condition. This information also explains why the crack which starts in the weld does not propagate in the weld. A fracture which may be partly of shear type once started in a weld has only a short distance of shear propagation until it is presented to the plate. At this point, if the plate is below its crack-running temperature,

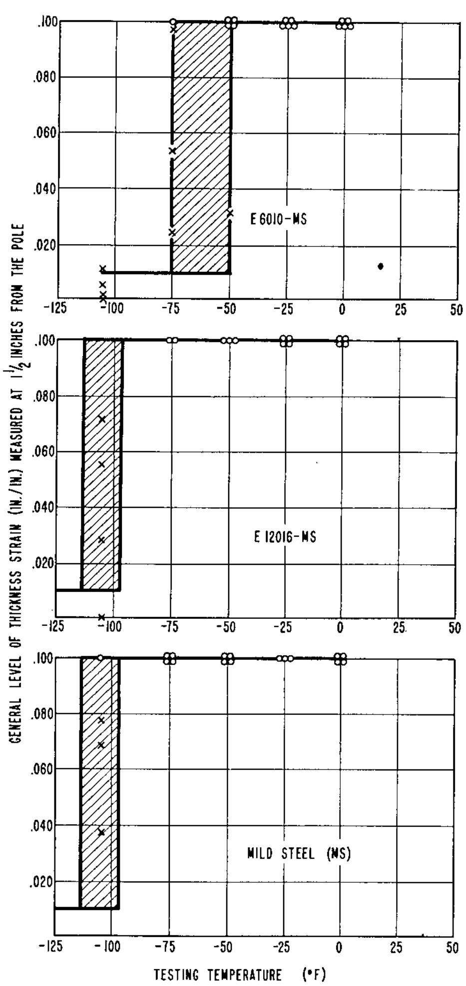


Figure 17 - Explosion bulge transitions for mild steel weldments. Circles indicate fractures occurring above 10% strain.

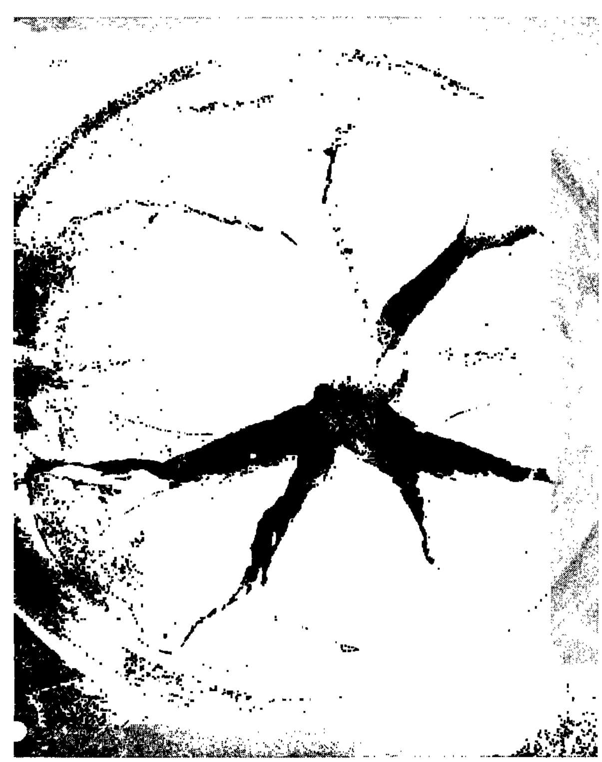


Figure 18 - Break-up characteristic of mild steel weldment - original failure in weld with propagation of fracture in plate

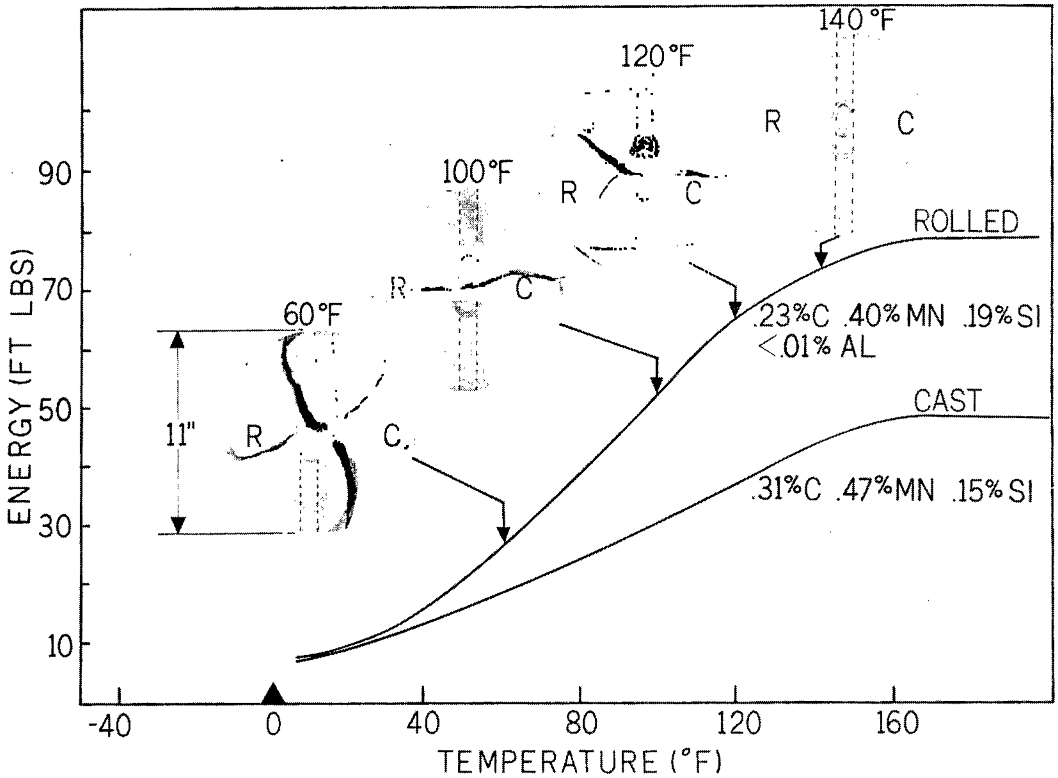


Figure 19 - Direct comparison of fracture characteristics of cast (C) and rolled (R) steels joined by welding to form a single test plate

a brittle, self-propagating crack is developed resulting in crack-up of the plate. Conversely, if the plate is at a temperature such that brittle cracks are not possible, failure may occur only if an alternate path is provided by the HAZ or the weld.

Case II. Evaluating the Performance of Various Weld Types in Quench and Tempered Armor Steel Intended for Service in Structures Subjected to Explosive Attack

For service such as holding bulkheads of naval vessels it is deemed mandatory that the plate element of the weldment should not fail by brittle cracking. Obviously if the loading is sufficiently high it is unavoidable that tear ruptures must occur. If the rupture is of ductile shear variety damage will be of localized nature confined to the site of attack. Figure 21 illustrates crack-starter tests of two alloy steels (B and A-1) which when properly heat-treated refuse crack-up to extremely low temperatures. Such plate material meets the requirements for proper performance at ambient temperatures by a wide margin. Steel A with moderate embrittlement (A-2) is still safe; however, with severe embrittlement (A-3) it is completely unsuitable. It is apparent that the performance of properly treated material when welded is determined entirely by the weld zone. The high quality of the plate is of no avail if improper welding produces a HAZ which permits brittle cracking at service temperatures also, if the weld itself is capable of running brittle cracks.

Figure 22 illustrates desirable performance for blast-resistant armor weldments. The weldment (grade 260 weld) failed after developing extensive deformation (20% reduction of thickness) and the mode of failure is entirely shear. The absence of brittle crack paths provides assurance of optimum performance—failures due to overmatching explosive attack should be of localized nature. Examples of other than optimum performance are shown in Figures 23-26.

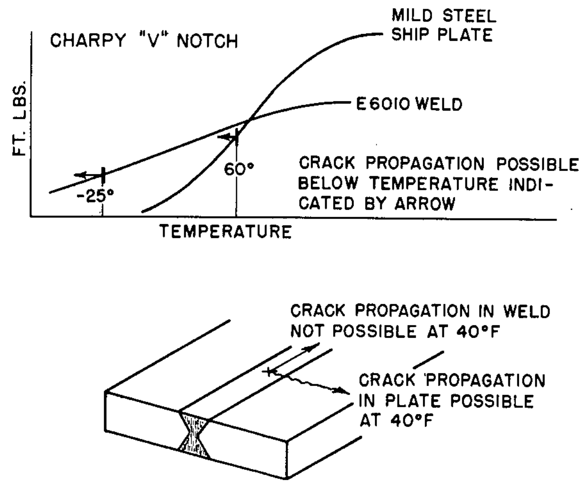


Figure 20 - Mechanism by which crack is initiated in weld having higher notch toughness than plate whereas cracks are propagated in plate. Since weld always operates in a notched condition because of flaws, crack initiates there unless the notch toughness of the weld is increased to such a point that the weld flaw system is made inoperative.

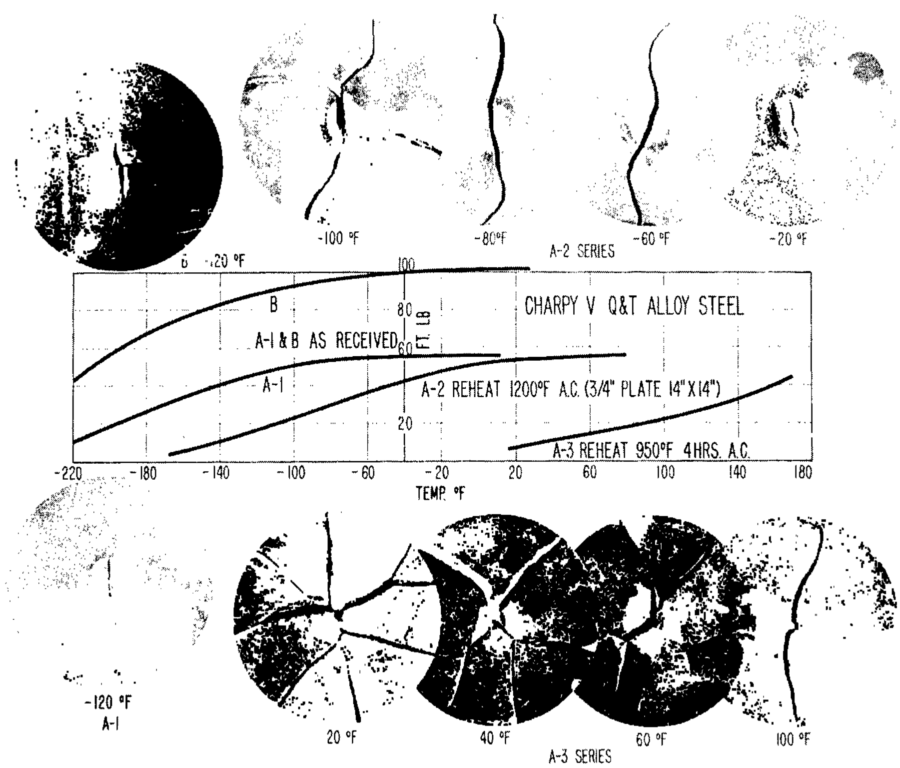


Figure 21 - Crack-starter test of two alloy steels in various conditions of heat treatment. Compare change in fracture appearance with Charpy V transition curves.

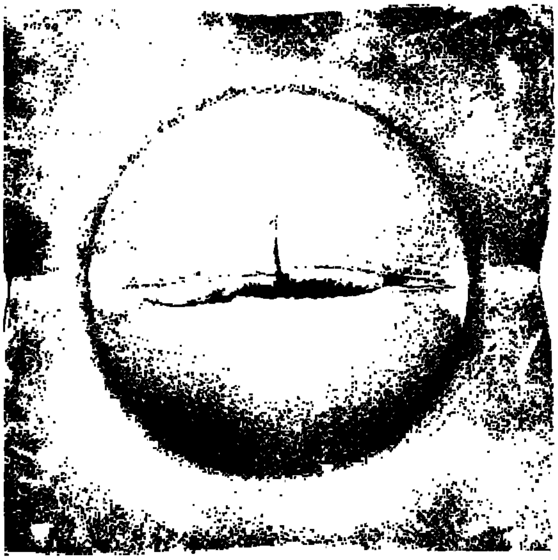


Figure 22 - Desirable performance for blast-resistant armor weldments (grade 260 weld; 20% reduction in thickness)

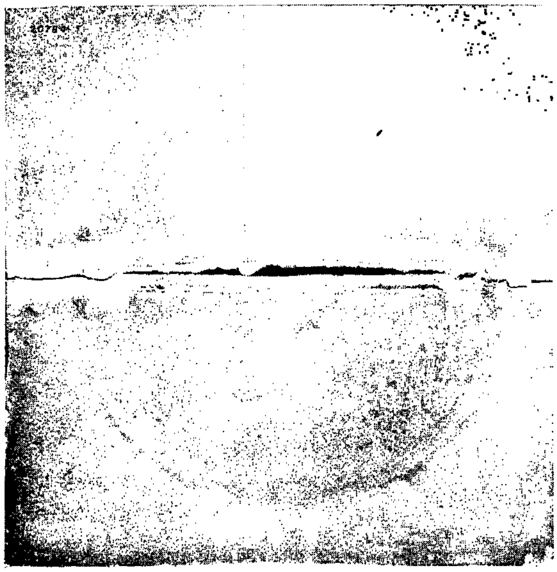


Figure 23 - High quality armor material (grade 260 weld) impaired by welding resulting in a brittle crack in the HAZ. Failure, once started, may extend over large areas of the structure.

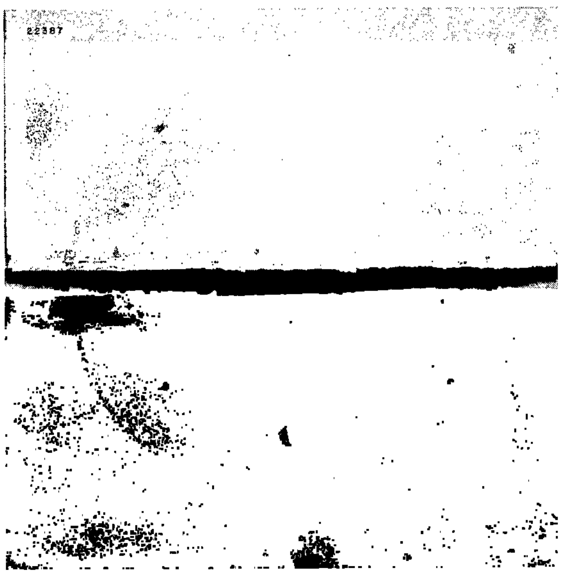


Figure 24 - Fusion line failure for an austenitic weld having a poor metallurgical structure at the region of high dilution. Again, the complete break suggests the possibility of extensive damage following failure.

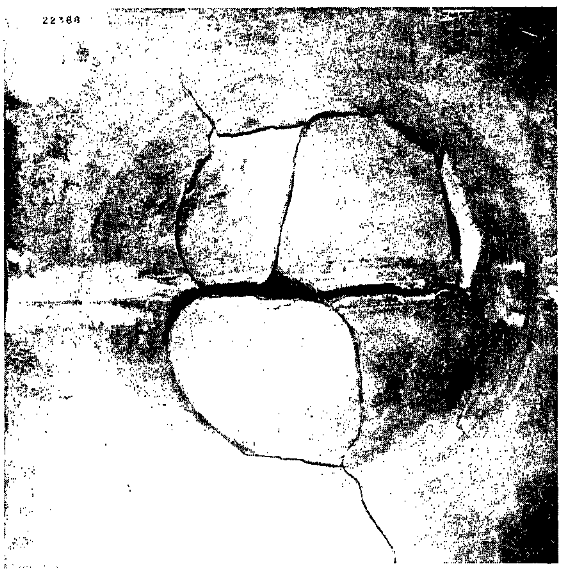


Figure 25 - Inadequate properties in all elements resulting in complete break-up

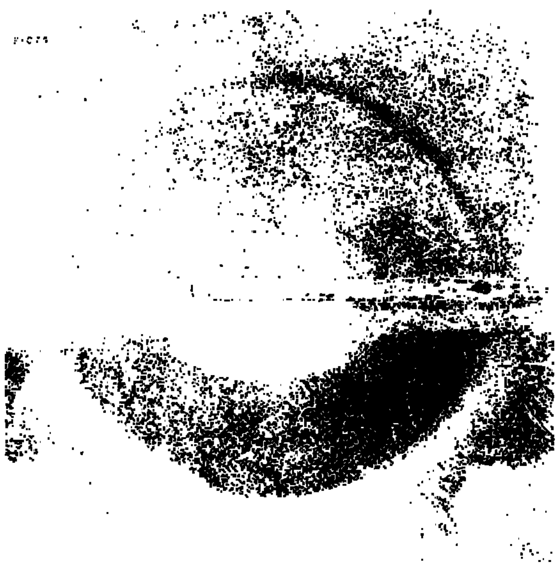
Figure 26 - Inadequate properties in all elements except the grade 260 weld

It is apparent from the above examples that the bulge test provides a basis for critical discrimination between weldments. The critical zone, if any, is rigorously defined thus providing information regarding suitability as well as indicating where improvement is needed. It is also apparent that ability to develop extensive deformation prior to fracture offers no safeguard from extensive damage in the event the attack is sufficient to cause a rupture. The development of rupture must be considered as a likely event in any strucutre which suffers intensely localized attack such as a high explosive blast.

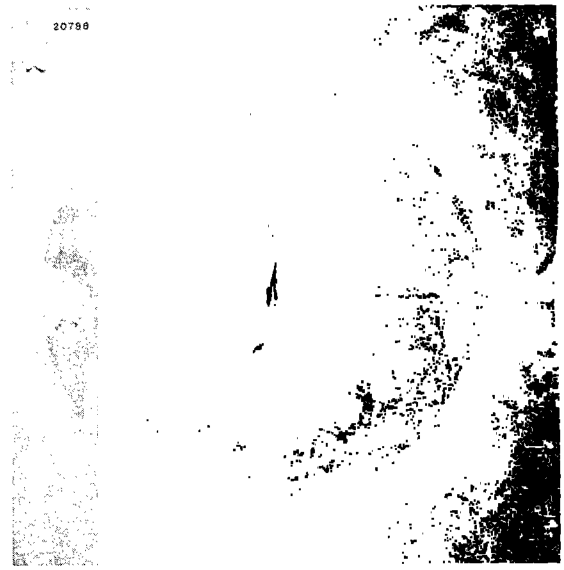
The possible effect of flaws in armor weldments having no brittle crack paths should be considered primarily from the aspect of decrease in the level of general deformation at which the initial rupture occurs. Even if a brittle crack path is not available the presence of flaws results in tears with a low-energy attack. If the flaws were absent, extensive deformation requiring a high-energy attack would be required to develop tearing. This has been demonstrated by the bulge test in that severe weld flaws such as concentrated porosity (Figure 27) or HAZ cracks result in failures at low levels of deformation. The break characteristics of the weldment without flaws as compared to that with flaws is exactly the same, the only difference being in the level of deformation developed prior to fracture.

APPLICATION TO ALUMINUM WELDMENTS

Weldments of high-strength aluminum alloys represent a special case distinct from steel weldments in that the propagation of brittle cracks is not a problem. The failures of such weldments are associated with undermatching welds of low ductility or with the softened over-aged zone adjoining the weld. Basically, the difficulty lies in the localization of strain in the weld zone due to metallurgical limitations of producing high-strength levels in the welds. This in turn is not a problem in steel welds since these can be made to have overmatching strength with relative ease. Figure 28 illustrates explosion bulge tests with photogrid studies indicating that conventional 61ST-43S weldments deform primarily by weld and HAZ strain resulting in early failure of the low ductility weld. Such weldments are to be considered unsuitable for service requiring the ability to endure plastic deformation (collision, explosion, etc.), By proper matching of plate and weld properties the resultant strain is distributed over the prime plate as well as the weld and HAZ zones as shown for the MG-5 weldment of Figure 28b. The combined approach of determining the limiting deformation at failure and strain distributions of the various zones represents a bulge test procedure customized to resolving the specific problem of aluminum welds.



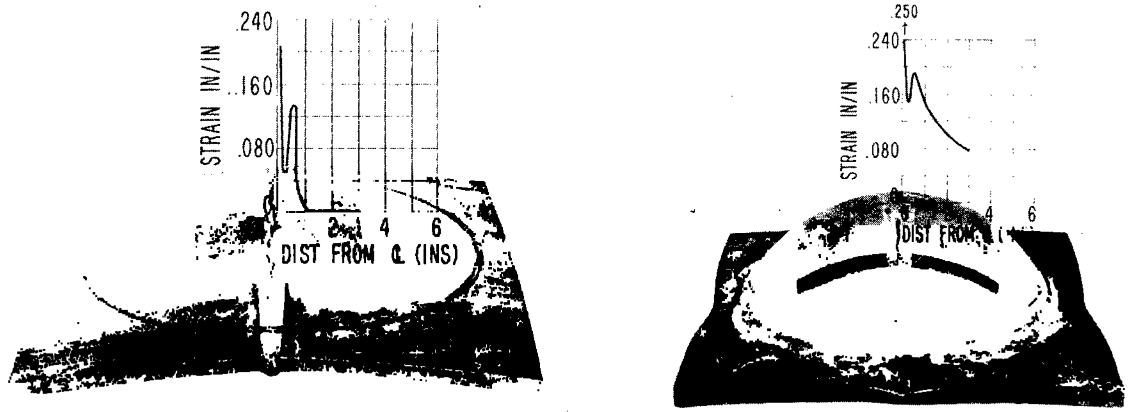
(a) Failure localized in weld at position of porosity. Properties of plate are such that brittle fracture is not possible.



(b) Failure initiated by weld porosity is confined to weld and short shear tears. Properties of plate such that partial fracture is possible.

(c) Complete break-up via a plate path because of inadequate plate properties

Figure 27 - Nature of failure of grade 260 weldments as the result of concentrated porosity is determined by properties of plate.



(a) 61S-T6 welded with 43S filler; depth of bulge, 3/4 inch

(b) MG-5 welded with MG-5 filler; depth of bulge, 5 inches

Figure 28 - Performance of aluminum alloy weldments related to distribution of deformation between weld, HAZ and prime plate

* * *

REFERENCES

1. Hartbower, C. E., and Pellini, W. S., "Explosion Bulge Test Studies of the Plastic Deformation of Weldments," Welding Journal, 30: 307S-318S, 1951

2. Hartbower, C. E., and Pellini, W. S., "Investigation of Factors which Determine the Performance of Weldments," Welding Journal, 30: 499S-511S, 1951

3. Williams, M. L., "Investigation of Fractured Steel Plates Removed from Welded Ships," National Bureau of Standards, Serial No. NBS-3, June 1, 1951

* * *

APPENDIX
Details of Bulge Test Equipment

(1) Dies (Figure A1) and base plates were originally cut from scrap 3-inch STS armor steel but alternate dies of alloy cast steels have performed equally well. The dies serve indefinitely.

(2) The expendable cardboard box is a standard item and may be purchased in several convenient lengths to provide the various standard standoff distances. The width dimensions are such as to provide approximately ½-inch clearance for easy fit over the dies. The box arrangement provides adequate stability to counter moderately strong wind conditions.

(3) Lead sheet or a lead plate casting placed over the bottom of the die prevents excessive damage to fragments and serves to protect the base plate. Very few fragments are lost inasmuch as the downward blast serves to collect the fragments in the die cavity. This is an important item in fracture studies.

(4) The explosive wafer is precast with a hole to accommodate a "Special Blasting Cap" (Electric) USA Spec. T-1267A Rev. 6-127142 having 12-ft enamel wire extensions. The cap is positioned at the center of the charge as shown in Figure A2.

(5) A four-pound Pentolite charge is convenient for plates varying from 1/4 to 1 inch. The nearest offset which should be used is 15 inches which represents a distance equal to the bulge diameter; closer offset results in poor clamping and concentrated loading at the center of the bulge. The highest feasible offset is approximately 48 inches. If the strength or thickness characteristics are such as to require offsets outside these limits it is preferable to change the weight of the explosive.

(6) Pentolite is used because of its ready availability and high sensitivity which ensures reproducible detonation. The explosion pulse duration is on the order of .0002 sec—the full bulge is developed during this interval. Any other explosive of similar high sensitivity may be used; Comp. C_3, a plastic demolition explosive, was used successfully during the development of the test but was discarded in favor of Pentolite because of the required forming of the plastic into a wafer from stick shape which is the normal packaging shape.

(7) Standard dry-ice cabinets of forced draft type generally used in laboratories provide excellent soaking facilities for the low-temperature tests. Refrigerators and electrical ovens serve for the higher temperatures. Soaking times of 3 hours after charging and 1½ hours after each shot are adequate for equalization. Cooling the sample 5^0-10^0F below the test temperature allows for heating during the time required for positioning. Measurements should be made to determine correct settings of temperature.

(8) For proper seating on the die face it is necessary to grind the weld reinforcement flush with the plate over the region which contacts the die support.

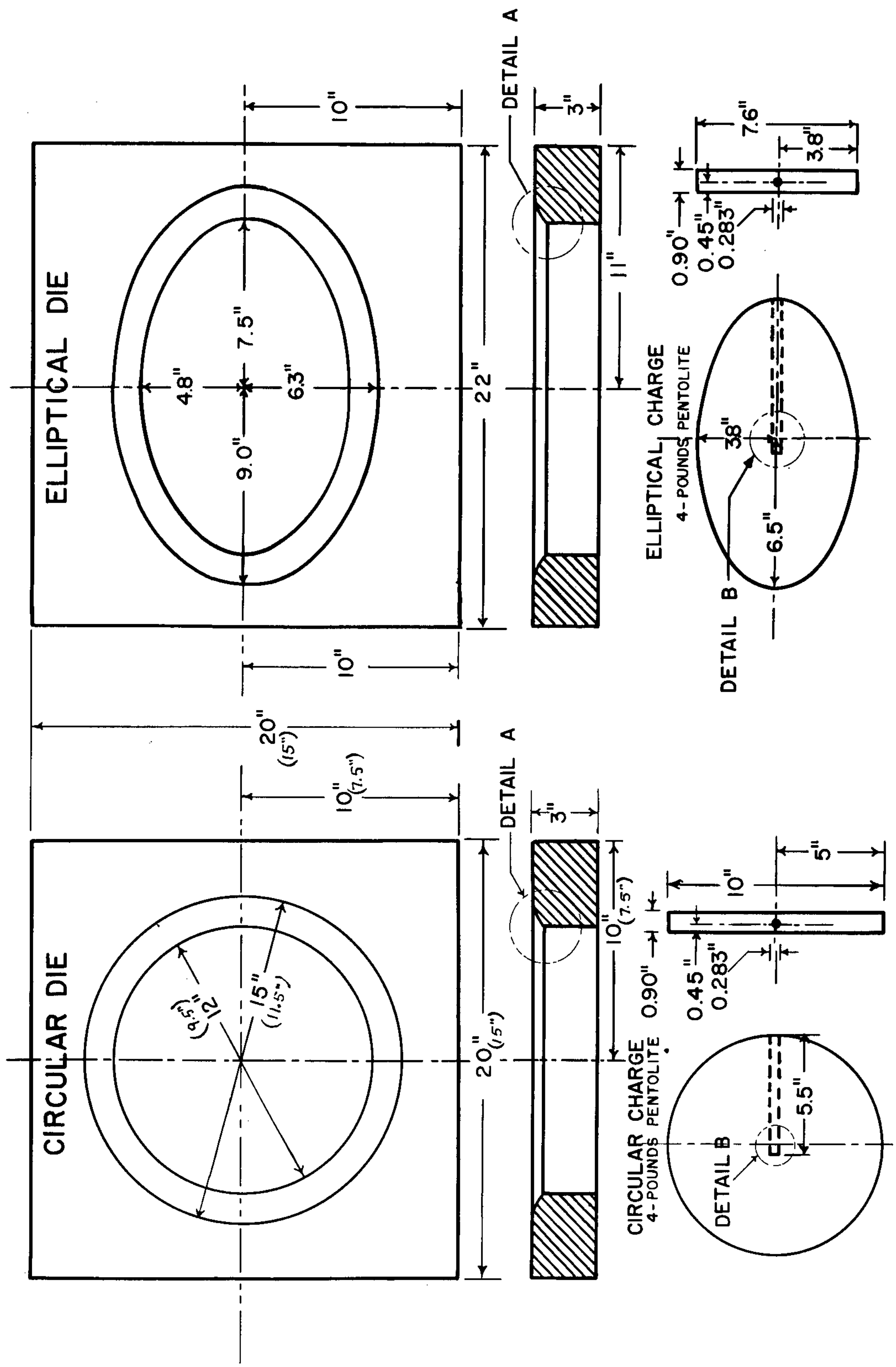


Figure A1 - Circular and elliptical dies with changes in dimensions for small circular die in parentheses

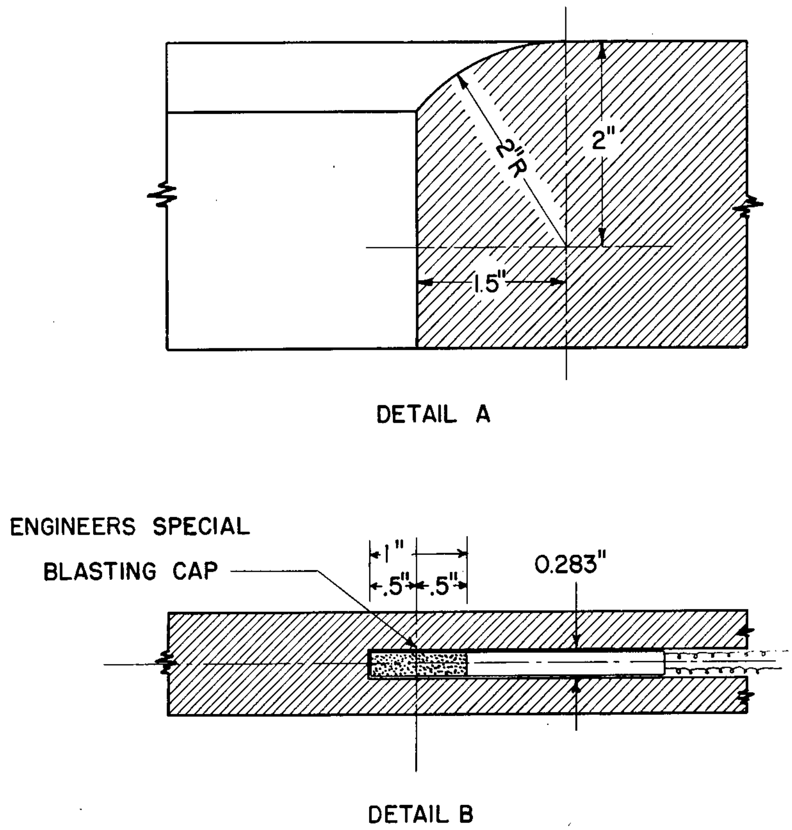


Figure A2 - Details of die radius and Pentolite charge

(9) The crack-starter weld is deposited in a chipped or machined groove approximately 3/16-inch deep and $2\frac{1}{2}$-inches long. The weld is completed in the short passes, starting at each end of the groove and finishing at the center. This technique prevents crater cracking at the ends of the weld which tend to give secondary breaks. Hardex 25 or 45 hard surfacing electrodes are suitable for this weld. For armor plate steels the hard surfacing weld is ground flush to prevent cracking at the toe of the weld. The ground notch is oriented parallel to the weld inasmuch as the ground weld is undermatching to the 125,000 T.S. plate, hence strains preferentially in a weld transverse direction.

* * *

NAVY-DPPO PRNC, WASH., D.C.