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NRL REPORT 3790

APPLICATION OF EXPLOSION BULGE TEST TO THE STUDY OF THE PLASTIC DEFORMATION OF WELDMENTS

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH

NAVAL RESEARCH LABORATORY

WASHINGTON, D.C.

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APPLICATION OF EXPLOSION BULGE TEST TO THE STUDY OF THE PLASTIC DEFORMATION OF WELDMENTS, by C. E. Hartbower and W. S. Pellini.
January 24, 1951, 29 pp. & figs., UNCLASSIFIED.

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(over)

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   Deformation
2. Welding-Test
   results

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It has been demonstrated that the stress and strain states imposed by the loading conditions are not accepted as such by the weld joint. Depending on the overmatching characteristics of the weld and its geometry, a system of stress and strain entirely foreign to the remainder of the structure may be developed in the weld and near-weld regions.

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C. E. Hartbower and W. S. Pellini

January 24, 1951

Approved by:

Dr. O. T. Marzke, Superintendent, Metallurgy Division

DEPARTMENT OF THE NAVY OFFICE OF NAVAL RESEARCH

NAVAL RESEARCH LABORATORY
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ABSTRACT

A method has been developed for semi-works-scale testing of full welds in heavy plate under combined stress conditions such as prevail in structures. The test features the bulging of welded plate in diaphragm fashion. Uniform loading of the test plate is accomplished by means of an air blast set up by the detonation of an explosive. By modification of bulge geometry it is possible to obtain a wide range of stress fields.

Photogrid deformation studies of prime and butt-welded plates, 3/4 inch thick, have been made on both spherical and ellipsoidal bulges in order to provide conditions of balanced (1:1), and unbalanced (0.8:1) stress fields. The test weldments consisted of a firebox-grade steel joined by means of single-pass submerged-arc welds and also by manual double-V butt welds. The welds investigated provided conditions of closely matching, and of overmatching, weld-metal and parent-plate flow strengths.

It has been demonstrated that the stress and strain states imposed by the loading conditions are not accepted as such by the weld joint. Depending on the overmatching characteristics of the weld and its geometry, a system of stress and strain entirely foreign to the remainder of the structure may be developed in the weld and near-weld regions.

The significance of these findings is discussed in terms of weld performance evaluation.

PROBLEM STATUS

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

AUTHORIZATION

NRL Problem MO3-16R
NR 443-160

APPLICATION OF EXPLOSION BULGE TEST
TO THE STUDY OF THE PLASTIC DEFORMATION OF WELDMENTS

DEVELOPMENT OF EXPLOSION BULGE TEST

Background

It is generally recognized that simple uniaxial stress conditions seldom, if ever, prevail in structures. Regardless of the gross conditions of loading, the design engineer is ordinarily faced with vector resolutions of loads involving either biaxial or triaxial stress fields. Inasmuch as quantitative engineering design data are at present available only in terms of simplified uniaxial loading tests, considerable effort in the field of applied mechanics has been expended in investigating the behavior of metals under multiaxial stress conditions. These investigations have been of two general types:

(a) Tube or bulge tests, which provide essentially biaxial loading conditions.

(b) Notch tests, which develop a high order of tensile stress triaxiality at the notch apex. There are no proven experimental procedures by which controlled triaxial loading (all stresses tensile) may be performed.

Briefly, it has been determined that stress conditions which are essentially biaxial do not appreciably change flow resistance or ductility in comparison to uniaxial stressing. Variations in the balance of such stress fields serve principally to modify the algebraic sign and direction of reference strains. Triaxial tensile stress fields, on the other hand, are known to increase flow resistance and decrease ductility. The effects are pronounced even at low average levels of triaxiality. The unfortunate requirement of a notch has tremendously complicated the interpretation of triaxial tests. To date, the factors which determine the degree of triaxiality of notch tests have not been resolved. It is not possible therefore to designate material properties in terms of definite triaxial stress conditions. In view of this limitation, the engineering field is forced to rely on the unreliable procedure of empirical correlation with service performance for the utilization of notch-test data.

The welding engineer is in a particularly unfortunate position, since very little is known of the performance of full welds except in simple uniaxial tension. Thus, even the most approximate form of empirical correlation between the performance of notched-weld tests (as represented by the bead-on-plate weldability tests) and full welds in service is not possible.

It appears imperative at this time that a part of the welding research effort be dedicated to furthering the study of the full-weld performance. The Hatch Corner and Box Girder investigations, with the related notched, bead-on-plate weldability-test studies, represented a specific type of strictly empirical approach to the performance of full welds in complex structures. The empirical correlations which resulted from these studies have been largely inconclusive, owing partly to the few structural tests which were performed and partly to the complexity of the performance interpretations which were required. Retrospectively speaking, it appears that too great a jump was made from the simplified bead-on-plate laboratory tests to full welds in complex structures. The basic difficulty has been and remains the lack of a suitable semi-works-scale test for investigating the performance of full welds. One of the real needs of the welding field at this time is a relatively inexpensive structural test of full joints that will feature a simple geometry and permit testing under controlled loading conditions. Such a test may be viewed as the intermediate step required to tie the results of laboratory metallurgical and weldability tests to the performance of weldments as component parts of structures.

This report is concerned with the development and initial use of a semi-works-scale test of full welds. The initial use made of the test entailed a fundamental study of the deformation characteristics of various weld joints.

Basis for Choice of Test Method

It has been stated previously that the experimental techniques available for the investigation of the behaviour of metals in controlled stress fields are limited to biaxial loading and include: (a) tube tests - which require axial tension concomitantly with internal hydrostatic pressure, and (b) bulge tests - which require fluid or gas pressure on edge-supported diaphragms.

Tube or bulge tests therefore provide a possible means by which full welds may be tested, within certain limitations, under controlled loading conditions. The limitations are that the weldment be in the form of a tube or plate and that the imposed load control be biaxial. There are relative advantages and difficulties to be considered in arriving at a choice between these test methods. The tube test has the advantage of providing uniform strain conditions over a wide test area. This advantage is partly theoretical inasmuch as excessively long tubes are required to provide a central zone sufficiently removed from the grips to eliminate end-bending effects. The disadvantages of the tube test are the complex equipment required and the experimental difficulties of setting up and conducting the tests. Tube tests are extremely expensive and have been primarily limited to fundamental research in the field of applied mechanics. It is interesting to note that a limited study of the performance of welds has been conducted by tube tests.[1] This investigation resulted in the only prior report of the performance of welds in controlled biaxial-load fields. The results of these tests are discussed in detail in a later section of this report.

The advantages of bulge tests lie in the simplicity of equipment and experimental procedures required. The principal disadvantage of these tests is the relatively small area of pole region which may be classed as effectively under uniform strain. The bulge test has been utilized by a number of investigators for the study of the flow and fracture of metal sheets under combined stresses.[2,3] The bulges are ordinarily produced by

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[1] "The Effect of Temperature and Welding Conditions on the Strength of Large Welded Tubes" by G. E. Troxell, E. R. Parker, H. E. Davis, and A. Boodberg, The Welding Journal, Vol. 27, (2), 35s-48s (Feb. 1948)

[2] "The Plastic Flow of Aluminum Alloy Sheet Under Combined Loads" by W. T. Lankford, J. R. Low, and M. Gensamer, Trans. AIMME, Vol. 171, 574-604 (1947)

[3] "Stress and Strain States in Elliptical Bulges" by C. C. Chow, A. W. Dana, and G. Sachs, Journal of Metals, Vol. (1), 49-58 (1949)

hydraulic pressure applied to a test diaphragm clamped over a circular or elliptical opening. It is well known that spherical bulges developed from a circular diaphragm represent a condition of balanced biaxial stress, and that the stress in ellipsoidal bulges is unbalanced with the major stress in the minor axis direction and the minor stress in major axis direction. The degree of stress unbalance developed in ellipsoidal bulges is a function of the relative ratios of the two principal axes of the ellipse but is not in exactly the same numerical ratio.

It should be noted that bulge tests of thick plates develop bending conditions which give rise to a reaction stress* component in the thickness direction. Although the value of this third stress component cannot be determined directly, it may, from theoretical considerations and from observations of bulge fracture performance, be considered minor in comparison to the two principal stresses in the plane of the plate. The important feature to be noted for such bulge tests is that performance of the full weld may be evaluated in terms of exacting control over two of the three possible principal-stress directions. Such tests offer particular promise for the investigation of the effect of weld orientation in relation to imposed biaxial-load fields. Inasmuch as biaxially loaded plates, with or without a minor third stress component, are fairly common in structures (ship-plate weldments for example), the information obtained has direct applicability in addition to fundamental research value.

The controlled biaxial-stress conditions made possible by bulge tests and the simplicity of the test weldment provide the desired features for a semi-works-scale test if sufficient force can be developed for bulging heavy-plate weldments. Snellings' procedures[4,5] for direct-explosion testing demonstrated that explosives could be utilized for such a purpose. Snellings' technique of contact explosion does not provide the uniform loading required for a true bulge test. Recourse can be made to offsetting the explosive and shaping the charge to a wafer so as to provide for a flat explosion wave of uniform intensity. It should be noted that removing the explosive from direct contact with the test plate has the advantage of minimizing the shock wave or brisance effect of explosives which are inherently variable and difficult to control. With offset conditions, the effect of the explosive is primarily that of rapid loading by very high gas pressure. The gas pressure from an explosion is inherently more reproducible and requires a minimum of procedural control. Contact explosion conditions, on the other hand, require exacting brisance control, which can be obtained only with specialized explosives.

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*Reaction stresses are defined as stresses resulting from restraint to plastic flow. Such stresses are ordinarily present in regions of severe strain gradients such as exist at notches or at thick sections undergoing severe bending. Standard texts such as Timoshenko's "Strength of Materials" and Nadai's "Plasticity" treat the bending problem quantitatively only for conditions such that the stress in the thickness direction is sufficiently small to be ignored; i.e., for bending of members such that the radius of curvature is very great compared to the thickness. Such simplified "plane stress" conditions (A. Nadai: "Plasticity," McGraw-Hill Book Co., New York (1931) page 182) do not apply for drastic bending conditions.

[4] "Direct Explosion Test for Welded Armor Plate" by W. O. Snelling, Report OSRD No. 1206, Ser. No. M-41, NDRC Project NRC-25 (Feb. 1943)

[5] "Direct Explosion Test for Welded Armor and Ship Plate: Prime and Welded Plate" by W. A. Snelling, Research Project NRC-25 under Navy Contract Nobs-31223, Final Report, Ser. No. SSC-4 (Aug. 1946)

Technique of Explosion Bulge Testing

A standard military explosive (Demolition Block M3, Composition C3) was used for all tests reported herein. This explosive, which has the appearance and consistency of soft wax, is readily shaped to a circular or elliptical wafer of the size and shape of the opening in the die.

The test weldment, which consisted of a 20″ x 22″ plate produced by butt-welding two 10″ wide plates, was placed over a circular (r = 6″) or elliptical (a = 7.5″ b = 4.8″) opening cut in a 4″-thick armor saddle-plate. The die opening was chamfered to provide smooth entry of the bulge into the die cavity. The explosive wafer was then located at a distance of 12 to 24 inches (depending on the standoff required) above the test plate. An expendible pasteboard box was used as a support. The arrangement is shown in Figure1. Detonation was by means of an electrical primer. The unsupported area of the plate was approximately 28% of the total area; the remainder of the plate was effectively clamped to the armor die by the gas pressure of the explosion, thus providing the required "hold-down" without need of a bolting ring. The effectiveness of the "hold-down" was evident from observation of bulged plates, which remained perfectly flat over the supported area.

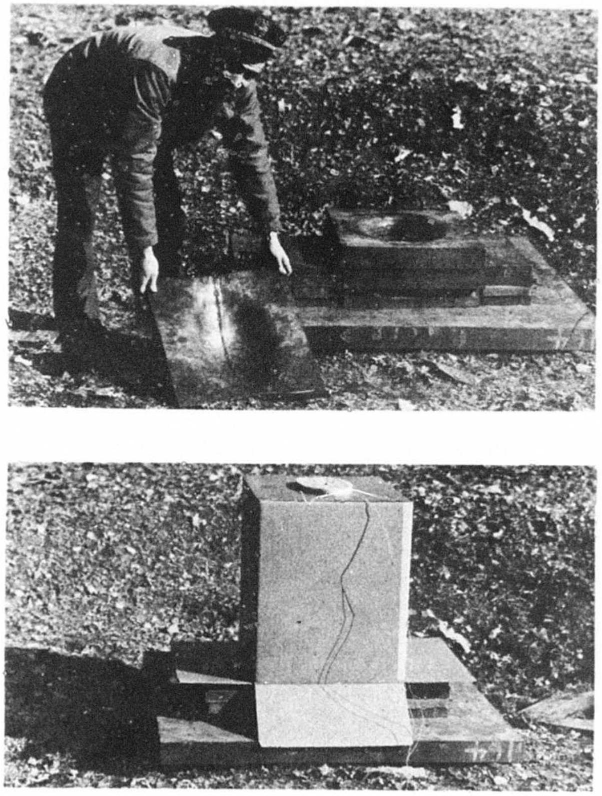


Figure 1 - Explosion bulge test equipment illustrating simplicity of test procedures

The simplicity of this test procedure permits testing at temperatures other than ambient by the simple expedient of soaking test plates in a controlled-temperature cabinet, removing them as required, and placing them over the die for test. Critical temperature control is readily obtained by spot-welding thermocouples to the plate, and detonating at the required temperature. For most work, however, the temperature drop during the time required for locating the plate and explosive is insignificant.

It was determined that the size of bulge could be exactingly controlled by varying the weight of charge and "standoff." Figure 2 presents an empirical chart of bulge depth versus weight of charge, with standoff a parameter, as determined for a high-tensile low-alloy steel. The plot of points of repeat tests indicates the high degree of reproducibility obtained. The excellent control possible with explosion loading tests was also shown in the weld strain studies to be described.

WELD DEFORMATION STUDIES

Choice of Weldments and Scope of Studies

It has long been almost axiomatic that a theoretically perfect weld requires: (a) exact matching of mechanical properties between weld deposit, heat-affected zone (HAZ), and base material; and (b) freedom from flaws. This general premise is being challenged at present by some investigators on the grounds that it is not realistic to expect attainment of this double goal in practice. A solution which has been proposed entails the use of weld deposits overmatching the flow strength of the parent plate, and featuring high notch toughness. In view of the diversity of opinion which prevails on the relative merits of matching vs. overmatching and the importance of this question to the welding field generally, it was decided to direct the bulge test to a study of this problem. As a first approach, it was deemed desirable to obtain basic information as to the nature of plastic deformation over the entire weld-joint zone of matching and overmatching weld deposits. The studies included balanced (1-1) and unbalanced (0.8-1) stress fields, with weld orientations varied

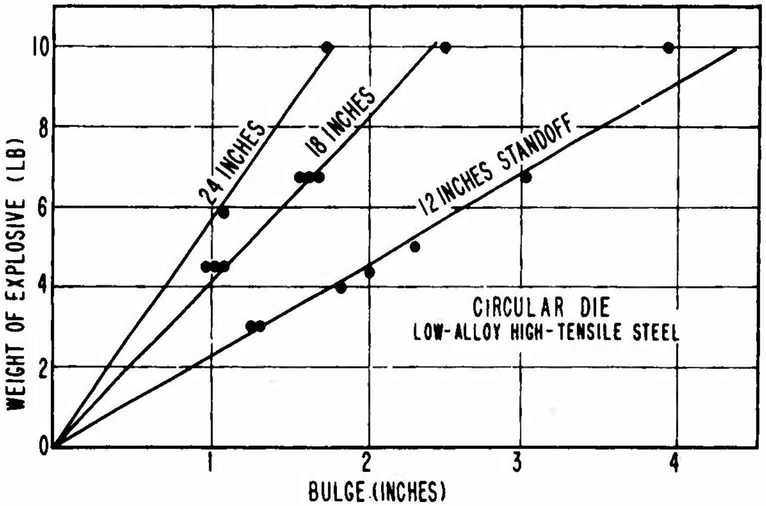


Figure 2 - Control of bulge deformation

relative to the major stress in the case of the unbalanced stress fields. Tests were also performed on prime plate material to provide a reference strain-field condition. All strain measurements were made at arbitrary levels of general strain well below the critical strain producing fracture. Inasmuch as the present studies were concerned only with strain-distribution characteristics and not with fracture, no attempt was made to hypothesize fracture modes. The relation of stress state to fracture is a subject of continuing research.

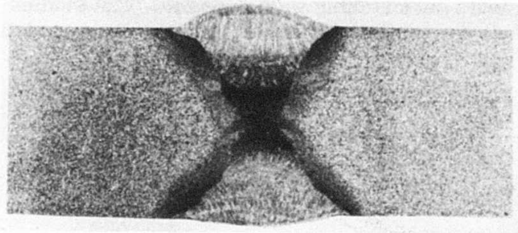
Material

The material used in this investigation was taken from a single heat of commercial silicon-killed firebox-steel plate, 3/4" thick, ordered to Specification A201 Grade A as follows:

Chemical Analysis (%)					Tensile Properties (psi)		
C	Mn	Si	P	S	Yield Point	Tensile Strength	Elongation
0.18	0.44	0.24	0.013	0.039	38,540	64,380	29.9%

Welding Procedure

As part of this investigation it was considered desirable to include a special research-type weld of the simplest possible geometry; viz., a single-pass butt-weld with heat-affected and fusion-zone demarcation lines vertical with respect to the plate surface (Figure 3). Thus, any cross section parallel to the weld would contain a single microstructure and would consequently be a plane of uniform physical properties.



Manual — Multipass

Submerged Arc — Single Pass

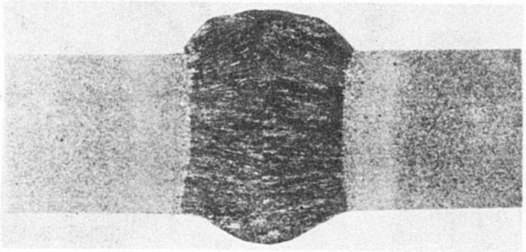


Figure 3 - Geometry of weld deposits

The joint preparation and welding technique used to obtain the desired weld geometry consisted of machine-beveling the plate to a 30-degree included angle and submerged-arc welding at 1300-1325 amperes, 32-33 volts, and 12 inches per minute travel. A refractory "back up" was used for support. Two types of weld deposits were produced with this square geometry: a low-alloy deposit (0.13% C, 2.0% Mn), which is widely used for welding low-alloy high-tensile steels; and a high-alloy submerged-arc deposit of composition similar to SAE 6130. A commercial submerged-arc-welding melt, size 20 x 200, was used for both welds.

For comparison with the research-type submerged-arc weld, manual-multipass, E12016, butt welds were prepared with a geometry similar to that commonly used in ship construction. The plate edge preparation consisted of a 60-degree double-V joint as shown in Figure 3.

Explosion Procedure

The unwelded bulges and all welded bulges except for the high-alloy submerged-arc weld were formed at 60°F using 4 pounds of explosive at a 12″ standoff. In order to deform the high-alloy weld without causing fracture, the testing temperature had to be raised to 180°F and the standoff increased to 18″. This change in test conditions resulted in a somewhat smaller bulge.

Measurement of Strain

Strains were determined by measuring the distortion of a 20-line-to-the-inch grid applied to the test plate by a photogrid process. (Details of application appear in the Appendix.)

Measurement of grid distortions was accomplished by means of a microscope mounted on a micrometer slide which in turn was supported by three adjustable legs (Figure 4). Two sources of error were involved in the strain readings, viz., the inherent error in the spacing of the grid lines (approximately ± 0.0005″), and the error of the observer in centering the microscope crosshair on the grid line and reading the vernier (again approximately ± 0.0005″). The scatter resulting from these errors was found to be excessive if the gage length of the strain determinations was taken as one grid spacing. Compensating errors in the grid spacing reduced the scatter band to a reasonable width at a gage length of 0.100 inch which was the gage length used throughout this study.

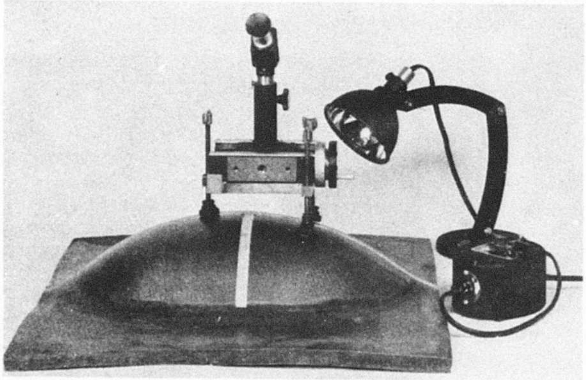


Figure 4 - Strain measurement

Microtension Test

As part of the problem of interpreting the deformation characteristics of welds, information is required concerning the individual flow properties of the various components of a weld joint. Inasmuch as there is no established method for testing the very small volumes of metal involved, a small notched tensile specimen was designed, together with a contractometer device for obtaining continuous readings of the reduction in diameter at the base of the notch. Figure 5 shows the contractometer and a specimen in place for test. It was thus possible to obtain true stress-strain or flow curves of small volumes of metal in the order of 0.002 cubic inches. The effect of the notch of the microtensile specimen in introducing triaxiality, and thereby raising flow strength, may be deduced from Figure 6, which presents for comparison base-metal, true stress-strain flow-curves, as determined (a) with a standard 0.357-in. tensile specimen, and (b) with the notched microtensile specimen.

DISCUSSION OF STRAIN DISTRIBUTIONS

Unwelded Prime Plate

The discussions which follow have been restricted to the conditions of strain state and absolute strain level at the pole of the bulge. The pole is defined as the region at the apex of the bulge which does not show strain distortions arising from hold-down or edge effects. Hold-down effects may be noted as peculiarities in the strain curves developed as the edge regions of the bulges are approached. These conditions are recognized as specific to bulge mechanics and therefore not pertinent to the present discussions. Absolute uniformity of strain level would be desirable over the entire pole region; but, as previously stated, bulge tests inherently approach but do not achieve such a condition. For purposes of this study it was considered necessary that a region of essentially

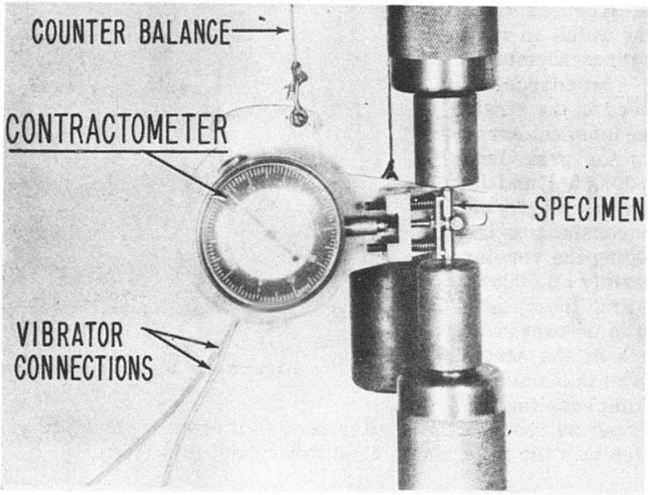


Figure 5 - Details of contractometer and microtensile specimen

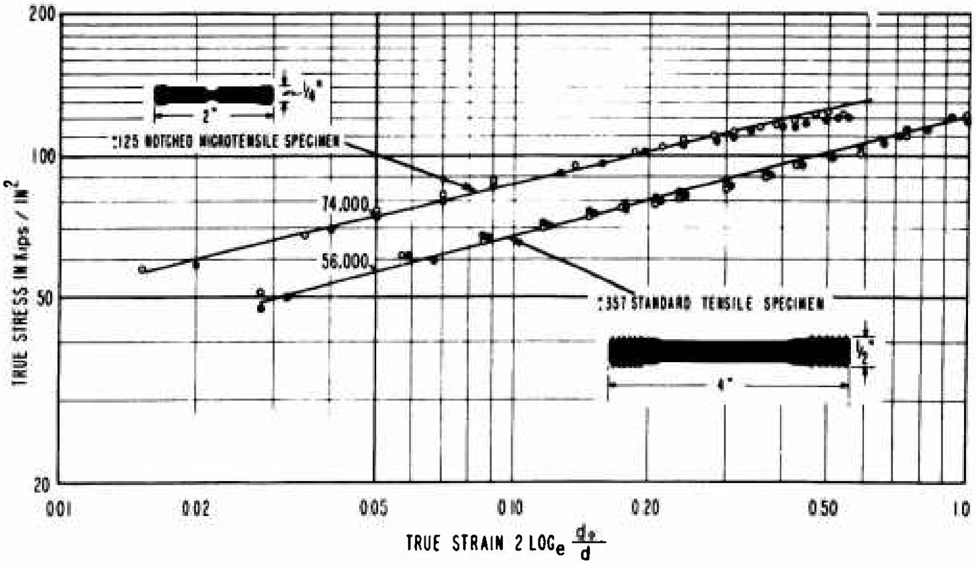


Figure 6 - Comparison of base metal flow curves illustrating the effect of notch on flow strength

uniform strain be developed which would be of sufficient size to encompass the weld, HAZ, and a portion of the unaffected plate in the test weldments.* This requirement was met in both the circular and elliptical bulges.

It should be noted (Figure 7) that the elliptical die geometry develops a bulge having an unbalanced biaxial strain field of 1-2 (0.050/0.100) ratio. If the plate is considered essentially isotropic, the stress field may then be deduced to be in the order of 0.8-1, i.e., the stress along the major axis is 0.8 of the stress along the minor axis.† It should also be noted that the component of the strain parallel to the minor axis (major strain) is consistently designated as e_1, and the component parallel to the major axis (minor strain) as e_2.

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* In consideration of the normal scatter, the strain was considered to be essentially uniform if the deviation of the faired-in curve from the maximum was no greater than 0.01 in./in.

† Reciprocal calculations for any stress or strain ratio may be made by means of the following formulae.

$S_1 - 1/2(S_2 + S_3) = D\,E_1$ S_1, S_2, S_3 Principal stresses

$S_2 - 1/2(S_1 + S_3) = D\,E_2$ E_1, E_2, E_3 Principal strains

$S_3 - 1/2(S_2 + S_1) = D\,E_3$ D = Plastic modulus

Accordingly, it may be calculated that balanced biaxial stress fields result in balanced biaxial strain fields, and unbalanced biaxial stress fields produce unbalanced strain fields. The strain ratios of unbalanced strain fields, however, are not simply in the ratio of the principal stresses. Thus, a strain ratio of $E_2/E_1 = 1/2$ represents a stress ratio $S_2/S_1 = 0.8/1.0$; $E_2/E_1 = 0/1$ represents a stress ratio $S_2/S_1 = 0.5/1.0$.

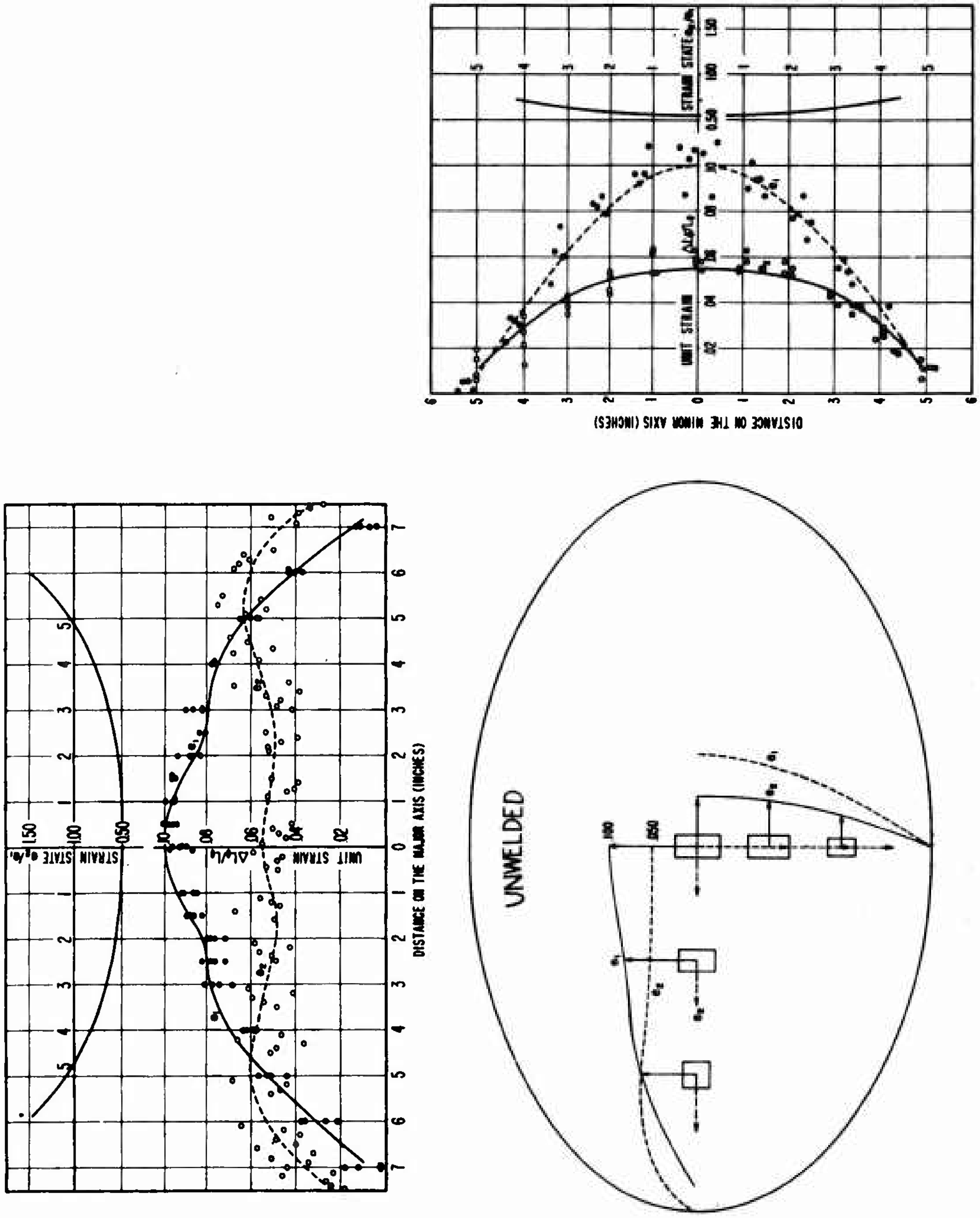

Figure 7 - Distribution of strain in an unwelded elliptical bulge

In the case of the circular bulge, the convention of designating the radial strain as e_1 and the tangential strain as e_2 was adopted. The circular bulge (Figure 8) develops a balanced biaxial strain field (0.070/0.070) which is the result of a balanced biaxial-stress field. The simplified sketch of strain distribution at the lower left of Figure 7 and 8 is intended to provide a means of ready reference and orientation for the reader. This sketch includes schematic elements which are scaled to represent grid distortion. Squares indicate equal extensions in all directions and rectangles indicate greater strain in one direction. In Figures 10 - 16 the schematic for the unwelded bulge will be included so that direct evaluation of the effect of the weld may be made. Note that Figure 7 is unique in that the strain distribution for the full length of both axes is shown, though only half of each axis is represented in the schematic. The ratio of strains e_2/e_1 defines the strain state and shows the degree of unbalance of the combined strains. The ratio has been computed from the distribution curves for e_1 and e_2, and is plotted against distance on the major and minor axes in each of the figures showing distribution of strain.

Welded Plates

The introduction of welds generally resulted in marked modification of the strain characteristics in the weld and near-weld regions as compared to the same position in the unwelded bulges. The plate regions removed from the weld zone, however, matched the strain characteristics of the unwelded bulges. It should be noted that modifications of strain fields in the weld and near-weld zones indicate concomitant modifications of stress fields. This is so because the principal strains bear a rigorous relationship to the principal stresses as described by the reciprocal calculations presented previously. Thus, the stress-strain conditions in the weld-joint area may differ considerably from the imposed stress-strain conditions in the homogeneous portion of the bulge. These localized changes are strictly the result of introducing heterogeneous zones having different properties from the remainder of the test area.

In order to interpret the strain-field patterns in terms of the intrinsic strength properties of the weld-joint zones, measurements were obtained by means of using the microtensile technique previously described, of the relative flow strengths of the weld deposit, of various positions in the HAZ, and of the prime plate. These data are presented in the form of flow curves in Figure 9, and summarized in the following table as relative levels of flow strength at a fixed level of strain — in this case arbitrarily chosen as 0.05 strain.

Table A
Relative Flow Strength (PSI at 0.05 Strain) of Weld-Joint Zones

	Weld	Max. HAZ	Plate
Low-Alloy Submerged Arc	81,000	78,000	74,000
High-Alloy Submerged Arc	117,000	78,000	74,000
E12016 Manual	140,000	78,000	74,000

The application of these data for the purpose of understanding the nature of weld deformation is simplified by utilization of the concepts of "Equivalent Load" and "Equivalent Strain" conditions. According to these concepts, each stress of the biaxial field is visualized as acting separately and developing certain specific effects which depend on the orientation of the stress to the weld. Any stress (major or minor) applied in a direction transverse to the weld is deemed to place the weld, the HAZ, and the prime plate in a

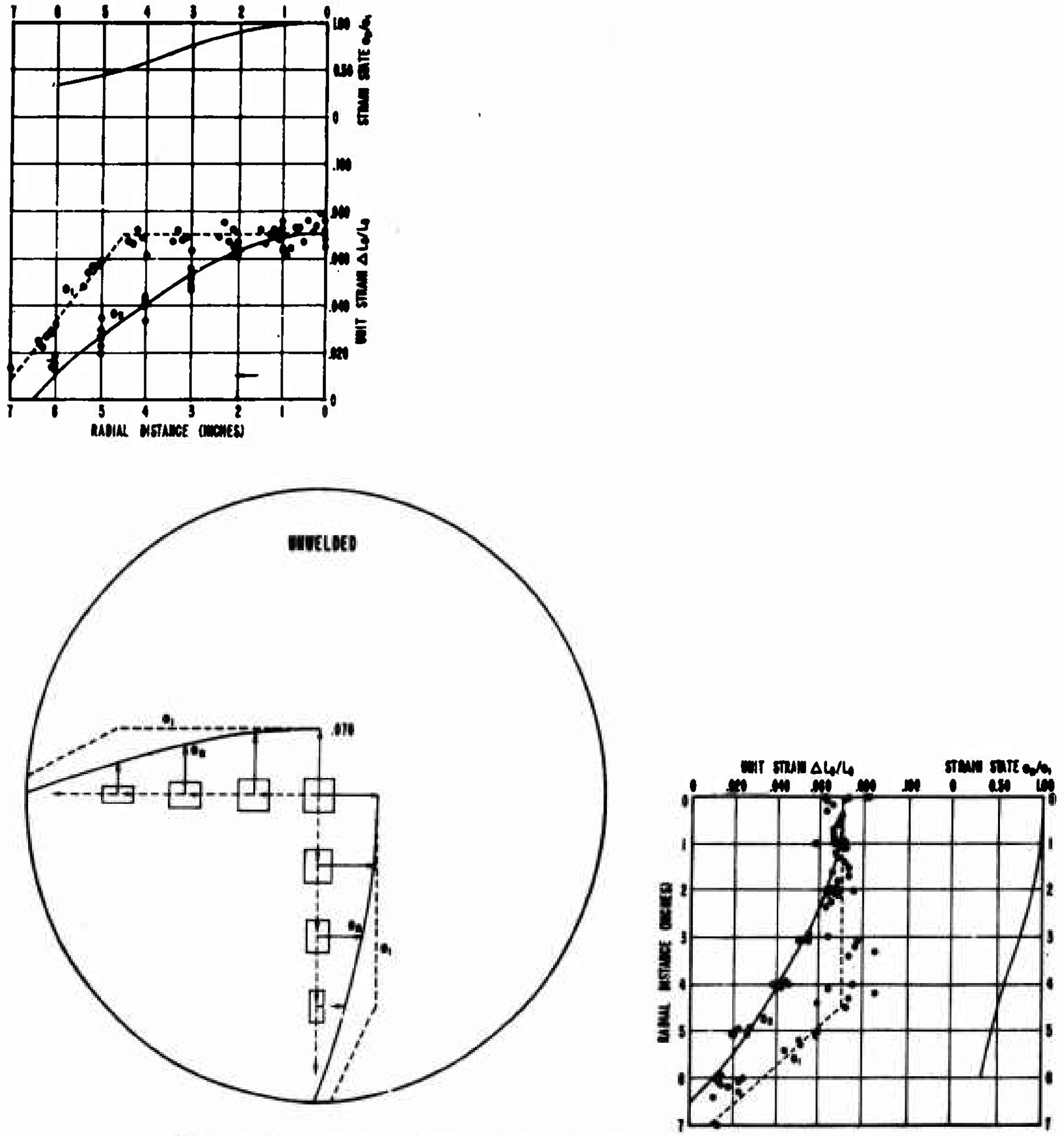

Figure 8 - Distribution of strain in an unwelded circular bulge

state of "Equivalent Load"; i.e., as a first approximation all component parts of the weld joint must perforce support the same load (but not the same stress because of section diminutions resulting from flow). The strain in these various components may, however, differ widely, depending upon their relative flow strengths. Any stress applied parallel to the weld is deemed to place all weld zones in a state of "Equivalent Strain"; i.e., as a first approximation, all components must strain essentially the same amount, but the stresses in the various components may differ widely, depending upon their relative strength levels. It will be shown in the discussion of weld flow characteristics which follows that the observed strains are in accordance with these concepts.

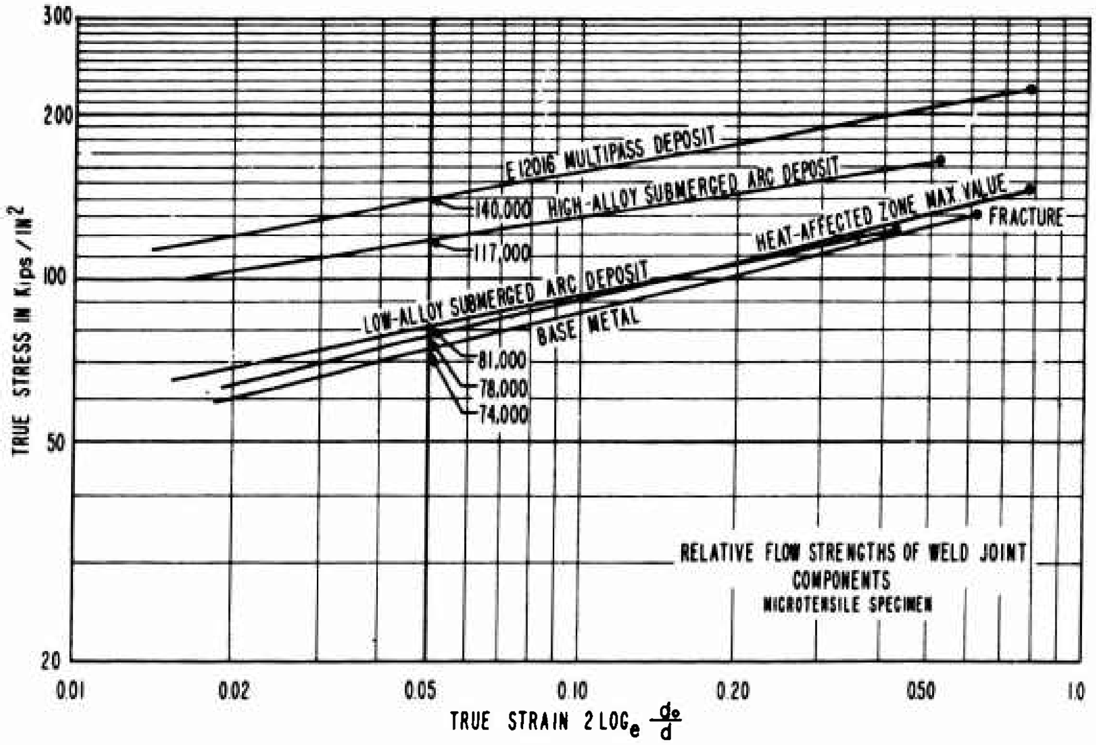

Figure 9 - Relative flow strength of weld-joint components

Low-Alloy Submerged-Arc Weld

The low-alloy submerged-arc weldments consisting of a single-pass, square-sided, butt weld with reinforcement ground flush were tested in three conditions:

(1) Balanced biaxial stress.

(2) Unbalanced biaxial stress with weld perpendicular to principal stress.

(3) Unbalanced biaxial stress with weld parallel to principal stress.

Pertinent data are presented in Figures 10, 11, and 12.

These weldments represent close matching of weld-joint and prime-plate flow strengths. As listed in Table A, the weld deposit and HAZ exceeded the plate flow strength by only 7,000 and 4,000 psi respectively. It is interesting to note that this very small difference in relative flow strengths was sufficient to decrease or deconcentrate strain from the weld region in the "Equivalent Loading" stress direction (transweld) in each of the three tests. Figure 10 shows that the normal balanced (0.070/0.070 ratio) strain condition produced in the unwelded circular bulge has been unbalanced to a 0.040/0.070 ratio by the presence of the weld. The change to an unbalanced strain field in the weld denotes a change in the stress field from the imposed balanced biaxial stress to unbalanced biaxial stress with the major stress in the weld longitudinal direction. It is surprising that the strain

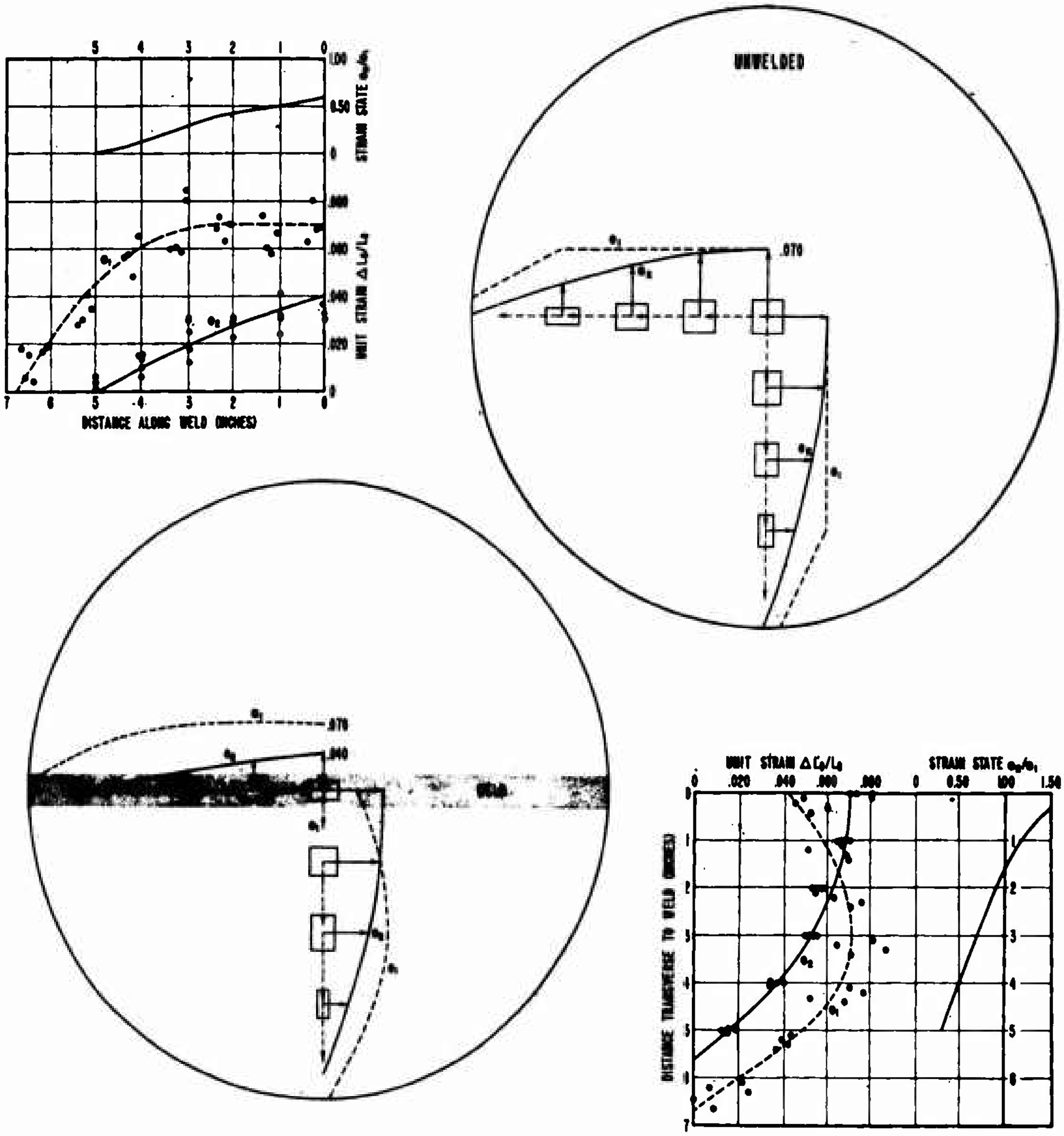

Figure 10 - Distribution of strain in a bulge with closely matching weld-metal and base-metal flow strengths. (Low-alloy submerged-arc deposit)

deconcentration effects extend into the unaffected prime plate approximately one-half inch beyond the edge of the darkly etching HAZ.*

Figures 11 and 12 show the effect of varying the orientation of the weld in the 0.8-1 unbalanced stress field of the elliptical bulge. A definite deconcentration of strain in the transweld or "Equivalent Loading" stress directions is noted in both tests. In the case of the weld located transverse to the major stress (Figure 11) the 1-2 (0.050/0.100) strain ratio of the unwelded plate is changed to 0.050/0.085 ratio by virtue of deconcentration of the major strain. In the case of the weld located parallel to the major stress (Figure 12) the deconcentration takes place across the minor stress direction, thus decreasing the minor strain value. This results in a strain ratio of approximately 1-3 (0.030/0.100). In both of these tests it should be noted that the strain along the weld or "Equivalent Strain" direction is not significantly changed in value from that indicated by the unwelded plate in corresponding directions, and that the strain deconcentration effects of the weld tend to extend outward beyond the weld into the unaffected plate as noted in the case of the circular bulge.

High-Alloy Submerged-Arc Weld

The high-alloy submerged-arc weldments were similar to the low-alloy submerged-arc weldments in having the same square geometry and in being made with a single-pass technique. It should be noted, however, that the explosion test conditions used for bulging were somewhat modified by raising the test temperature and increasing the standoff distance, as described previously, in order to prevent fracturing of the weld at the bulge size desired for strain measurement. Strict comparison on the basis of absolute magnitude of strain cannot therefore be made; comparisons based on ratios of strains are, however, considered valid. These welds overmatched the prime plate by approximately 43,000 psi (117,000 psi vs. 74,000 psi). Tests were performed in unbalanced tension† with the weld oriented parallel and perpendicular to the principal stress direction (Figures 13 and 14).

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*This condition is believed to arise from the restraint action (Poisson effect) extending out as reaction stresses from the weld region, which is in a less advanced stage of deformation through the thickness direction (e_3 strain). Constancy of volume considerations dictate that the algebraic total of the $e_1 + e_2 + e_3$ strains equal zero. Inasmuch as the transweld strain is less than the corresponding strain of contiguous material and the weld longitudinal strain is the same as that of contiguous material, it follows that the (e_3) thickness strain in the weld must be of lower-than-general value. This effect is distinctly visible as a relief of the weld in the case of strongly overmatching deposits.

†Inasmuch as the data obtained for the low-alloy weldment with balanced tension (circular bulge) indicated the same general trends and characteristics shown in unbalanced tension (elliptical bulge), subsequent weld tests were limited to unbalanced tension.

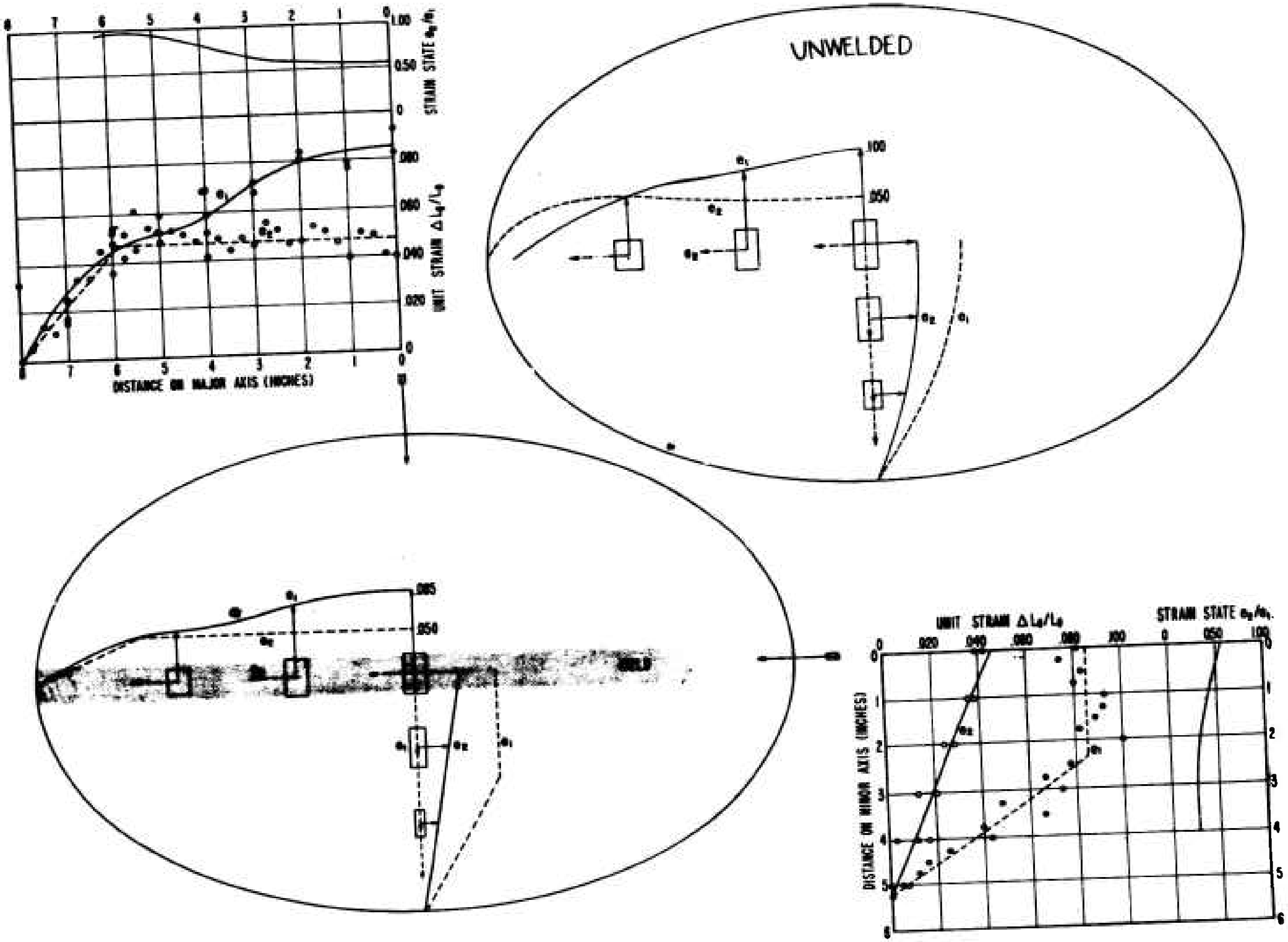

Figure 11 - Distribution of strain in a bulge with closely matching weld-metal and base metal flow strengths. (Low-alloy submerged-arc deposit)

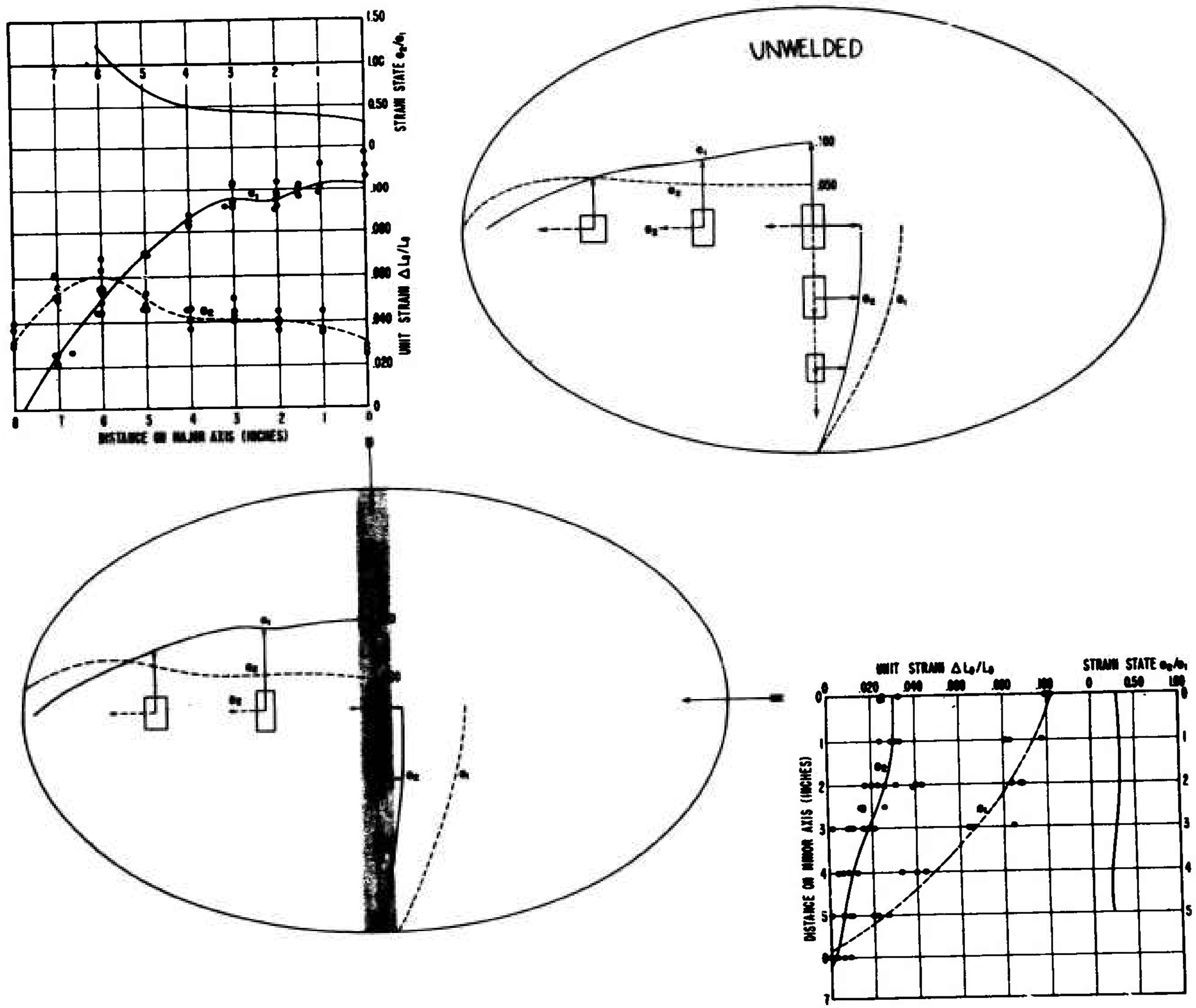

Figure 12 - Distribution of strain in a bulge with closely matching weld-metal and base-metal flow strengths. (Low-alloy submerged-arc deposit)

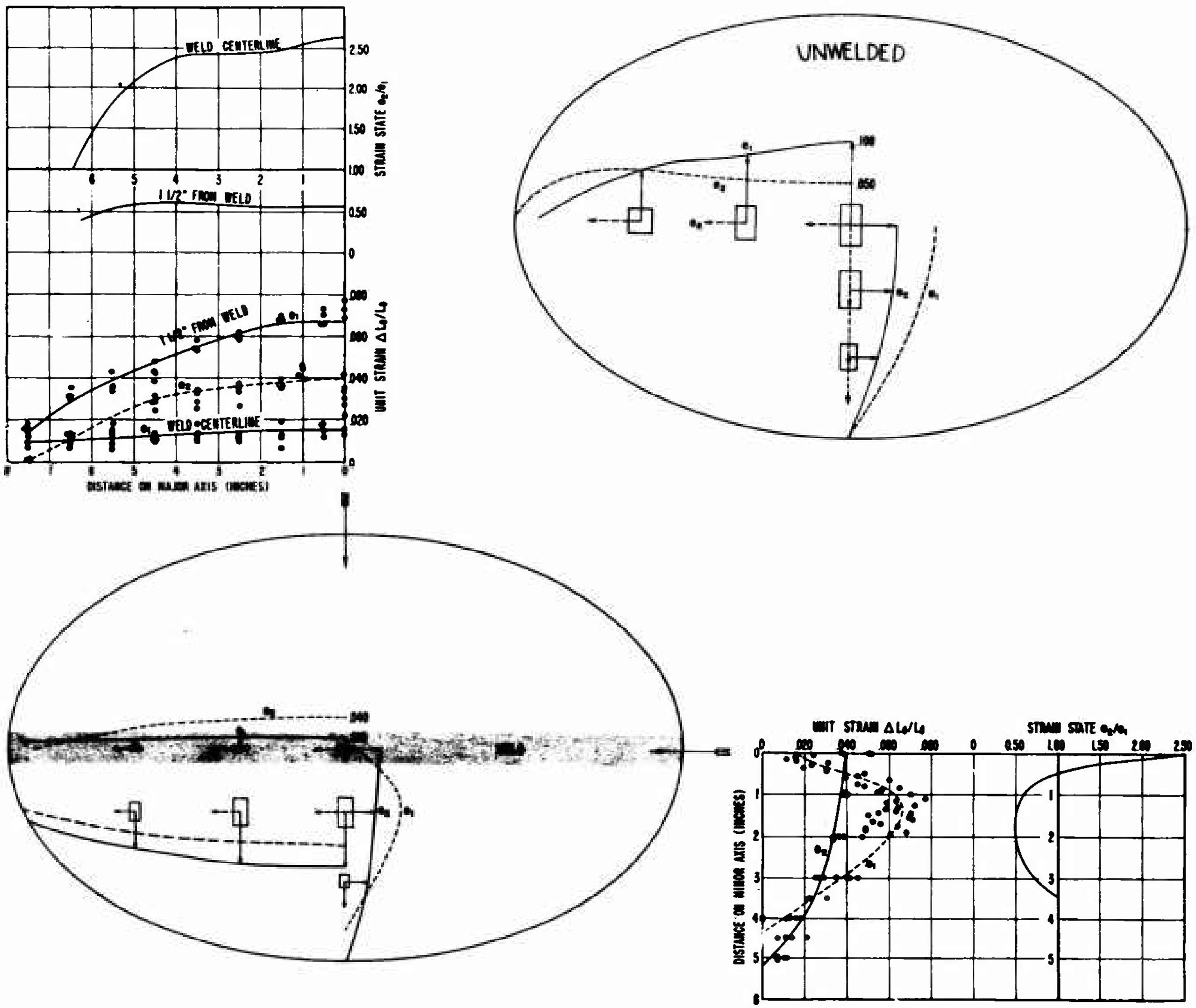

Figure 13 - Distribution of strain in a bulge containing a high-strength butt weld. (High-alloy submerged-arc deposit)

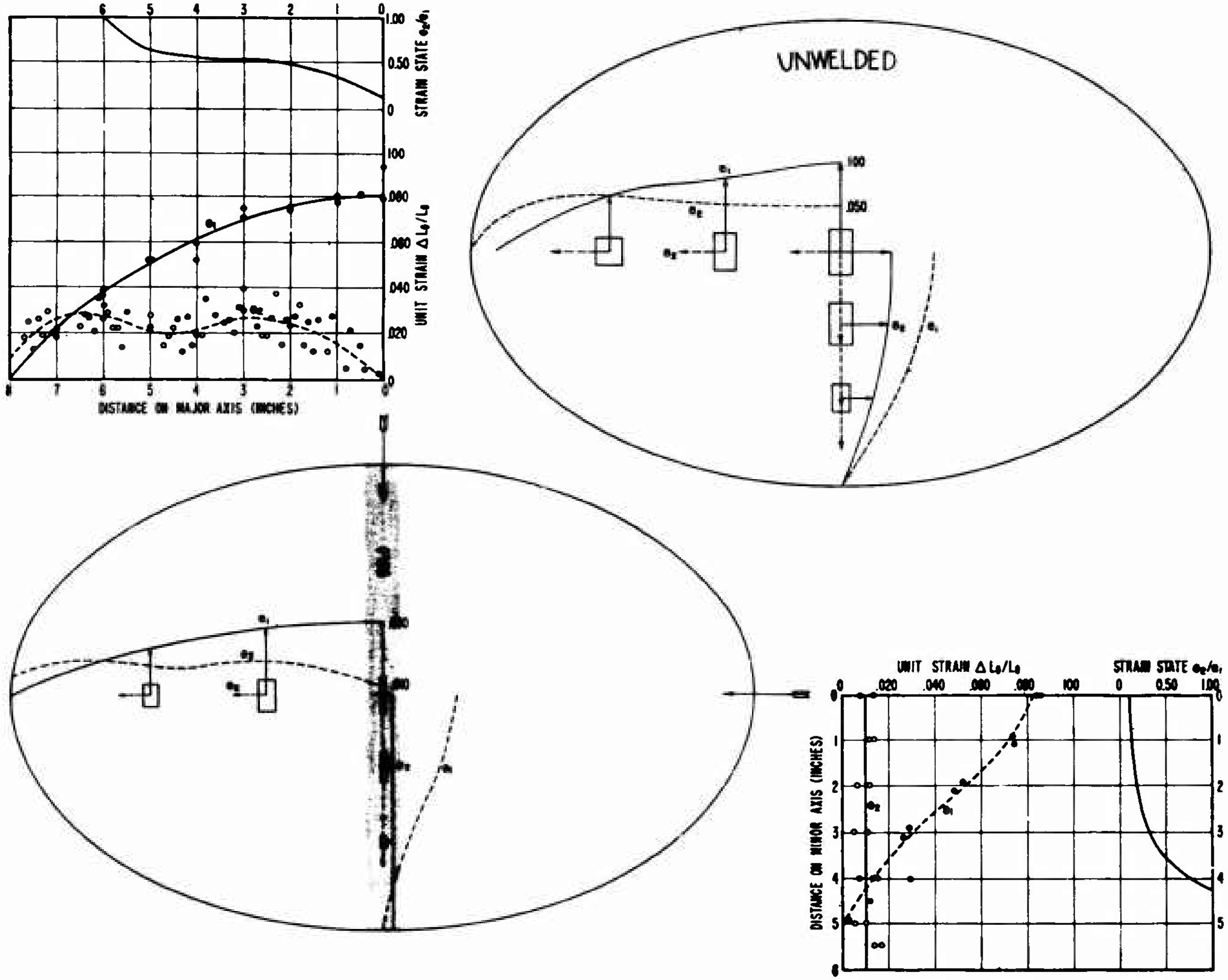

Figure 14 - Distribution of strain in a bulge containing a high-strength butt weld. (High-alloy submerged-arc deposit)

It is noted that with the major stress oriented across the weld, the resultant strain in the transweld direction (Figure 13) was deconcentrated to the extent of unbalancing the strain ratio from 1-2 (0.050/0.100 unwelded) to approximately 3-1 (0.040/0.015) thus marking a complete reversal of the strain (and stress) field. In the case of the weld orientation which placed the minor stress across the weld (Figure 14) the strain deconcentration effect changed the strain ratio from 1-2 (0.050/0.100) to 1-8 (0.010/0.080). Although exact comparison cannot be made, it should be noted that the strain in the weld direction is of approximately the same magnitude as the corresponding strains in the unwelded bulge; namely, 0.080 vs. 0.100 and 0.040 vs. 0.050 in the major and minor stress directions respectively.

The strain-deconcentration effect of the weld extends into the base plate for approximately the same distance noted for the low-alloy weld.

It is interesting to note that comparison with the lower-strength, square-sided, single-pass weld clearly shows a more severe deconcentration effect for the higher-strength deposit.

E12016 Weld

E12016 weldments consisting of multipass, double-V, butt welds with the reinforcement removed were tested in unbalanced tension with the weld oriented parallel and perpendicular to the principal stress direction (Figures 15 and 16).

This weld represents considerable overmatching of the prime plate. As shown previously (Table A), the weld flow strength at 0.05 strain exceeded that of the plate by 66,000 psi (140,000 psi vs. 74,000 psi). Severe deconcentration effects were noted in the transweld direction of both tests performed. In the case of the major stress acting across the weld (Figure 15), the 1-2 (0.050/0.100) unbalance of the unwelded bulge was modified to 1-1 (0.040/0.040) balance as the result of deconcentrations of the major strain. In the case of the minor stress acting across the weld (Figure 16) the minor strain was reduced from 0.050 (unwelded) to 0.015; thus, the strain unbalance changed from 1-2 (unwelded) to approximately 1-7 (0.015/0.100). In either case (weld parallel or perpendicular to major stress) the strain along the weld was not significantly changed from the values noted for the unwelded plate in corresponding positions and directions. A strain survey made 1-1/2 inches from the weld and parallel to the weld (Figure 15) further substantiates this conclusion. The strain deconcentration effect of the weld is noted to extend into the unaffected base plate for a distance of approximately one-half inch beyond the edge of the darkly etching HAZ.

Although the degree of overmatching of the E12016 weld was greater than that of the high-strength square weld, the strain deconcentrations in the transweld direction were significantly lower. It is believed that this behaviour results from the square geometry of the lower strength weld. (See Figure 3 for etched cross sections of the square and double-V welds). It may be deduced that the V-geometry places the high-strength weld material in parallel loading with the lower-strength base-plate material, resulting in a combined strength of intermediate value; the square geometry obviously does not permit such a condition.

Summarization of Strain Distributions

A generalized analysis of the strain distributions of closely matching and overmatching welds in biaxially loaded stress fields indicates the following basic pattern:

(1) The presence of overmatching welds results in marked modification of the strain field, not only in the weld deposit and HAZ zones but also outward into the unaffected base material.

(2) The change in the strain field caused by overmatching welds is determined by a deconcentration of the strain component transverse to the weld. Weld strains in the direction of the weld length are not significantly affected. This mechanism appears to be general for biaxially loaded stress fields, and is independent of the orientation of the weld relative to the major stress direction.

(3) The orientation of overmatching welds in unbalanced biaxial load fields determines the maximum and minimum values of the greatest deformation (principal strain) developed in the weld. A maximum value is reached when the weld is oriented in the direction of the major stress, and is always along the length of the weld regardless of relative overmatching characteristics. A minimum value of the principal strain is reached when the weld is oriented in the direction of the minor stress. However, the direction of the minimum principal strain varies with overmatching characteristics; it is ordinarily transweld, but shifts to a longitudinal direction if overmatching and consequent deconcentration effects are sufficiently severe to reverse the strain field.

(4) The degree of strain deconcentration produced by overmatching welds appears to be a function not only of the relative degree of overmatching but also of the geometry of the weld.

(5) The strain modifications observed in the weld and near-weld zones may be translated in terms of modifications in stress fields. Generally, in keeping with the noted changes in strain fields, it may be deduced that (a) overmatching welds in balanced biaxial loading will develop highly unbalanced biaxial stress conditions, (b) overmatching welds in unbalanced loading will approach stress balance and even produce a complete reversal of the direction of major stress if the weld is placed in the direction of the minor load, and (c) overmatching welds will develop increased stress unbalance if the weld is placed in the direction of the major load.

(6) It should be noted that items 1-5 are specific to conditions entailing plastic deformation of weldments. In the elastic range, the elastic strains of all components are determined by the elastic modulus, which is essentially invariant for steels. Accordingly, no modifications of elastic strains should be expected and the weldment should strain as if it were metallurgically homogeneous.

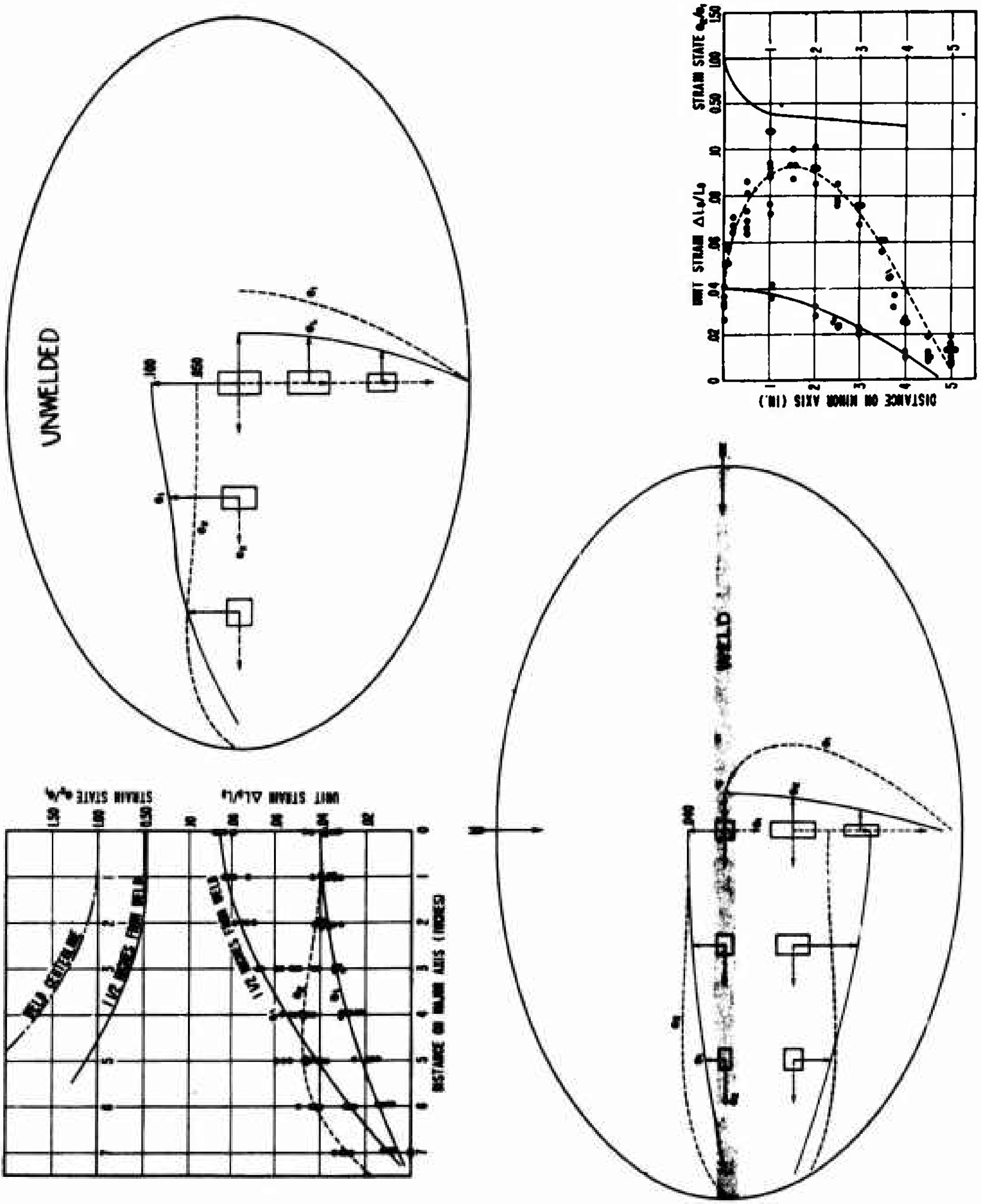

Figure 15 - Distribution of strain in a bulge containing a high-strength butt weld. (E12016 electrode)

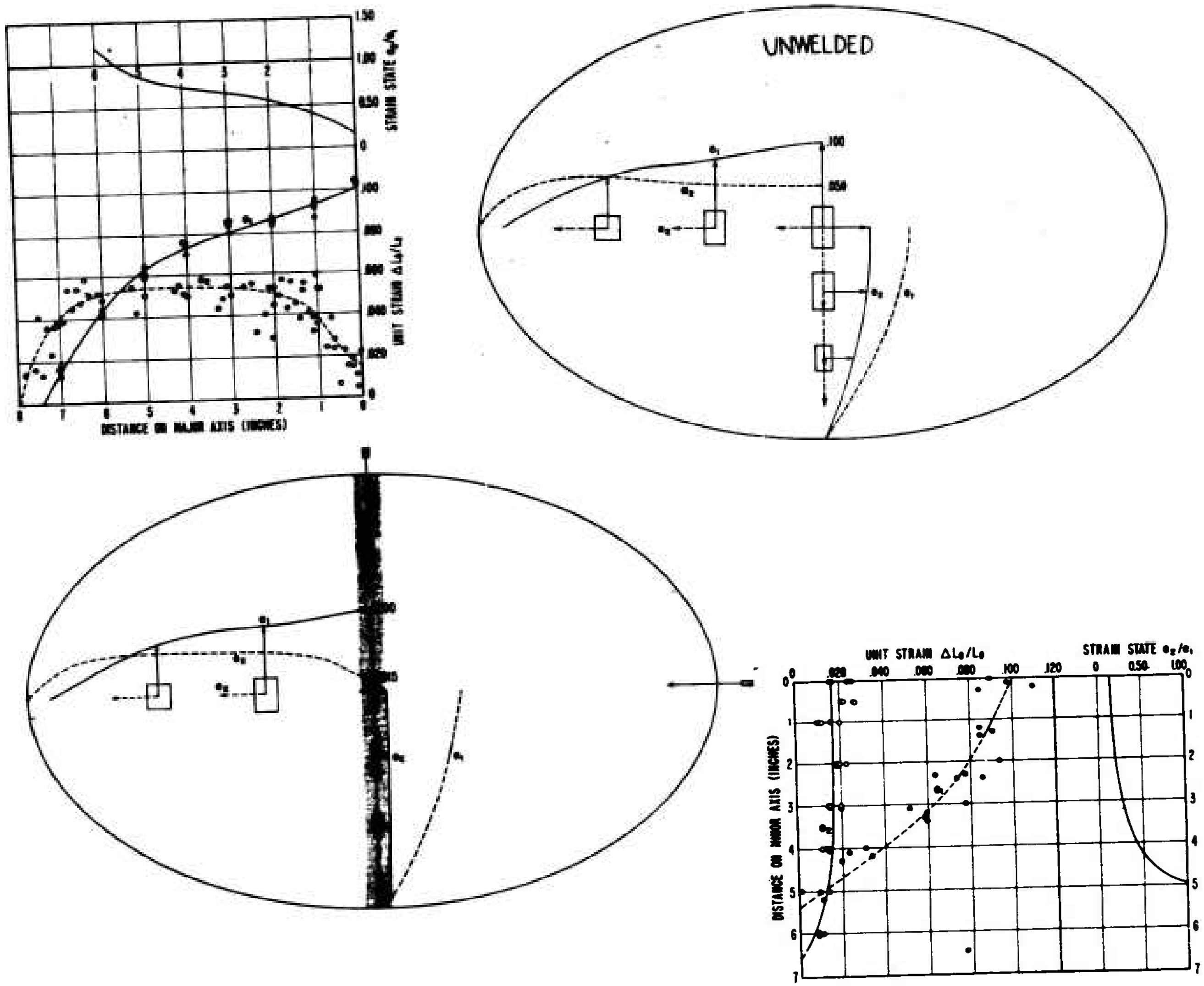

Figure 16 - Distribution of strain in a bulge containing a high-strength butt weld.
(E12016 electrode)

GENERAL DISCUSSION

The problem of the performance of welds in structures is basically a problem involving the performance of welds under a great variety of stress conditions. If information could be obtained as to the pattern of weld behaviour under general conditions of stress, a rational basis for the evaluation of structural performance would be provided to the design engineer. Such an approach to the weld-performance problem would require the use of a semi-works-scale or structural-model technique by which weldments featuring practical full welds might be tested under a wide range of known and controlled stress conditions. Such a test should not be considered as a substitute for laboratory tests such as notched bead-on-plate weldability tests or the standard flat-plate ASM-ASME bend tests, but as a simplified structural test serving to link the results of the laboratory to structural performance.

The California tube tests[6] are an example of a structural-model approach. Full welds in tubes made from 3/4" plate were tested in various biaxial stress fields. These tests required specialized weldments and equipment, and were excessively expensive for comprehensive investigations.

The results of the California tests, although so severely limited in number that a general pattern of weld behaviour could not be deduced, have great practical significance. These tests showed that the mode of failure of weldments is specific to the stress system imposed on the weldment. Thus, the futility of any indirect empirical attempt to relate quantitatively the performance of welds in structures – which may involve a number of weld joint designs and cover a spectrum of stress conditions – to the performance of a single welded specimen featuring a simplified bead-on-plate and tested under a specific and single condition of stress was clearly indicated. This does not imply that significance may not be drawn from the performance of simple specimens in laboratory tests, but that the basic pattern of weld performance as a function of stress system must be known in order to evaluate the significance of such tests in terms of structural performance. Extension of bulge-test techniques to the testing of simple plate weldments provides a means by which structural-model tests may be conducted at relatively low cost, and hence in sufficient variety to allow comprehensive investigations.

The application of the explosion-bulge test to the study of weld deformations has served to provide basic information prerequisite to a comprehensive approach to the fracture problem. It has been demonstrated that the conditions of stress and strain imposed by the loading conditions on the structural components remote from the weld joint are not accepted as such by the weld joint. Thus, depending on the overmatching characteristics of the weld and its geometry, an entirely foreign system of stress strain may be developed in the weld and near-weld regions. These effects obviously require consideration in any evaluation of weld performance as a function of applied stress conditions.

The method of explosion loading used in this investigation naturally raises questions as to the significance of bulge tests. The weld-deformation studies of the slowly loaded California tube tests, which involved balanced and unbalanced biaxial loading similar to stress fields of the bulge tests, provide an opportunity to check the validity of the strain and stress reversals noted in the explosion tests. A numerical evaluation may be made by comparing the strain distribution in tube and bulge under balanced biaxial loading where the weld and plate combinations were closely matching.

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[6] Troxell, et al., op. cit.

Table B
Comparisons of Strain Distributions

	Bulge Tests	Tube Tests
Materials	3/4" Plate 65,000 T.S. Square Submerged-Arc Weld (7,000 psi overmatch)	3/4" Plate 60,000 T.S. Multipass VV Weld E6020 (7,000 psi overmatch)
Stress System	Balanced Biaxial Tension	Balanced Biaxial Tension
Strain Ratio*	Plate 1/1 Weld Long./Trans. 1/0.57	Plate 1/1 Weld Long./Trans. 1/0.8

*The strain ratios are as given in Figure 10 and are hence specific for a deformation level of 0.07 in./in. uniform strain. The strain ratios for the tube test held for a wide range of general deformation from approximately 0.05 in./in. to 0.15 in./in. strain.

Exact numerical correspondence should not be expected, inasmuch as the bulge test weld was of square geometry and the tube test-weld featured double-V geometry. The nature of the strain reversals, however, are in the same directions and of the same order. The transweld strain deconcentrations noted in the tube test featuring a 0.5/1 unbalanced stress-ratio follow the pattern shown by the bulge tests. (Since bulge tests were performed at 0.8/1 unbalanced stress ratio, numerical comparisons cannot be made.) The concepts of weld-deformation mechanics deduced from the bulge studies should therefore be considered to be general to weld performance and not specific to high rates of loading.

Further evidence of the general validity of the bulge-test data was obtained by a study of the strain distributions in slow-bend specimens containing the high-strength square weld used in the bulge tests. The subject weld was tested in longitudinal and transverse bend; comparison was also made with an unwelded specimen. In order to obtain uniform bending conditions over the test area of the specimen, four-point loading was employed. Figure 17 illustrates the severe strain-deconcentration effects (transweld strain reduced from 0.035 at 1-1/2" from the weld centerline to 0.007 at the weld centerline) developed in the weld region as the result of transverse loading. Longitudinal loading of the weld on the other hand indicated no deconcentration of weld strain. As in the case of the bulges, the strains longitudinal to the weld closely matched the longitudinal strains of the unwelded test specimen.

These studies collectively demonstrate the importance of weld orientation with respect to the principal stress direction in determining the degree of strain developed in welds. There are, therefore, interesting possibilities of application from practical as well as from laboratory viewpoints.

From an engineering viewpoint it would be desirable to take advantage of the wide range of strain levels which may be developed in a weld by intentionally orienting the weld in a favorable direction whenever feasible. For uniaxial or strongly unbalanced biaxial loads, it is possible to reduce the value of the principal strain by orienting the weld transverse to the direction of principal load. In the case of balanced loads such manipulation is not possible.

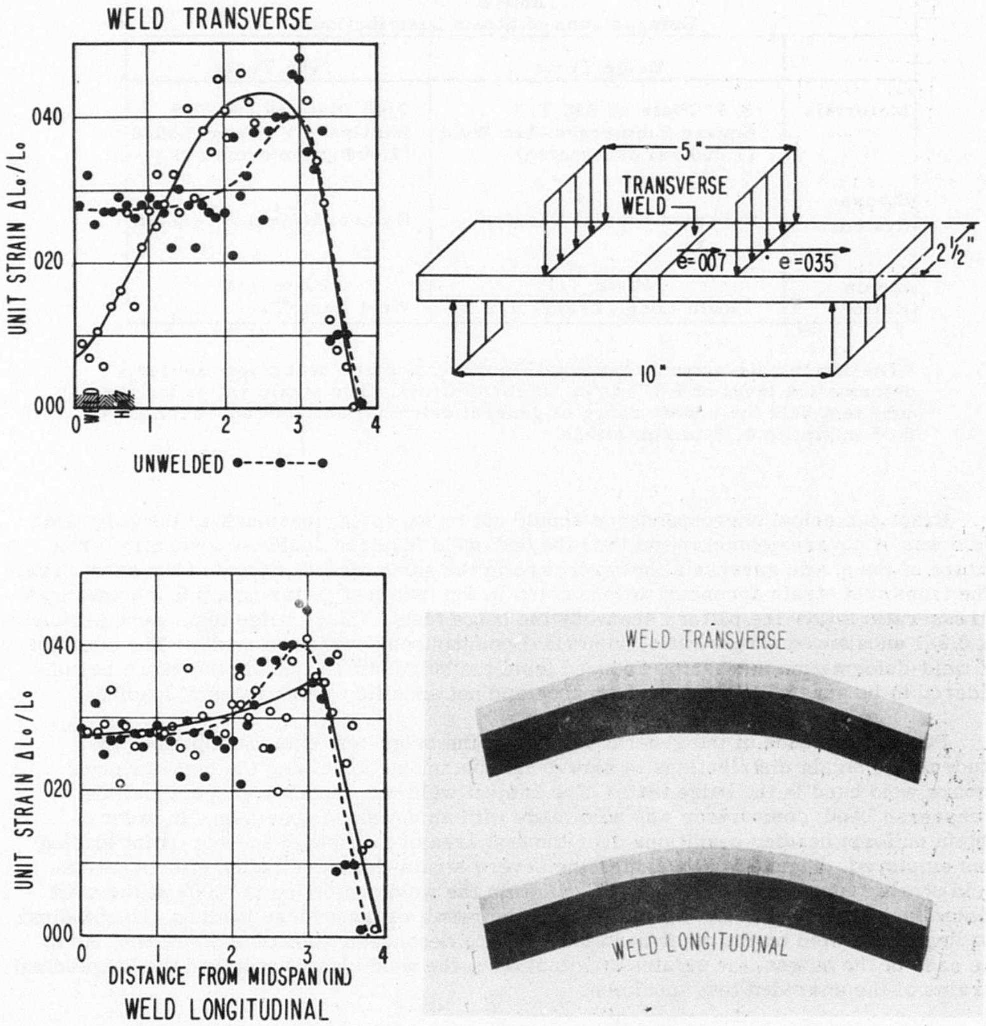

Figure 17 - Distribution of strain in a slow-bend specimen containing a high-strength butt weld. (High-alloy submerged-arc deposit)

For conducting laboratory tests such as the standard ASME Boiler Code, flat-plate, free-bend tests, which are aimed at actually testing the ductility of the weld deposit, it would appear necessary to test under the most severe weld-strain-producing condition. This condition should logically be that of a weld oriented in the longitudinal direction of the bend specimen. Since the tests are at present conducted using a transverse weld, severe deconcentration effects should be expected with overmatching deposits, thus providing a condition highly favorable to the weld. With such a testing condition the strain burden would be largely transferred to the parent plate. It should be observed, however, that tests aimed at detecting gross weld flaws inherently parallel to the weld, such as lack of fusion or incomplete penetration, require transverse loading tests. Logically the purpose of the test should form the basis for the selection of loading conditions.

ACKNOWLEDGMENTS

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The authors are indebted to personnel of the Explosive Ordnance Disposal Unit at the U. S. Naval Powder Factory, Indian Head, Md., particularly LT W.R.Brooks, USNR and LT M.L.Yager, USN, without whose assistance and cooperation these tests would not have been possible.

***

APPENDIX

Technique for Photogrid Application

Precision grids have been used by many investigators for the analyses of plastic strains.* The application of the photogrid process to explosion-bulge testing required some modification of procedure and particular attention to technique. The following section details the procedures which were evolved.

Materials and Equipment Required

Carbon tetrachloride
No. 1 abrasive paper
One percent solution of ammonium hydroxide
Black Gum contact emulsion (DYRITE)
Deep-etch developer (calcium chloride)
Methanol

Spray gun and filtered air supply
Negative precision grid
Vacuum printing frame
Single 35-amp carbon arc
Developing and washing tanks

SURFACE PREPARATION

The test plate was surface-ground and then washed with carbon tetrachloride to remove any grease and oil deposited during grinding and handling. It was then rubbed with No. 1 abrasive paper to impart a cross-hatch pattern of minute scratches in the surfaces to be grided. As a final precaution to assure a clean surface, the plate was swabbed with cotton saturated with a one percent solution of ammonium hydroxide. The cotton revealed the presence of any foreign matter, and swabbing was continued until the last vestige of stain had disappeared.

The emulsion was applied by spraying six thin layers of emulsion using approximately 40 pounds pressure from a filtered air supply. If necessary, the emulsion was thinned to a spraying consistency with distilled water. Care had to be exercised to obtain a uniform coating without the formation of droplets. Each layer of emulsion was allowed to dry throughly before applying the next layer.

Exposure and Development

The sensitized plate and negative grid was placed in the printing frame which consisted of an airtight receptacle with a transparent flexible cover. By evacuating the receptacle

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* "Strain Analysis by Photogrid Method" by W. F. Brown, Jr., and M. H. Jones, IRON AGE, Vol. 158, pp. 50-56, September 12, 1946, for a thorough and excellent treatment of the subject

the grid was clamped in intimate contact with the test plate by the flexible cover. The emulsion was exposed for seven minutes to the ultraviolet rays of the carbon arc lamp placed approximately 3-1/2 feet from the printing frame.

Developing was accomplished by rubbing the exposed surface with a cheesecloth pad saturated with calcium chloride deep-etch developer. The unexposed emulsion was removed by this operation leaving a sharp black grid on the plate. After the surplus developer had been removed by an air blast, the plate was submerged in a tank of methanol. It was then rinsed several times with clean methanol to eliminate any trace of calcium chloride. Finally, it was dried in a filtered air blast, and a thin coat of clear lacquer was sprayed over the grid as a preservative.

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