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Effect of Residual Stresses on the Low Cycle Fatigue Life of Large Scale Weldments in High Strength Steel[1]

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A determination was made of the influence of various mechanical finishing procedures on residual stresses and the resulting effect on the low cycle fatigue life of tee-fillet welds in 1 $^1/_2$ in. thick rolled steel plate with a yield strength of 80,000 psi. Included in this work were tee-fillet welds in the as-welded, ground, shot-peened, ground and shot-peened, and mechanically peened condition. Residual stresses were measured by a hole drilling technique developed at the Naval Applied Science Laboratory for application to linearly varying biaxial stress fields. This method has been found suitable for determining residual stresses at any point over a limited area at the toe of the weld. Fatigue tests were conducted on plate type specimens, 32 in. by 29 in. by 1 $^1/_2$ in. which were simply supported at two edges, free at the other two edges, and uniformly loaded with compressed air to develop a zero to maximum tension range of stress at the toe of the fillet weld. It was found that tensile residual stresses do not have a significant effect on fatigue life for the type of pulsating load used. Compressive residual stresses have been found to have a beneficial effect on fatigue life. Welds with relatively high residual stresses which were ground smooth to eliminate "stress raisers" showed very good fatigue resistance.

Introduction

For the past 10 years considerable effort has been exerted on the study of materials for submarines and research vehicles which can operate at great depths in the ocean. In one of these studies, Wenk [1][2] pointed out that with the development of new materials it is feasible to design submarine hulls for operation at depths up to three miles without sacrifice of speed or "payload." As a result of repeated dives to these great depths at which hydrostatic pressures are extremely high, the structure experiences cyclical loading, and low cycle fatigue emerges as a serious problem. In this connection, many universities, private laboratories, and Government laboratories have undertaken research programs in this area on full and scale models, large scale specimens and structural elements, and small laboratory specimens. Under suitable loading conditions each specimen type can be made to represent a specific application. Structural models are excellent for evaluating design details and seeking out weaknesses in new designs. Large scale specimens and structural elements permit a realistic comparison to be made of various fabrication parameters at an appropriate scale without the expenses of making large models. Small laboratory specimens provide a much less expensive means of screening materials, studying mechanism of fatigue, shape factors, and many other parameters.

The Naval Applied Science Laboratory has been conducting low cycle fatigue and related studies on high strength materials using large scale specimens and structural elements. Recently completed was a program to determine the effect of fabrication improvement techniques on low cycle fatigue of large scale tee fillet weldments in a high strength steel with yield strength of 80,000 psi. Concomitant with this work, some effort was exerted towards the measurement of the residual stresses developed by the different fabrication processes.

A sample of recent investigations [2-5] on the effect of residual stresses on fatigue crack initiation indicates that the relative nature of the applied cyclic load is an important factor on results. Under cyclic loads, zero to tension, there does not appear to be any effect if residual stresses are tensile. However, under reversed loads, the effect becomes apparent and increases with decrease in stress range to some limit. Most of the results reported were based on artificially induced residual stresses or reduction of welding residual stresses by stress relieving. In all

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[1] The opinions or assertions contained in this paper are the private ones of the author and are not to be interpreted as official or reflecting the views of the Naval Service.

[2] Numbers in brackets designate References at end of paper.

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Nomenclature

A = normal stress in x direction at origin, psi
B = normal stress in y direction at origin, psi
D = shear stress over entire plate, psi
E = modulus of elasticity, psi
ν = Poisson's ratio
σ_x, σ_y = normal stresses in Cartesian coordinates, psi
τ_{xy} = shear stress in Cartesian coordinates, psi
σ_1, σ_2 = principal normal stresses, psi
σ_r, σ_θ = normal stresses in polar coordinates, psi
a = radius of drilled hole
c = stress gradient applicable to $_x$, psi per in.
k = stress gradient applicable to $_y$, psi per in.
x, y = Cartesian coordinates
r, θ = polar coordinates
$(\epsilon_r)_R$ = relaxation strain in radial direction, in. per in.

cases reviewed, there was no indication that residual stresses were actually measured.

The objective of this work is to present the results of residual stress measurement and low cycle fatigue evaluation of a batch of large scale plate specimens produced under identical conditions except for finishing by the various fabrication methods. Of particular significance is the large size specimen which permits the use of full thickness plate with full size weld, the application of realistic welding procedures and improvement methods, and the actual determination of residual stresses by a procedure specifically developed for fillet welds. However, the work is limited to tee-fillet welds subjected to a cyclic load, zero to maximum flexure with tension at the toe of the fillet.

Material, Specimens, and Fabrication

Rolled plate, $1^{1}/_{2}$ in. thick, which was given a quench and temper heat treatment to provide a yield strength of about 80,000 psi was used in the fabrication of specimens for these studies. The basis tee-fillet welded plate specimen used for both residual stress measurement and low cycle fatigue testing is shown in Fig. 1. The specimen is 32 in. by 29 in. and large enough to retain all local residual stresses and to permit residual stress measurements which are free from plate edge effects. Chemical analysis and mechanical properties of one plate which may be taken as typical are shown in Table 1.

Table 1

Chemical analysis, percent		Mechanical properties	
C	0.17	Yield strength, ksi	83.2 (L)
		0.2 percent offset	87.2 (T)
Mn	0.28		
		Tensile strength, ksi	104.6 (L)
P	0.010		102.6 (T)
S	0.019	Elongation, percent in 2 in.	29.0 (L)
			26.0 (T)
Si	0.24	Reduction in area, percent	74.6 (L)
Ni	2.24		68.9 (T)
Cr	1.47	Charpy V-notch at −120 deg F	123.0 (L)
Mo	0.43	average ft-lb	84.0 (T)

(L) Longitudinal, parallel to direction of final roll.
(T) Perpendicular to direction of final roll.

The full penetration tee-fillet welds were fabricated by the manual metal arc method as follows:

1 Plates were held flat and web vertical.

2 Top surfaces of plates were ground clean and flat $1^{1}/_{2}$ in. to each side of the centerline.

3 Machined or flame cut surfaces in contact with weld metal were ground clean prior to welding.

4 Preheat temperature was 200 deg F and interpass temperature was 200–300 deg F.

5 MIL-11018 electrodes were used for all welding. These were baked at 800 deg F and stored in an electrode oven at 200–300 deg F prior to welding.

6 Length of weld was divided into five blocks, and block technique was used for first five passes deposited in alternate blocks from center out to end of plate.

7 Remaining passes were welded end to end using $^{3}/_{16}$ in. electrodes.

8 Energy input was held to 45.0 ± 5.0 kilojoules per inch.

9 Welds were examined by magnetic particle inspection after the fifth and final passes.

Mechanical peening of the fillet welds was performed with a Navy No. 2, Type 2, pneumatic chipping hammer using two differently blunted chisels in succession. The point of the first chisel was a $^{1}/_{4}$ in. radius hemisphere which deformed the metal along the heat affected zone satisfactorily, but the brinelling effect left a dimpled surface. The point of the second chisel was a $^{1}/_{4}$ in. radius quarter cylinder which obliterated peaks and ridges and left a smooth shallow groove approximately 0.05 in. deep.

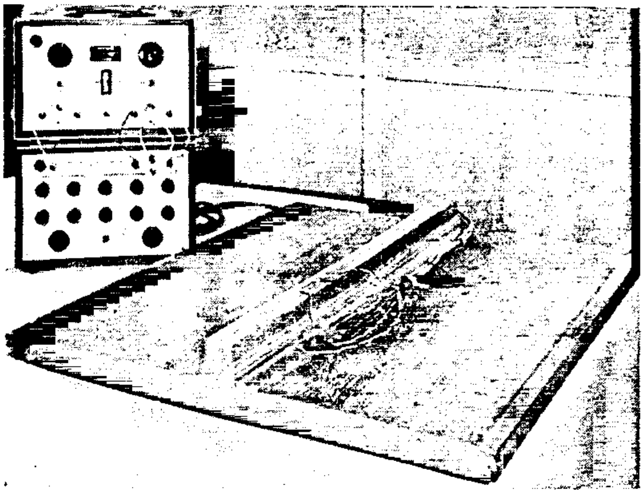
Fig. 1 Plate type fatigue specimen 32 by 29 by $1^{1}/_{2}$ in. with ground tee-fillet weld and instrumentation for measuring relaxation strains by the hole drilling method

Grinding of the tee-fillet welds was performed with a pneumatic six inch vertical grinder using a cup wheel with bottom edge shaped to a radius of $^{3}/_{8}$ in. The flat face of the cup wheel was held against the plate and moved along the fillet leaving a curved fillet with grinding scratch marks parallel to the weld. These scratches were then removed by grinding with a conical stone, leaving the finishing scratches normal to the weld length.

Shot peening of the fillet welds was done under contract in accordance with laboratory specifications. Intensity 8-10C2 using SAE 330 steel shot, Rockwell C 40 to 50, was specified, manually directed at a pressure of 80 psi and 70 cfm. Intensity of shot peening was verified by using an individual Almen strip for each specimen and by inspecting each peened surface at 10 magnifications. Examination of a section of the peened weld indicated cold work to a depth of 0.008 in. This procedure was employed on both as welded and ground tee-fillet welds.

Residual Stress Studies

Residual stress measurements were made by the method developed by Cordiano and Salerno [6]. They developed a theory for the calculation of relaxation strains effected by drilling a hole in a plate with a linearly varying biaxial-stress field and applied the theory for the experimental determination of residual stresses at the toe of large scale tee-fillet welds. Thus, referring to Fig. 2, it is assumed that residual stresses at the surface of a plate near a fillet weld are in a state of plane stress; that because of geometry the principal stress σ_1 and σ_2 are in the x and y direction, parallel and normal to the weld, respectively; that these residual stresses are zero at some distance from the weld and rise linearly as they approach the weld; and that the stress field does not vary as the plate is traversed parallel to the weld. These residual stresses may be represented by

$$\begin{aligned} \sigma_x &= cy + A \\ \sigma_y &= ky + B \qquad (1) \\ \tau_{xy} &= D \end{aligned}$$

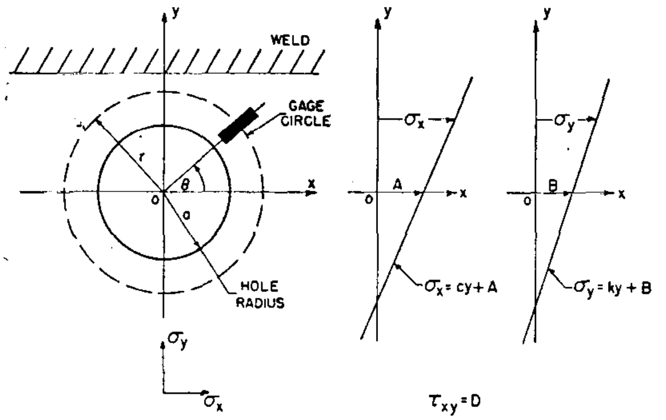

Fig. 2 Coordinate system and assumed stress distribution

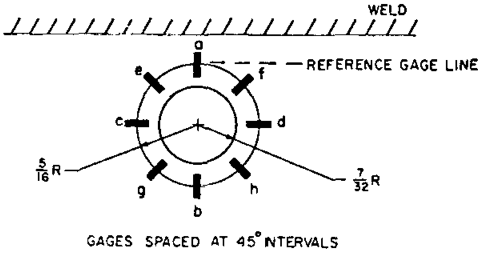

Fig. 3 Strain gage arrangement at tee-fillet weld

where A, B, c, k and D are constants to be evaluated.

If a hole of a given radius is drilled at some point 0, which is taken as the origin of polar coordinates, as shown in Fig. 2, the above theory shows that the change in radial strain, the relaxation strain, is given by the following equation.

$$E(\epsilon_r)_R = \frac{A+B}{2}(1+\nu)\frac{a^2}{r^2} - \frac{A-B}{2}\left[4\frac{a^2}{r^2} - 3(1+\nu)\frac{a^4}{r^4}\right]\cos 2\theta$$
$$- \frac{cr}{4}(1+\nu)\frac{a^4}{r^4}\sin\theta + \frac{kr}{4}\left[(\nu-3)(\nu+1)\frac{a^2}{r^2}\right.$$
$$\left. + \nu(1+\nu)\frac{a^4}{r^4}\right]\sin\theta - \frac{(c-k)r}{4}\left[(5+\nu)\frac{a^4}{r^4}\right.$$
$$\left. - 4(1+\nu)\frac{a^6}{r^6}\right]\sin 3\theta - D\left[4\frac{a^2}{r^2} - 3(1+\nu)\frac{a^4}{r^4}\right]\sin 2\theta \quad (2)$$

where A, B, c, k and D are the constants of equations (1). Since there are five constants, A, B, c, k and D to be determined, at least five independent measurements of $(\epsilon_r)_R$ are to be made in five radial directions θ. It should be noted that the first two terms of equation (2) represent the known expression for relaxation strain in a biaxial stress field where A and B are the principal stresses. The next three terms of equation (2) represent the relaxation strain corresponding to the linear variation of the principal stresses with y where c and k are proportionality constants which give a measure of the strain gradient, and the last term represents the relaxation strain due to the shear stress D.

The strain gage arrangement employed in the measurement or radial relaxation strains by the hole drilling technique is shown in Fig. 3. Eight strain gages spaced 45 deg apart are shown. Although five independent relaxation strains are required to determine the five constants of equation (1), this eight-gage arrangement gives a uniformly weighted representation of the stress field around the hole. In addition, the resulting eight equations may be readily reduced to five through a combination which eliminates D and permits the use of the averages of symmetrically located gages e and f, c and d, and g and h. This gives a system of five equations and four unknowns, A, B, c and k. These unknowns may be readily determined by the application of the method of least squares.

The following techniques and procedures were followed in drilling the holes and measuring relaxation strains:

1 The hole centers and reference gage line for each of the fabrication conditions were located as shown in Fig. 3. For the as-welded and shot-peened fillets, the reference gage line was located $^1/_{32}$ in. away from the toe of the weld. For the ground, ground and shot-peened, and mechanically-peened conditions, the reference gage line was located along a line representing the toe of the weld prior to finishing by the respective fabrication procedures.

2 Foil strain gages, type C6-1X1M50A, with a gage length of 0.050 in., carefully cemented at appropriate locations and protected with a coat of wax, were used for the measurement of relaxation strains.

3 Strain gages were located on a $^5/_8$ in. dia circle concentric with the drilled hole.

4 Each set of gages was connected to a Baldwin switching and balancing unit and type N or Model 120 Baldwin strain indicator.

5 A portable magnetic base drill, aligned by means of centering pin in the chuck directly over the center of the hole was used for drilling.

6 Drilling was accomplished in increments using $^3/_{16}$, $^5/_{16}$, $^3/_8$ and $^7/_{16}$ in. dia standards drills in succession while a stream of compressed air was directed towards the drill to blow the chips away, thereby avoiding damage to the gages. This procedure was followed in order to achieve the largest size hole without damage to the gages.

7 Each hole was drilled to a depth of $^7/_{16}$ in., the maximum depth required for complete relaxation of residual strain at the surface.

8 Measurements of relaxation strain were taken for all gage locations after each increment of drilling. Relaxation strains were measured on each of the plate type specimens using the hole drilling technique described above.

Low Cycle Fatigue Studies

Low cycle fatigue evaluations on 52 plate specimens, similar to that shown in Fig. 1, were conducted in the NASL plate fatigue machine shown in Fig. 4. The machine which operates on compressed air consists of a loading frame, a system of solenoid valves and pressure switches, a deflection recorder and other incidental devices. The loading frame permits simple support of the specimen along the 32 in. edges and leaving the 29 in. edges free. Cyclical loading is obtained by means of two solenoid valves one normally opened and one normally closed, which are actuated by two pressure switches, one set to operate at zero pressure and one set to give the desired stress in the specimen. Compressed air is supplied to the lower surface of the specimen giving a uniformly distributed load. Cyclical stress varies from zero to a maximum in flexure at the center of the plate. The machine is instrumented to provide a continuous chart record of deflection at the center of the specimen throughout the test. Corresponding deflection data may also be obtained by means of two dial indicators located at the quarter points along the weld or line of maximum deflection. An electrical cycle counter is also included in the solenoid valve control circuit to indicate the total number of loading cycles at any time. Prior to testing SR-4, A-7, $^1/_4$ in. strain gages were applied to selected locations on each plate in order to measure strains. Some gages were placed along the toe of the weld in order to obtain a measure of actual strain over an area affected by residual stresses and stress concentration. Other gages were placed elsewhere on the plate in order to provide experimental correlation with the calculated nominal stress levels applied to the plates.

Each specimen was set up in the plate machine as for fatigue testing. Load-deflection and load-strain data were obtained for equal increments of load (pressure) from zero to the maximum to be applied. The specimen was then subjected to cyclical loading, zero to maximum flexure at the rate of 12 cpm. A continuous chart record of cyclical deflection at the center was obtained for the entire test of the plate. During the course of the test, minimum and maximum dial indicator deflection readings were recorded at intervals of 500 loading cycles. In addition, observations were made throughout the test to determine the approximate number of loading cycles at which a crack started and progressed to various lengths along the toe of the weld. The cracks were detected by observing the movement of SAE 10 oil, applied in a very light coating along the toe of the weld, into and out of the crack as the plate flexed under load. All specimens were cycled until the crack was sufficiently large to cause the deflection to increase 100 percent over the initial deflection. At this point the crack was approximately 0.6 in. deep, and the plate had just about reached terminal failure.

Results and Discussion

A typical representation of the change in relaxation strain with increase in hole diameter is given in Fig. 5 for a ground tee-fillet weld. It is apparent that, as expected, the relaxation strains around the hole are not uniform, and that for gages *a*, *e* and *f* they are relatively large. Similar plots for other fabrication methods shown elsewhere [6], indicate some variation from those of Fig. 4. The pattern of relaxation strains for as-welded tee-fillets is similar except strains for gages *a*, *e* and *f* rise more sharply. For shot-peened, and shot-peened after grinding tee-fillets, the curves for gages *a*, *e* and *f* show a reversal in direction at a hole diameter of approximately 0.35 in. [6]. For mechanically peened tee-fillets, curves for gages *a*, *e* and *f* drop sharply starting at the origin [6].

Equation parameters *A*, *B*, *c*, *k* and *D* calculated from measured relaxation strains at a hole diameter of 0.438 in. by means of equation (2) for ten of the plates studies are given in Table 2.

Table 2 Residual stresses at toe of fillet welds

CONDITION OF TEE FILLET WELD	PLATE NUMBER	EQUATION PARAMETERS					RESIDUAL STRESS *	
		A KSI	B KSI	D KSI	c KSI/IN	k KSI/IN	σ_x KSI	σ_y KSI
AS-WELDED	53W9	-1	32	0	260	268	88	124
	54W10	3	34	-1	278	240	99	117
GROUND	57G9	-1	27	-3	279	200	86	90
	58G10	-15	21	1	169	222	38	90
SHOT-PEENED	53P9	-23	2	-1	127	134	21	48
	54P10	-28	0	-1	170	136	30	47
SHOT-PEENED AFTER GRINDING	57N9	-23	-1	-2	157	135	25	41
	58N10	-11	2	-3	222	120	58	40
MECHANICALLY PEENED	57AP10	-48	-54	2	-27	-77	-56	-78
	57AP11	-49	-63	-3	-110	-173	-83	-117

*All values above 80 ksi are in the plastic range and therefore represent "equivalent elastic" stresses.

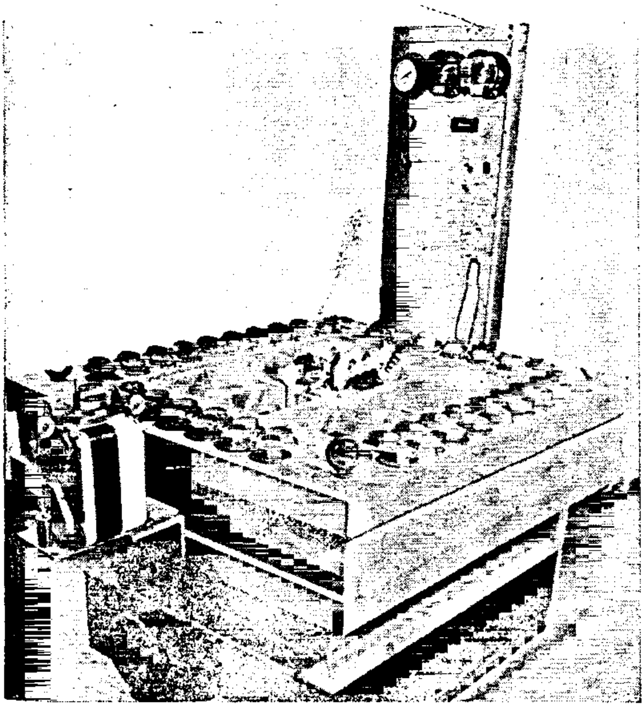

Fig. 4 Fatigue machine for uniformly loaded plates with two edges simply supported and two edges free

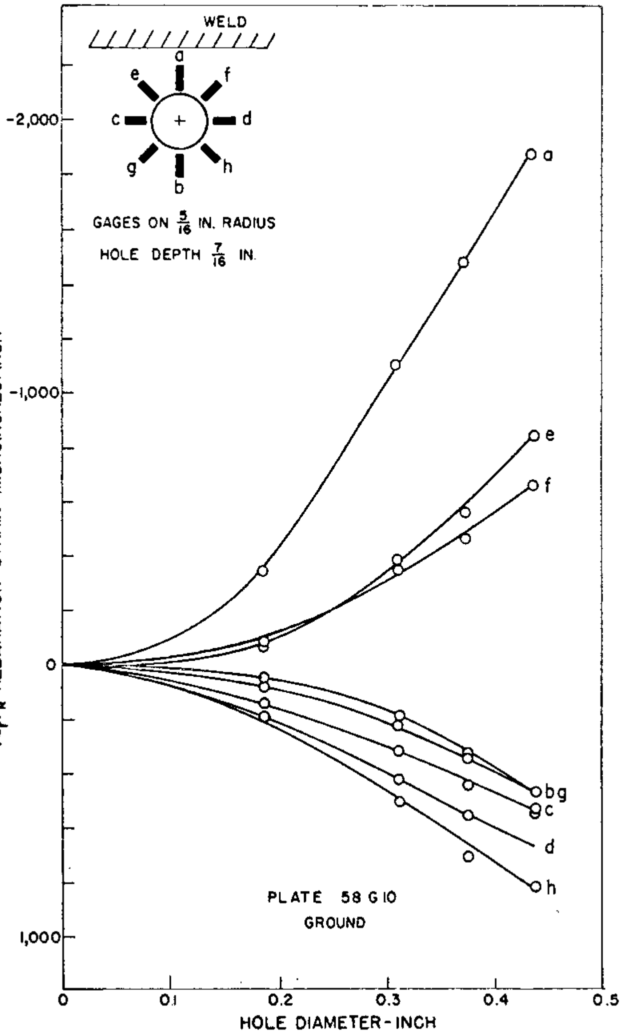

Fig. 5 Measured relaxation strain versus hole diameter at various strain gages

1 Tensile residual stresses have very little, if any, effect on fatigue life when the actual maximum stress is in the plastic range.

2 Compressive residual stresses have a significant beneficial effect on fatigue life.

Grinding tee-fillet welds in high strength steel significantly improves the low cycle fatigue life, notwithstanding the retention of high tensile residual stresses.

Acknowledgment

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References

1 Wenk, E., Jr., "Feasibility of Pressure Hulls for Ultradeep Running Submarines," JOURNAL OF ENGINEERING FOR INDUSTRY, TRANS. ASME, Vol. 84, Series B, No. 3, Aug. 1962, pp. 373–393.

2 Gurney, T. R., "Fatigue of Welded Military Structures," *British Welding Journal*, Vol. 15, 1968, pp. 30–36.

3 Gurney, T. R., "Some Exploratory Fatigue Tests on Notched Mild and High Tensile Steels," *British Welding Journal*, Vol. 12, 1965, pp. 457–461.

4 Gurney, T. R., "Influence of Artificially Induced Residual Stresses on Fatigue Strength of Load Carrying Fillet Welded Joints in Mild Steel," *British Welding Journal*, Vol. 8, 1961, pp. 541–553.

5 Dugdale, D. S., "Effect of Residual Stress on Fatigue Strength," *Welding Journal*, Vol. 38, 1959, Research Supplement, pp. 45s-48s.

6 Cordiano, H. V. and Salerno, V. L., "Study of Residual Stresses in Linearly Varying Biaxial Stress Fields," *Experimental Mechanics*, Vol. 9, Jan. 1969.