1964

Measurement of residual stresses-- a literature survey

William B. Seaman
Lehigh University

MEASUREMENT OF RESIDUAL STRESSES--
A LITERATURE SURVEY

by

William Ben Seaman

A Thesis
Presented to the Graduate Faculty
of Lehigh University
in Candidacy for the Degree of
Master of Science

Lehigh University
1964

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

May 1, 1964
(Date)

Dr. Lambert Tall
Professor in Charge

Professor William J. Eney, Head
Department of Civil Engineering

ACKNOWLEDGMENTS

The work necessary for this thesis was performed while in Fritz Engineering Laboratory of the Department of Civil Engineering, Lehigh University, Bethlehem, Pennsylvania. Professor William J. Eney is Head of the Department of Civil Engineering and Dr. Lynn S. Beedle is the Director of Fritz Engineering Laboratory.

The author wishes to acknowledge his gratitude to Dr. Lambert Tall, thesis supervisor, for his continued advice, suggestions and help.

The assistance extended by the author's associates in Fritz Laboratory, especially Mr. Fiorello R. Estuar who helped review the thesis, is gratefully acknowledged. Miss Marilyn L. Courtright and Miss Zenaida Zita typed the manuscript and their patience and cooperation are appreciated.

TABLE OF CONTENTS

ABSTRACT

Many studies on the effects of residual stresses have been conducted. While conducting these studies, the problem arises of how to measure residual stresses. Different methods have been developed for the different structural shapes.

A summary of the different methods for measuring residual stresses is presented. Seventeen of the methods are described and referred to in the discussion of the methods used.

The method used to determine the residual stress in a member is chosen by referring to the type of residual stress to be measured and the shape of the specimen. Residual stresses have been measured in tubes, rails, thin and thick plates, and structural shapes.

I. INTRODUCTION

Residual stresses and their effects on the strength of structural members have been under study for over seventy years. In 1914, Heyn[1] discussed internal strains in cold-wrought metals and some of the difficulties caused by these internal strains. From then to the present time, many studies have been performed on the effect, measurement, control, and the formation of residual stresses. Numerous papers have been written on all of these subjects.

This paper is an attempt to correlate and review some of the many papers written on the measurement of residual stresses. A recent survey[2] lists sixteen mechanical methods and some twenty odd physical methods used in measuring residual stresses. The literature on the use of x-ray diffraction for measuring residual stresses has been reviewed in The Welding Journal.[3] Barrett[4] and Lynch[5] have also completed a review on various methods of measuring residual stresses.

Residual stresses are formed when non-uniform plastic flow occurs in any forming operation such as the autofrettage of guns, in shot blasting, in the rolling of shapes, in surface rolling, and in strains encountered during service. Misfits in erection also lead to residual stresses. Residual stresses are caused by high thermal gradients, such as in welding, quenching, and by phase changes in the structure of the steel such as the decomposition of austenite.

A residual stress may be defined as that stress which would exist in an elastic solid body if all the external load, acceleration and gravitation were removed.[6] Unfavorable residual stresses result in a lower proportional limit and lower endurance limits in fatigue. Residual stresses are closely related to warping during machining of a member and to cracks formed during quenching and grinding. However, if the stresses are favorably distributed, they may increase the effective strength of structural members subjected to fatigue.

The nature of the distribution of residual stress in a metal piece can be predicted with reasonable accuracy from a knowledge of previous heat treatment and forming operations required in the fabrication of the piece. However, the magnitude of these stresses is affected by many factors and can be predicted only approximately. Since many residual stress problems are too complex to allow even an approximate prediction of the stress distribution, the stress distribution must be obtained by actual measurement.

The many methods devised for measuring residual stresses include methods for determining (1) longitudinal stresses in rods, tubes, and rails (uniaxial and biaxial methods), (2) longitudinal stresses in wires, (3) circumferential stresses in cylinders and disks, (4) stresses in thin walled cylinders, (5) stresses in plates, and (6) surface stresses by x-rays. There are also non-destructive methods and methods involving brittle lacquers.

This paper will consist of:

1. Discussion of residual stresses
2. An historical survey

3. Discussion of the different methods for measuring residual stresses

4. Discussion of selected papers

5. Bibliography

The discussion of selected papers will be from sources published in English.

II. RESIDUAL STRESSES

The formation of residual stresses may be classified under the two principal headings of: formation of stresses due to inhomogeneous volume changes, and formation of stresses due to inhomogeneous shape changes[7]. The non-uniform volume changes are due to variations in rates of thermal contraction of different parts of the piece being cooled. In the process of forming a shape by cold-working, stresses are formed by the non-uniform shape changes associated with cold-working.

The residual stresses formed by cooling are compressive stresses at the surface (the surface cools the faster) and tensile stresses in the slower cooling material. This process can be described in the following manner: (1) The relatively cooler surface of the piece is prevented from contractinb by the hot core which causes the fibers near the surface to be in tension and the core fibers in compression. Deformations may occur, if tensile stresses are high enough, in the outer or inner portions of the body. (2) Cooling progresses until the tensile and compressive stresses equalize and the stresses in the piece become zero. (3) On cooling past this point of zero stress, the core contracts a greater amount than the faster cooling material due to the deformation which occurred in the first stage of cooling and to the temperature difference between the surface and slower cooling material[8]. These basic stages may be applied to the formation of residual stresses where there is a temperature gradient while cooling.

Baldwin[9] reports that the longitudinal residual stress pattern existing in a rolled strip may actually have two configurations. One configuration would be tensile stresses in the center and compressive stresses at the rolled surfaces. The other is just the reverse with the tensile stresses at the rolled surfaces and compressive stresses in the interior of the strip. (see Ref. 10)

Although heat treatment, bending, rolling, and extruding produce stresses which vary through the section of a component while operations such as turning, milling, grinding, shot blasting and plating produce stresses which, in general, are confined to the surface, they both have some practical significance. When there are significant residual stresses in a material, the performance of the piece may be affected in one of the following ways:[11]

1. Distortion during machining
2. Tension and compression properties are usually modified so that a lower elastic limit is observed
3. Addition of service stresses could cause permanent failure of a structural member
4. Fatigue properties depend on type of stress pattern present
5. Possibility of failure by stress corrosion is increased when tensile stresses are exposed on the surface.

It has been shown that plastic strain occurs in structures containing residual stress before the yield strength is reached[12,13]. Beedle and Tall[14] after an extensive study of the strength of rolled columns, summarized their findings as follows:

1. Residual stresses are formed in a structural member as a

result of plastic deformation that occur during cooling, after welding or during cold-straightening operations.

2. The most important stresses in H-columns are at the flange tips which are compressive stresses.

3. Residual stresses reduce buckling strength because of early localized yield.

4. Residual stresses lower the proportional limit and cause the stress-strain diagram to be non-linear beyond that point and up to the yield stress level.

5. Cold-bending residual stresses are no more critical than are cooling stresses.

6. Columns built-up by welding will contain tensile residual stresses close to the yield point.

7. The influence of residual stresses on the strength of higher strength steels is not as pronounced as on columns of A7 steel.

Experimental investigations into the magnitude and distribution of longitudinal residual stresses arising in plates due to edge and center welding [15] indicated that the stress distribution is approximately parabolic in shape, except at the weld itself. The results of this study made it possible to predict approximately the magnitude and distribution of the residual stresses formed in the fabrication of a welded built-up section (made up of relatively thin plates), Estuar and Tall [16] used these results in a study on the strength of welded built-up columns of medium slenderness ratios and of medium size. Their results showed that rolled sections were up to 10% stronger than corresponding welded built-up shapes.

Residual stresses are a potent medium for propagating brittle fracture if the residual stress is critically distributed (9,17,18). The presence of residual stresses hastens the formation of micro-cracks in a specimen subjected to a low cyclic stress (17, 19). Welded plates with high residual stresses have a slightly lower fatigue strength than similar plates which have been stress relieved (20).

The buckling strength of columns, elastic stability of beams, columns, and plates in plate girders, and cracking of welds are all influenced by the presence of residual stresses.

The relief of residual welding stresses may be accomplished by the addition of working stresses, overloading, peening, stress relief annealing, and heat treatment. These methods are all grouped under relief due to thermal action or relief due to mechanical action.

Complete relief of residual stresses by the thermal relief method probably is never achieved in practice and the treatment necessary to produce large reductions in stress has a detrimental effect on certain properties of the material (21). Heat treatment, which involves heating to beyond the stress relief annealing range followed by controlled cooling, is used when the stress relief annealing method cannot be employed.

The mechanical method of stress relieving may be subdivided into relief due to removal of stressed metal and relief due to plastic deformation caused by external forces.

III. HISTORICAL SURVEY

The first work in measuring residual stresses was performed by Kalakoutzky [22] and followed by Howard in 1893. Howard [23] reported longitudinal compressive stresses on the basis of an increase in length after boring out. He considered these stresses uniformly distributed over the cross section, while Kalakoutzky's report was on a method for determining the circumferential surface stresses in cylinders.

A method was proposed by Bauer and Heyn [24], and later compared with a model by Heyn [1], which considered a residually stressed cylinder containing longitudinal stresses in the outer portion and compressive stresses in the core. This method, an approximation since only longitudinal stresses are considered, consisted of removing a succession of thin layers from the outside of the rod.

Mesnager [25] recognized the limitations of the Bauer and Heyn results and developed a method for round bars or tubes which consisted of removing material from the center of the cylindrical rod or tube. He then measured both the longitudinal and circumferential strain in the remaining portion. Sachs [26] and Buehler [27] greatly simplified the calculations of Mesnager's method. Stablein [28] and Sachs and Espey [29] have developed methods for cold-rolled strip and thin walled tubing, respectively.

Laszlo [30], in 1925, developed a method for measuring residual stresses in plates by removing thin layers from one side of the plate and then measuring the deflection of the gage length.

About this same period, Lester and Aborn[31] made the first attempt to measure stress by x-ray. Due to the relatively inefficient cameras available at that time, only small articles such as wire and sheet were investigated. In 1930 Sachs and Weert introduced the flat-back reflection camera[32,33].

The introduction of the x-ray technique enabled the determination of strains perpendicular to the surface or the two principal stresses in the surface. Barrett and Gensamer[34] and Haskell[35] suggested the determination of the total stress state from measurements of several line distances in the film. However, Glocker[36] developed a method requiring four exposures for the measurement of the complete stress state. Other various methods suggest a further decrease in the number of exposures by utilizing the fact that a complete reflection circle represents the strains in various directions parallel to the elements of a cone.

Hatfield and Thirkell[37] developed a method based on the fact that diametral rings cut from cups or bowls and then split in two, will open out to a larger curvature. Following the thinking of Hatfield and Thirkell, Anderson and Fahlman[38] devised a method for thin walled tubing which they used to determine the stress at the surface of a tube by slitting a strip from the wall of the tube in the longitudinal direction and then measuring the deflection. Other methods were developed for studying thin-walled tubes including work by Sachs and Espey[29], Anderson and Fahlman[39] (cutting out a circumferential tongue), Crampton[40], Pinkerton and Tait[41], Krecek[42], and Treuting and Read[43].

Buchholtz[44], Siebel and Pfender[45], and Bierett[46] used a method of subdivision to determine the stresses in a welded plate using an entensometer. Also some measurements were taken with a comparator[47,48] using a similar subdivision method.

Extensive work on round columns made it necessary to determine the residual stress distribution. Nitta[49] used a modified Sach's boring-out method and a method referred to as the beam dissection method.

Mathar[50] developed a method for determining stresses in plates by drilling a small hole in the member to disturb the equilibrium of forces. Gadd[51] employed a method using a stress coat as an indicator in conjunction with the relief method of drilling small holes as proposed by Mathar.

Of the various attempts to measure residual stresses existing in the interior of a material, Gunnert[17], Sachs[26], Stablein[28], Norton[52], and Soete and Vancrombrugge[53], have contributed the most to this problem.

A few successful attempts have been made to calculate the residual stresses by theoretical investigations of processes which cause residual stresses to form such as quenching, casting[54], welding[55], and mechanical working[56].

IV. SELECTED PAPERS

In the following, brief descriptions of seventeen papers pertaining to the methods for measuring resdiual stresses are given. The papers were selected with the intention of presenting a descriptive outline of the different methods available for use in the study of residual stresses.

1. A METHOD FOR MEASURING INTERNAL STRESS IN BRASS TUBES

by R. Anderson and E. Fahlman[38]

A method referred to as the "strip method" for determining the initial stresses in cold-drawn tubes is presented. The method is based on the assumption that the stresses present in drawn tubes are longitudinal tensile and compressive stresses only.

A narrow strip, 2.75 in. long and 0.10 in. wide in a 3.25 in. long specimen, is slit longitudinally from the specimen. The longitudinal stress is detected visually by the springing out of the strip, and the amount of stress can be calculated from the amount of springing and the elastic modulus of the material.

The following equation was rerived for calculating the internal stress in tubing by the strip method:

$$S = \frac{t\,E\,i}{L^2}$$

where, s = unit stress on strip

L = length of sprung strip

t = thickness of strip

E = modulus of elasticity of material

i = amount of spring in the strip (see Fig. 1)

When examining the effect of heat-treatment on the release of stress, a slit is cut on one side of the specimen to determine the original stress. The specimen is then heat-treated, and the stress determined by cutting a slit on the side opposite the first strip. The difference between the two stresses will give the stress relieved by heat treatment.

2. DETERMINATION OF INHERENT STRESSES BY MEASURING DEFORMATIONS OF DRILLED HOLES (50)

by J. Mathar

This test method is based on the distrubance of the equilibrium forces caused by drilling a hole in a metal piece. The holes are so small that the piece can still be used. The method can be used to determine inherent stresses in castings, welded parts, rolled structural shapes and finished structures.

The part to be tested is subjected to a known, uniform and uniaxial stress. The tensometer is placed in the direction of the stress and a small hole is drilled between the foot points (see Fig. 2). Since the hole becomes an ellipse due to tensile stresses, the distance between points a and b will be increased. By determining the relationship between this distance and the stress, either by calculation or by a calibration test, the stress in the test piece can be calculated from the increase in distance between a and b.

The small drill used in drilling the holes has a maximum diameter limited by the permissible weakening of the test piece and a minimum diameter limited by the accuracy of the measuring apparatus. In the tests reported in this paper, a double drill was used (see Fig. 3). The effect of the large bit starting to cut is shown by a discontinuity in the depth vs. elongation curve for the hole.

If the test piece is subjected to a biaxial state of stress, the deformation must be measured in three different directions. This may be facilitated by drilling three different holes and measuring each at a different angle.

After testing, the piece may be used again by inserting a rivet or plug in the hole. The supporting strength of a structure or the utility of a part will seldom be affected by the slight weakening produced by the test.

3. A NEW METHOD FOR DETERMINATION OF STRESS DISTRIBUTION IN THIN-WALLED TUBING (57)

by G. Sachs and G. Espey

A quantitative manner for determining the stress distribution in thin-walled tubing is presented. Former methods have employed a method of relaxation by cutting a strip or tongue from the specimen. This method accomplishes relaxation by extending the simple splitting or slitting methods to specimens from which successive surface layers have been removed by pickling.*

A theory is developed for calculating the longitudinal and circumferential residual stresses. The equations derived to determine the stresses are rather complicated and lengthy. They include the amount of wall removed by pickling and the deflection after slitting.

Two parallel lines are scribed on the tube a suitable distance apart and then two perpendicular lines are scribed at points equidistant from the ends. The tubing is split along its length (through one side only). Measurements are taken before and after splitting by means of a measuring microscope or comparator.

The authors also use a method developed by Anderson and Fahlman (38) to relieve the longitudinal stresses by slitting a tongue along the length of the specimen. They modified the procedure by slitting the tongue from specimens previously split

* Pickling is the process of removing layers of metal by immersing the metal in an acid or other chemical solution.

longitudinally to release the circumferential stress.

The stress distribution can be determined by following two different sequences of relaxation. In one sequence, the splitting and slitting are done and then the specimen is subjected to pickling. After each pickling operation, the wall thickness, change in diameter, and the longitudinal deflection are measured.

A specimen is pickled to a predetermined wall thickness, split and the change in circumference is measured. Finally a tongue is slit and the end deflection measured. This method is more advantageous since it is easier to control the uniformity of pickling.

A procedure is given for computing the stress distribution by the use of an example. In the tests reported, pickling was performed from the outside to the inside and from the inside to the outside in order to determine the total stress distribution.

4. STRESS MEASUREMENT BY X-RAY DIFFRACTION (58)

by J. Norton and D. Rosenthal

This paper emphasizes the nondestructive feature of the x-ray diffraction technique for stress measurement and on the fact that the method detects elastic strain only. Two different techniques are presented for measuring the sum of the principal stresses. A normal method which is based on a perpendicular measurement in the stressed and in the unstressed condition and an oblique method based on a perpendicular and an inclined measurement to give a stress in a particular direction. Three measurements are required to obtain two stresses at right angles to each other.

The technique of x-ray measurement is best described by referring to Fig. 4. A beam of monochromatic light is defined by a collimating system to a narrow pencil of rays and passed through a hole in the center of the film. The diffracted cone, formed by the diffraction of the rays by the tiny crystals illuminated, is recorded on the film.

The precision of the measurements depends on the apex angle (see Fig. 4) of the cone and improves as this angle becomes smaller. It is therefore necessary to select a wave length which will give a diffraction circle of sufficient size. Under conditions giving sharp diffraction circles, the films can be read with a precision in stress measurement of ± 1500 psi.

For x-ray stress measurement to be applicable, the user must have a thorough understanding of the problem. The technique itself is easily learned, but if the specimen is in an unsuitable condition for measurement, only disappoint will result. However, when properly applied the method yields reliable information and often information which could not be obtained in any other way.

5. A CRITICAL REVIEW OF VARIOUS METHODS OF RESIDUAL STRESS MEASUREMENT (4)

by C. Barrett

This paper contains a very good review of the various methods for determining residual stresses. The standard methods are based on the fact that relieving the stresses will alter the dimensions of a body.

Methods for measuring longitudinal stresses in rods, tubes, and rails are presented. The author discusses both the uniaxial and the triaxial methods which have been developed. Kalakoutzky, Howard, Heyn, Sachs, Espey, and Horger are some of the men who have contributed to these methods. References to their work may be found in the bibliography.

The determination of longitudinal stresses in wires, circumferential stresses in cylinders and disks, and stresses in thin-walled cylinders are discussed, and references given of the many papers written on these subjects.

Work done by Mathar, Spraragen, and Claussen on stresses in plates are also discussed along with non-destructive methods with strain gages, methods involving brittle lacquers and stress measurement by x-rays. A qualititative test for residual stresses in brass tubes is reviewed in this paper.

6. A METHOD OF MEASURING TRIAXIAL RESIDUAL STRESS IN PLATES

by D. Rosenthal and J. Norton (52)

The method as employed by the authors applies the principal of relaxation. By cutting a small block from the piece to be tested, the stress distribution in the interior of the piece is determined. The method is well suited to the investigation of residual stress distribution in thick plates.

A brief description of the procedure may best be described by referring to Figs. 5 and 6. The stress along the axis of the weld will be referred to as longitudinal stress and that perpendicular to the weld will be called transverse. Strain gages, are placed on both surfaces of the block to be removed. A thin block is removed as shown in Fig. 5 and the relaxation of the block is measured in the direction of its long axis.

Next the stress remaining in the block itself is determined. This is accomplished by splitting the block in half and from each half, slices about 1/8 in. thick are removed. These slices are removed progressively from the mid-section outward (see Fig. 6). After each slice is removed, the relaxation in stress is measured on the two outer faces.

When the distribution is desired for both longitudinal and transverse stresses, either x-ray diffraction or two blocks at right angles may be used.

The paper contains experimental verification of the method and an appendix which gives the formula for determining the stresses. The appendix gives a very detailed account of determining the stresses across the thickness by using either strain gages or x-ray diffraction.

7. RESIDUAL STRESS INDICATION IN BRITTLE LACQUER (51)

by C. Gadd

By using brittle lacquer, a quick overall picture of location, direction and kind of stress can be obtained. Brittle lacquer has seen wide spread use in determining stresses due to external loading of a structure.

The residual stress study is accomplished by coating the part with brittle lacquer. The stresses are relieved by drilling a small hole not over 1/8 in. in diameter to a depth of 1/16 to 1/8 in. at the points to be checked. A crack pattern characteristic of the type of stress in the area is brought out by this relaxation. The different forms of crack patterns and their state of stress are shown in Fig. 7. Stresses are usually so low that chilling of the lacquer is necessary to bring out the crack pattern.

Gadd feels that since the extent of the pattern is a function of the stress in the entire layer drilled through and due to the irregularity often encountered in residual stress distributions, no quantitative interpretation of the results should be attempted. The two main features of this method is its simplicity and that it is free of material limitations.

Some of the applications of brittle lacquer are in determining residual stresses in quenched bars, aluminum castings, torsional suspension bars, and material after shot peening.

8. A METHOD FOR THE MEASUREMENT OF RESIDUAL WELDING STRESSES

by J. Meriam, P. De Garmo, and F. Jonassen (59)

A method is proposed for measuring residual stresses by attaching SR-4 type strain gages to the weld and adjacent plate surfaces. Relaxation would be accomplished by removing each plug of metal containing a gage by drilling tangent holes around each gage and then removing the plug with the attached gage.

Several types of gages are used, depending on the location and strain measurement.measurement desired. The gage lengths are 1/4 in., 1/2 in., and 3/16 in.. A rosette with a 13/16 in. gage length and a 1/2 in. long gage which is composed of two overlapping grids are also used.

The strain gages are read only twice; once prior to drilling and once after completion of drilling and the plug has been removed. A portable SR-4 strain indicator is used and care is taken to have both active and dummy gages from the same lot. The active gage is used to determine the change in strain after relaxation.

Relaxation is accomplished by drilling 1/4 in. tangent holes around a number of gages and then subdividing into individual squares containing a gage on each side of the plug. The drilling of such holes minimizes and localizes the heating so the strain gages are not damaged or the stress conditions changed.

The relations between strain and stress is taken to be a straight line. With this assumption, the residual stresses existing in the plane of the plate at a point may be calculated by the following equation:

$$\sigma_x = \frac{E}{1-\nu^2}(e_x + \nu e_y)$$

$$\sigma_y = \frac{E}{1-\nu^2}(e_y + \nu e_x)$$

However, the maximum stress is generally not represented by $_x$ or $_y$ and a third strain reading is needed in a direction other than x or y.

9. PLASTIC BEHAVIOR OF WIDE FLANGE BEAMS

by W. Luxion and B. Johnston[60]

The subject of this paper is the plastic behavior of steel beams. However, it is one of the first papers which reported a method of measuring residual stresses by a method referred to as "sectioning".

The results of wide flange sections tested as simple beams are reported. These tests studied the basic bending behavior at initial yielding and in the plastic range.

The method of sectioning as referred to in this paper consists of the following steps. In order to eliminate the possibility of relieving any of the residual stress before measuring, a four foot test length was used. The 10-inch gage lengths are laid out in the center of the four foot section (see Fig. 8).

Whittemore strain gage holes are drilled, prepared, and a complete set of readings taken around the section. The four foot length was then sawed out of the beam length. Finally, all the gage lengths are isolated by sawing 1/4 in. on each side of each pair of holes.

Readings are then taken on the isolated strips and the relaxation of the strain computed. The stress parallel to the gage length can be computed by the following equation:

$$\sigma = (\varepsilon_1 - \varepsilon_2)\, E$$

ε_1 = initial strain reading

ε_2 = final strain reading

A positive value indicates tensile stresses while a negative value indicates compressive stresses.

The whittemore strain gage consists of a fixed peg, a movable peg, and a dial gage. The movable peg is attached to a one-ten thousandths dial gage. The accuracy of the method depends on the care taken in preparing the holes and the care taken while taking readings.

10. A METHOD FOR THE DETERMINATION OF INITIAL STRESSES

by C. Riparbelli [61]

The method proposed consists of introducing a circular discontinuity in the surface of a body containing residual stresses, and measuring the resulting strains occurring in the vicinity of the hole by means of electric strain gages. The stress of the entire body can be determined by measuring the stresses at the hole due to the concept of a uniform stress field.

A complete and balanced strain gage arrangement is employed. The sensitivity of the gage increases as the ratio of gage area to hole diameter decreases. The highest sensitivity is obtained when the resistance in the tensile and compressive regions add. The many strain gage arrangements which may be used are shown in the reference.

The analysis and equations for determining the stresses by using the different strain gage patterns are presented in detail. The applicability of this method to the stress analysis of large structures is discussed. A problem of determining residual stresses in bent plates of small thickness is analyzed thoroughly.

11. THE DETERMINATION OF INITIAL STRESSES AND RESULTS OF TESTS ON STEEL PLATES

by E. Suppiger, C. Riparbelli, and E. Ward(62)

This paper consists of three separate reports concerned with the general problem, evaluation, method, experimental techniques, and test results of the hole method. The hole method as proposed by Mathar(50) used mechanical and optical extensometers to measure the strains. The method discussed here uses SR-4 strain gages.

A strain rosette centered on the stress point is applied to the surface of the plate on each side. Strain readings are taken before drilling a small hole in the center of the rosette. The principal stresses in the plate before the hole is drilled are computed from the strain readings taken before and after drilling the hole.

The rosette is used to measure the strain differences in three directions. By using these three readings, the magnitude and direction of the two unknown principal strain differences may be determined. A dyadic strain-circle construction was used to determine the principal strains.

12. APPLICATION OF OPTICAL INTERFERENCE TO THE STUDY OF RESIDUAL SURFACE STRESSES

by H. Letner[63]

The adaptability of optical interferences when used in conjunction with the technique of removing uniform layers of stressed material from the specimen is discussed rather thoroughly. The necessary apparatus and experimental procedures are described in detail.

The development of the equations for determining the residual stresses proposed by Stablein[28] is presented as background for discussion of the biaxial case. Equations are given which enables the user to calculate the principal residual stresses.

A graphical representation of the service profiles derived from interference patterns gives a quantitative study of residual stresses. An interferometer, suitable for making the required measurements contains a monochromatic light source, a quartz optical flat, polished plate glass for the partial reflector, a glass mirror to permit horizontal mounting of the camera, a camera, and a box for a light shield.

The interference pattern is formed by the monochromatic light passing through the optical flat to the polished surface of the specimen. A photograph is taken of the pattern by means of the camera focused between the specimen and the optical flat. The pattern is then analyzed as described in the paper.

Preparation of the specimen entails the polishing of the surface to be tested. Then the specimen and optical flat are placed in the interferometer which was described above. The photographs are taken with the specimen and optical flat in the same relative orientation in order to eliminate possible errors.

13. A QUALITATIVE STUDY OF RESIDUAL STRESSES IN WELDS BY PHOTOELASTICITY

by M. Mark(64)

The residual stresses present in a longitudinal butt weld are investigated by simulating welds in bakelite and applying the photoelastic method to the specimen. A brief qualitative study of residual stresses by photoelasticity is discussed in the paper.

Since two pieces of bakelite will not fuse together, a strip heater is applied to the center line on each side of an unrestrained piece of bakelite to simulate a weld. The plate is slowly withdrawn from between the strip heater, allowing the annealed material to set progressively. Then the bakelite contains residual stresses as in welding.

Bakelite is used since the distribution of residual stresses can be seen by viewing the specimen in a polariscope using polarized light. The dark and bright bands seen in the monochromatic light are outlines of the stress pattern.

The photoelastic stress patterns are analyzed and the principal stresses determined. For ductile materials, it is sufficient to determine the fringe pattern since it indicates the areas where the difference in principal stress or maximum shear is the greatest.

14. SIMPLIFIED MEASUREMENT OF RESIDUAL STRESSES

by J. Waisman and A. Phillips (65)

A rapid and accurate method is presented for measuring the residual stress gradient developed in plates by various manufacturing operations. The basic technique employs the removal of layers from one surface of the specimen and the simultaneous measuring of the curvature changes which accompany the removal.

The procedure is as follows: the specimen to be tested is covered on one face and the edges with a material resistant to the etchant. The specimen is then placed in the liquid which will attack the exposed surface and remove layers of metal progressively. If these layers contain residual stresses, their removal will cause progressive curvature changes. The change in the deflection of the specimen is measured and from this the residual stress gradient can be calculated.

Appendices are included which contain the formulas for calculating residual stresses and a sample calculation.

15. RESIDUAL WELDING STRESSES

by R. Gunnert (17)

Three conditions should be fulfilled by any method used to measure residual stresses. The method introduced in this paper attempts to take these conditions into consideration. The principal involves measuring lengths in four directions on the test surface and then relieving this surface by drilling it out from the surrounding material.

Eight gage holes are drilled as shown in Fig. 9. The gage lengths are short so the local stresses may be determined as closely as possible and the peak values traced. This will cause very slight changes in length upon relieving the stresses which makes it necessary to use an accurate method for determining the change. Electrical strain gages may be used, but the use of a tensometer is less time consuming and has sufficient accuracy.

The tensometer is placed with the balls on the bottom of its legs in the gage holes. The weight of the apparatus should be evenly distributed to both balls. Measurements are taken before cutting and after the relaxation has been completed.

Relaxation is achieved by means of a core drill which produces a groove around the measuring surface as shown by the two outer lines in Fig. 9. The core drill is guided by drilling a small hole in the center of the measuring surface and using a spring guide. The measuring surface is not affected by drilling the groove around it.

Mohr's circle construction can be used in determing the principal stress or the use of a nomogram is the quickest way. The use of the monogram is illustrated in the paper.

The paper also discusses the nature and intensity of residual welding stresses, reaction stresses, the relief of residual welding stress, and the effect of residual welding stresses on the structural strength of a component.

16. METHOD FOR MEASURING THE RESIDUAL STRESSES IN THE INTERIOR OF A MATERIAL

by R. Gunnert (66)

The method presented in this paper may be used to determine the residual stress distribution in heavy plates. The stresses are relieved by milling-out a plug which contains the small measuring holes.

Small holes (3 mm in diameter) are drilled parallel to each other through the thickness of the piece. Initial readings are taken with an extensometer equipped with a special device at the surfaces and at different distances through the thickness. A reference block is employed to compensate for any changes in temperature between the first and final readings.

The stresses are relieved by freeing the measuring points from the surrounding material. A special drill is used to cut a cylinder, containing the measuring holes, out of the plate. It is now assumed that this cylinder is approximately free from stresses. The dimensions of the cylinder should be kept as small as possible so the assumption that the cylinder is free of stress will hold.

The stress can be determined by using this equation:

$$\sigma = \frac{\Delta'' - \Delta'}{9} E$$

where E = modulus of elasticity

$\Delta'' - \Delta'$ = change in distance at point.

The above equation is not valid for a biaxial stress system. The stress (σ_a) in the direction parallel to the weld will be given by

$$\sigma_a = 2.44\,(\Delta_a + 0.3\Delta_b).$$

The stress (σ_b) perpendicular to the weld will be given by

$$\sigma_b = 2.44\,(\Delta_b + 0.3\Delta_a).$$

These two equations for biaxial stress are derived with the assumption that stress at right-angles to the surface of the plate are zero.

The description of the measuring jig, hole drilling jig and extensometer are given in the paper. The measuring device is very accurate if proper care and time are taken while performing the tests.

17. THE MEASUREMENT OF DEFORMATIONS AND STRESSES WHEN WELDING VERY THICK ST.3 STEEL PARTS

by S. Kurkin, M. Fishkis, V. Vinokurov, A. Gasaryan (67)

Experiments are described which are carried out to determine the magnitude and nature of residual stresses in very thick welded, steel plates. The purpose is threefold: (1) development of deformation in the course of time; (2) the nature of the residual stress field in butt welds; (3) the effect of heat treatment on relieving residual volumetric stresses.

The determination of deformation over periods of time is made with a standard indicator head. Gauge marks are drilled in the weld and alongside it to take the jaws of the extensometer. Measurements were taken immediately after the weld had fully cooled, 5-7 hours later, and then every 24 hours for several days. These measurements were taken to see if deformation of a structure continued for a longer period after welding.

Since tri-axial stresses exist only in the heart of the metal, they cannot be accurately determined by mechanical measuring devices. A method has been published* which details a sequence of cutting and

* S. Kurkin and V. Vinokurov, Doklady Vysshei Shkoly, 1956, No. 3

measuring operations. The method provides results from which an idea of the tri-axially stressed state can be expressed.

The method consists of cutting half inch strips from the welded plate parallel to the weld. An extensometer is used to measure a gage length on both sides of the plate before cutting. The thickness of the plate is also measured before cutting. After cutting, repeated measurements are made to determine the deformations along the test piece and across its thickness. The deformations obtained are mean values of the deformed thickness and the deformed gage length of the strip.

Equations are given to determine σ_{xo}, σ_{yo}, and σ_{zo}. The equations are quite lengthy but rather simple to employ. The equation for σ_{zo} is given here:

$$\sigma_{zo} = \frac{E(UA + B)}{(1- \ ^2)\ l} - \frac{bl}{2} + b\ x$$

where A, B, and b are all constants depending on the measured strains (ε).

Experimental results of tests on 500 x 500 x 100 mm (about 20 x 20 x 4 in.) test pieces are given. The results indicate that heat treatment conditions are extremely effective for stress relief in thick plates and the method stated above may be used to advantage to determine the optimum heat treatment conditions.

V. DISCUSSION

The various methods for measuring residual stresses are discussed in this section. The methods presented in the preceeding section will be given the most consideration.

The stress measured by Anderson and Fahlman[38] with their strip method was not the absolute stress, but the differential stress existing in the outer and inner layers of the tube. This method is applicable only when the residual stress distribution is linear through the section. The deflection of the strip is affected by the method used to cut the strip. The cutting operation plastically deforms the metal in a certain depth from the cut and relieves the stress within this layer of metal. This effect is small if care is taken during the cutting operation.

The hole method as proposed by Mathar[50] may be used to determine the residual stresses in monaxial or biaxial conditions. The method is usually limited to a piece with equal stresses in a layer about three quarters of an inch thick. Since only small holes are drilled to accomplish the relaxation, the piece so tested may be used in a structure by filling the hole with a plug or rivet.

One of the drawbacks of this method is the calibration of the piece needed to calculate the stress. The calibration test is performed under tension with the same physical properties of the piece to be tested. The calibration curve obtained is only valid for plates of the same width used in the test.

Mathar states that it is not necessary to drill completely through thick pieces in order to determine the stresses at the surface, since the stresses liberated by the removal of material some distance below the surface have no appreciable effect on the surface deformations.

The most popular method for determining the residual stresses in a thin walled tube is the method proposed by Sachs and Espey[57]. The stresses can be found with considerable accuracy. This method is more general in that any type of stress distribution may be obtained.

The original articles should be consulted for the details of the methods because the derivation of the formulas must be understood, and detailed discussions of the cutting and etching technique should be studied before undertaking an analyses.

The x-ray diffraction method of measuring surface residual stresses in metals has been used quite extensively. The method has certain valuable features; namely, its non-destructive nature, its measurement of the actual stress in absolute terms, and its ability to make measurements on a relatively small area.

Occassionally the results from the x-ray method have conflicted with what was predicted by other means. The x-ray method does give the true story, within its limitations, if properly applied. Work by Frommer and Lloyd[68] has shown that the x-ray method forms a research tool of great versality and of real practical value to the light alloy industry.

Some of the disadvantages are that the length of time needed for one exposure (and usually more than one exposure is required) may be up to a quarter of an hour. The equipment is expensive and a skillful operator is required. Good accuracies, approximately ± 2,000 psi in steels, are obtained only with specimens that yield sharp diffraction lines. Quenched steels, cold-worked metals, and steels exceeding 40 or 50 Rockwell C in hardness produce larger errors. Complications arise when the specimen to be examined has a large grain size. These difficulties may be overcome by suitable oscillation and translation of the specimen during testing[68].

One of the first methods proposed to study triaxial residual stresses in heavy plates applied the principal of relaxation. The method does not give the local value of stress but an average over a length and width which at best are half of the thickness. Therefore, this method is only an approximation.

The linear law of relaxation in the middle portion of the block has been established only for the stress pattern which gives the same average at both ends of the block. The increasing influence of the shearing stress relieved along the side faces of the block causes the method to become more and more of an approximation. The procedure is based on the assumption that the influence of the stress acting in the thickness direction becomes negligible after the block has been split in two. This assumption is quite acceptable for a thickness of one inch or less.

These limitations are involved not in the principal of relaxation but in the procedure used to obtain the desired relaxation. Other procedures may be better suited to the particular pattern of stress to be investigated.

The method as proposed by Kurkin and Vinokurov* measured triaxial residual stress by measuring both change in length and change in thickness of the test strip after cutting. The equations derived for determining σ_x, σ_y, and σ_z are lengthy and more assumptions are made which may not be valid. The direction x was taken along the length, z through the thickness, and y across the width. The test results reported showed σ_z to be approximately 4300 psi. From this the conclusion was drawn that the stresses across welds in the test pieces investigated were close to zero[67].

The method as proposed by Gunnert[66] for measuring the stresses in the interior of a metal has several disadvantages. Great care must be taken during the drilling of the holes to avoid any abfupt changes in the hole. It is difficult to place the measuring instrument at the same depth in the hole for the required second measurement. Actual test measurements results in an error of $\pm$ 0.001 mm which corresponds to a stress error of about 2.8 ksi, but great care was taken when making these measurements.

Other methods have been proposed for measuring residual stresses in plates. The plug removing method proposed by Meriam, De Garmo, and Jonassen[59] uses short SR-4 strain gages to measure the change in

* See footnote p. 33

strain after removing a plug of metal containing the gage from the specimen. The strain readings obtained are measures of the relaxation of the surface of the plate under the gage.

The stresses in the thickness direction of the plate are neglected. They may be neglected for only thin plates, however. Further experimental work(59) has shown that the measurement of residual stresses, averaged over the thickness, give satisfactory results by this method.

Another method which has become widely used is the method of sectioning. It has been applied to the determination of residual stresses in beams(12,60), plates(15), and columns(16). The method is reliable and good accuracy can be obtained by careful experimental work. The results obtained agree closely to the results obtained by stub column tests(69).

Relaxation by sectioning has been attempted on heavy plates used for welded built-up sections. The method is rather time consuming and expensive due to the number of cuts needed.

These are two methods of using brittle lacquers in studying residual stresses. One method consists of coating the specimen with lacquer and the subjecting the specimen to an externally applied load. The lacquer will crack first when the residual and applied stresses combine to yield the greatest tensile stresses. The location of the cracks will indicate the location of high tensile residual stresses.

The second method[51], discussed before, employs relaxation by drilling a small hole. The manner of clustering of the cracks indicates whether the stresses are tensile or compressive. Obviously the hole must be drilled with as little cold-working of the surrounding material as possible. Both these methods give qualitative rather than quantitative results.

The method of observing welding residual stress by the use of photoelasticity is also a qualitative method. The results of the photoelastic study indicate that residual stresses due to welding may be reduced by effectively decreasing the temperature gradient over the area surrounding the weld[64]. This qualitative method may be used to investigate the residual stresses set up by different welding temperatures and number of weld passes.

As has been shown throughout this paper and in the bibliography, there are numberous methods available to measure residual stresses. There are many variations of the basic methods which may be used. The method chosen by an experimenter will depend on the type of residual stresses to be measured, the shape of the test specimen, the cost and time required to conduct the test, and the accuracy desired.

VI. FIGURES

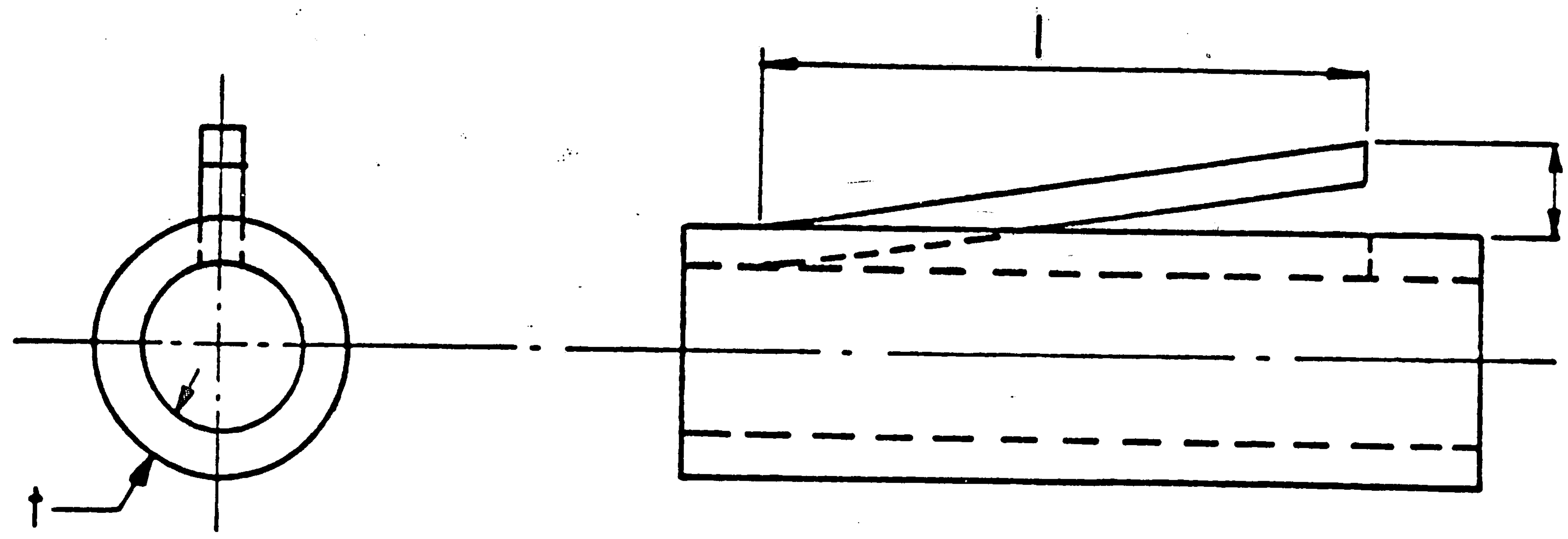


Fig. 1

The Strip Method

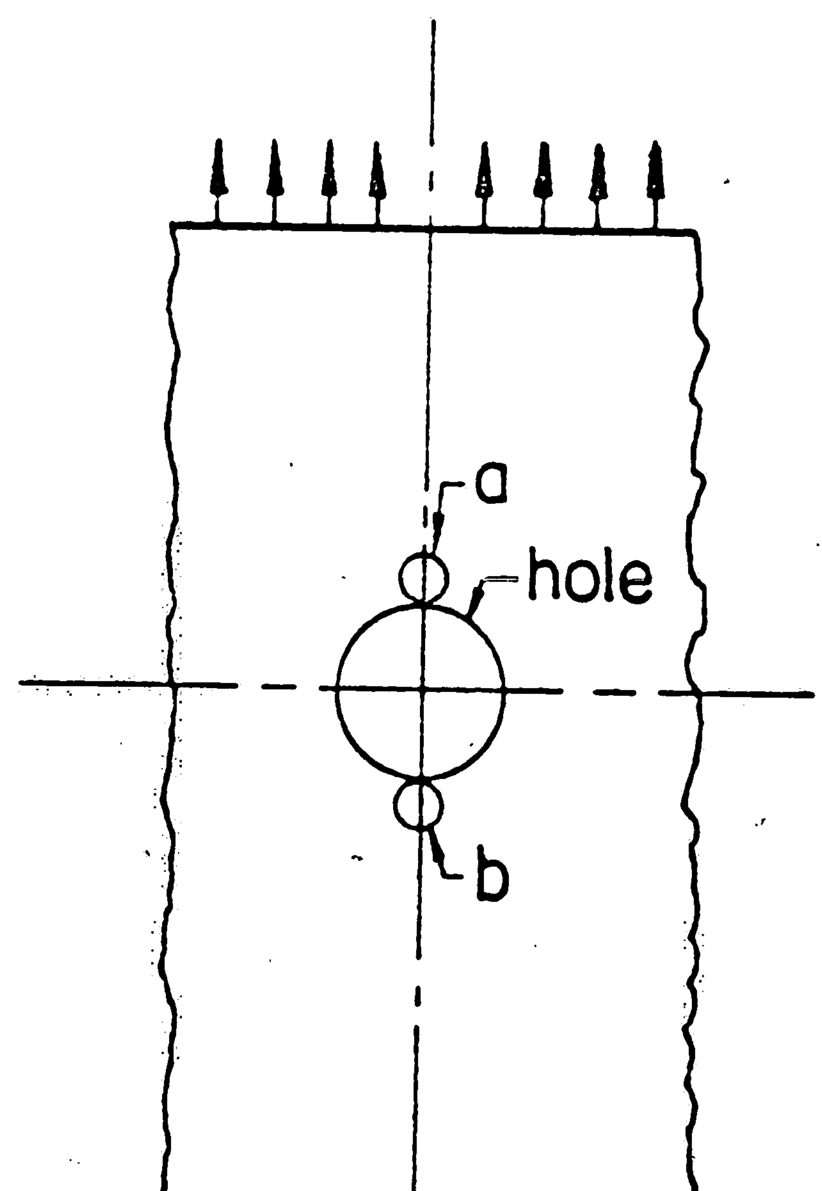


Fig. 2

Location of Holes in Mathar's Method

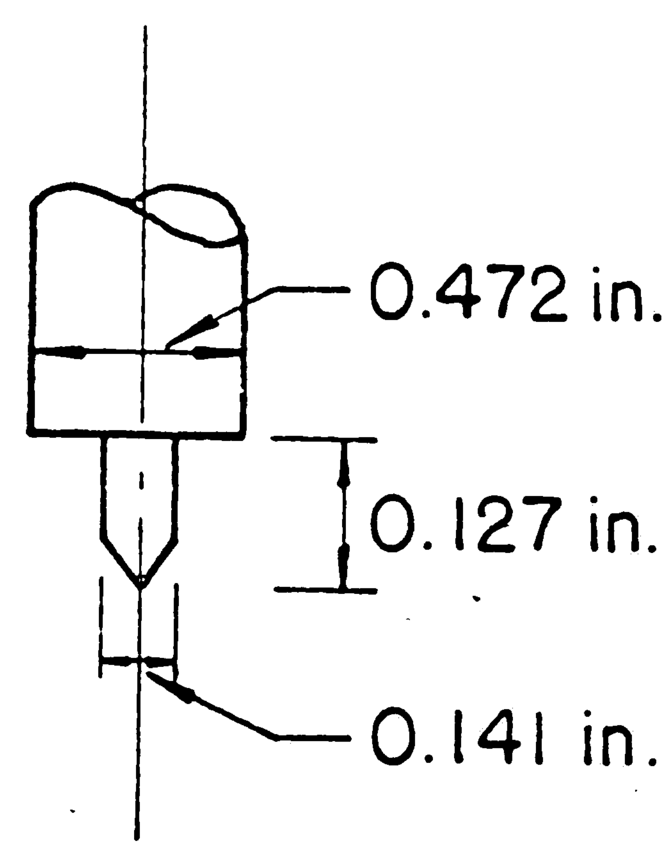


Fig. 3

Drill Used in Mathar's Method

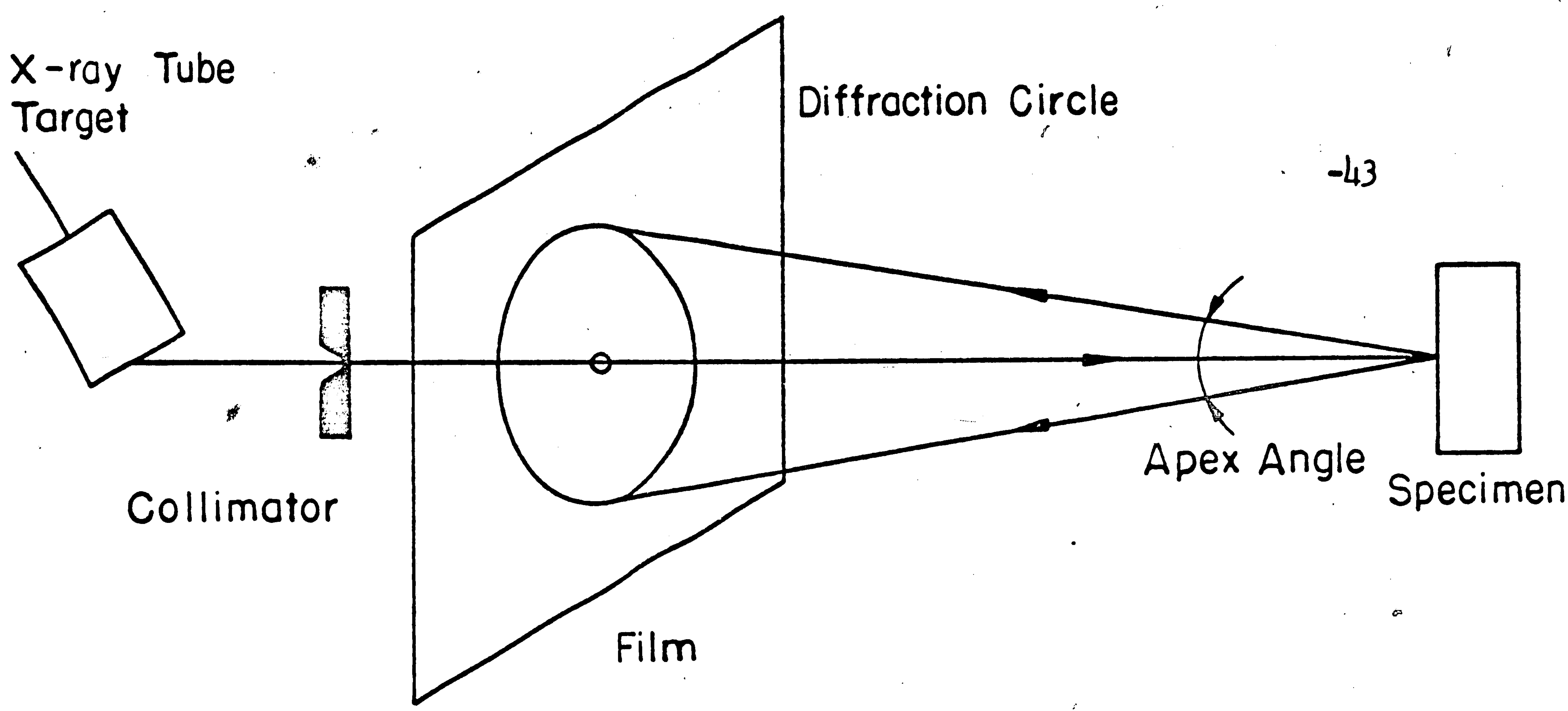
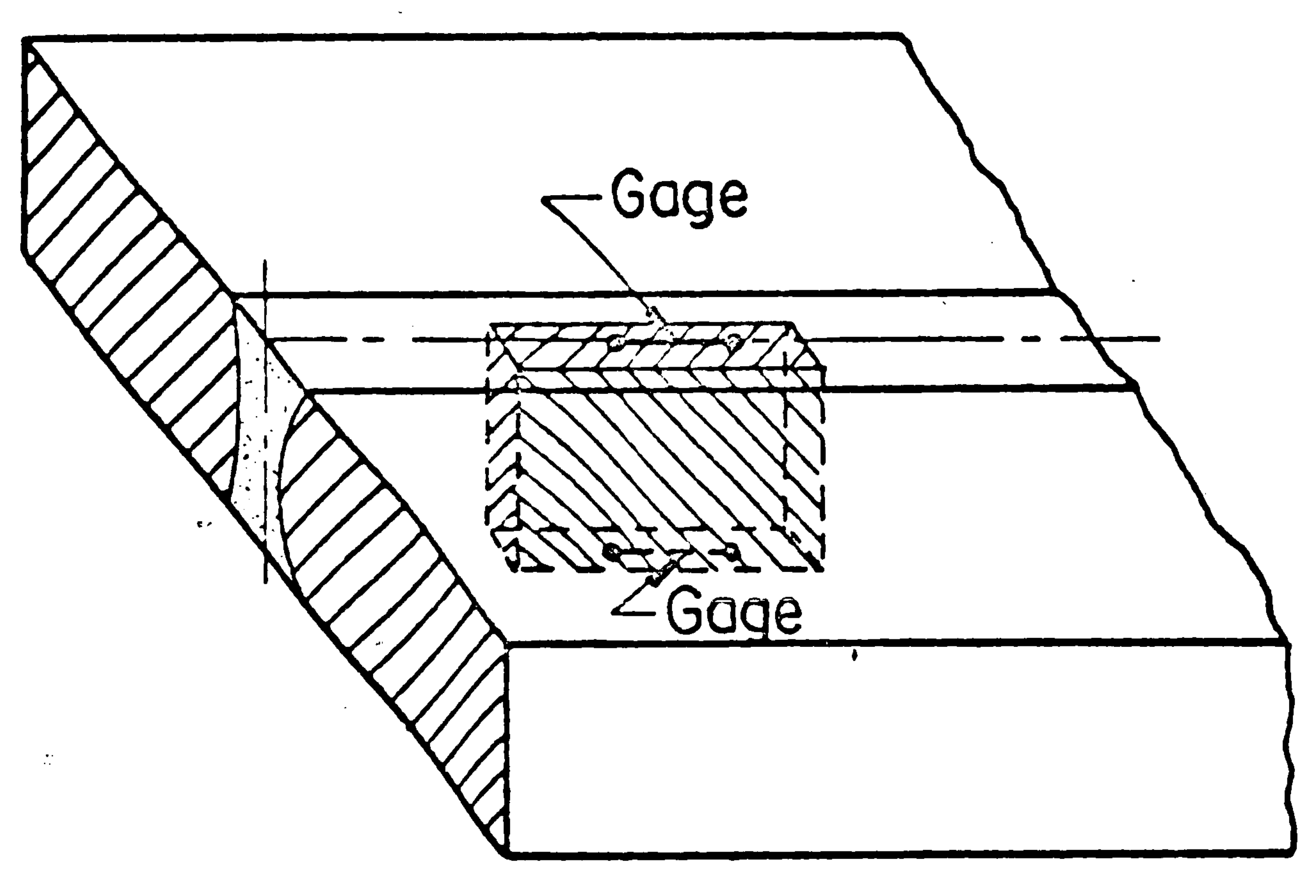


Fig. 4

Set-Up of X-ray Method for Measuring Residual Stresses



Placement of Gages in a Tri-axial Method

Fig. 5

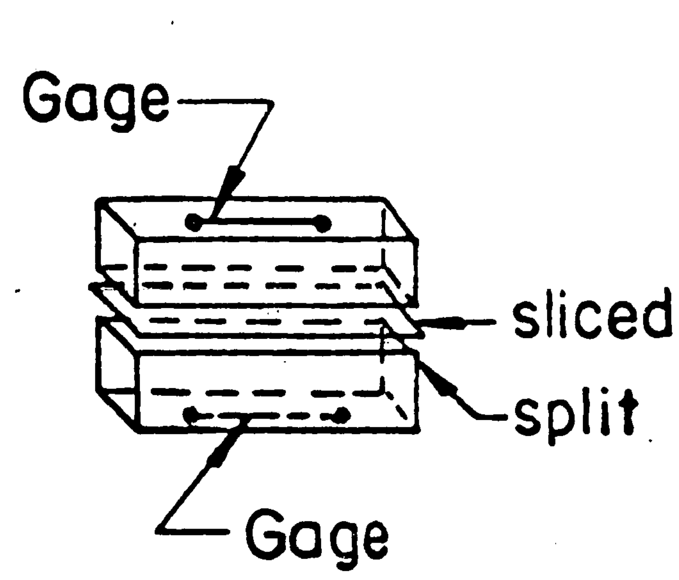


Fig. 6

Sectioning for Tri-axial Method

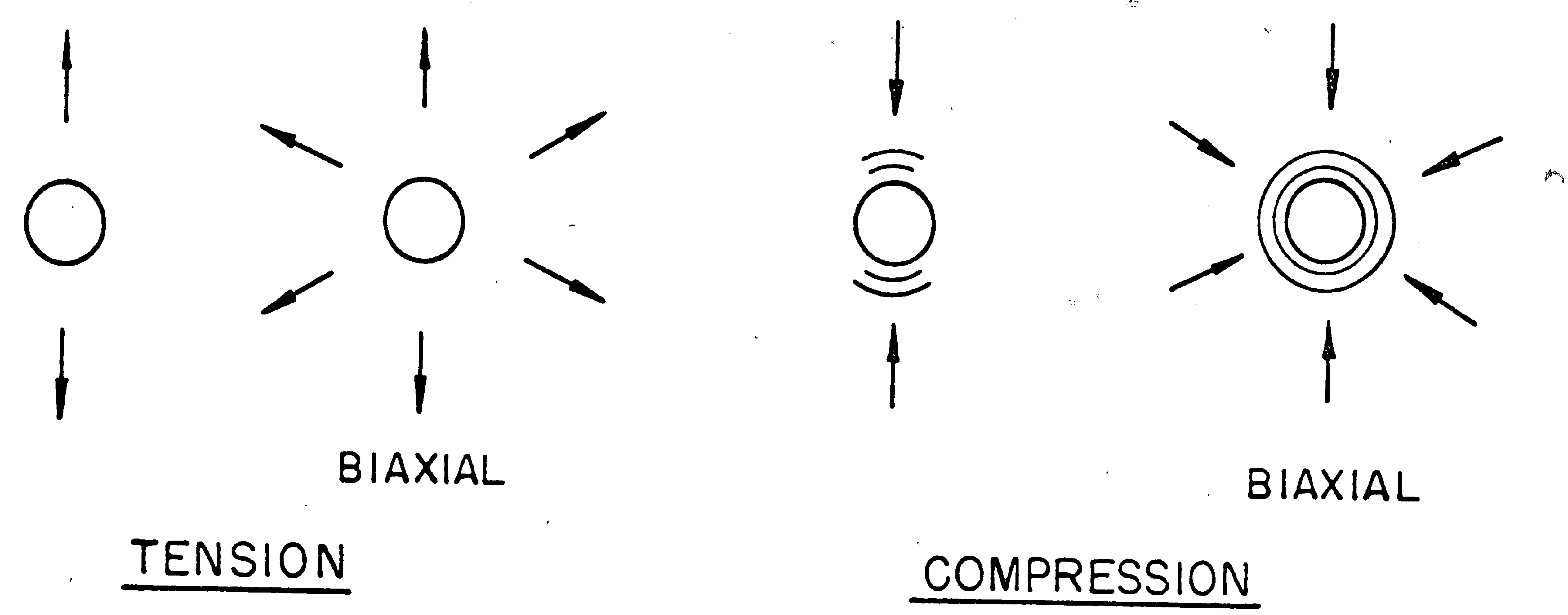


Fig. 7

Qualitative Study of Residual Stresses by Brittle Laquer

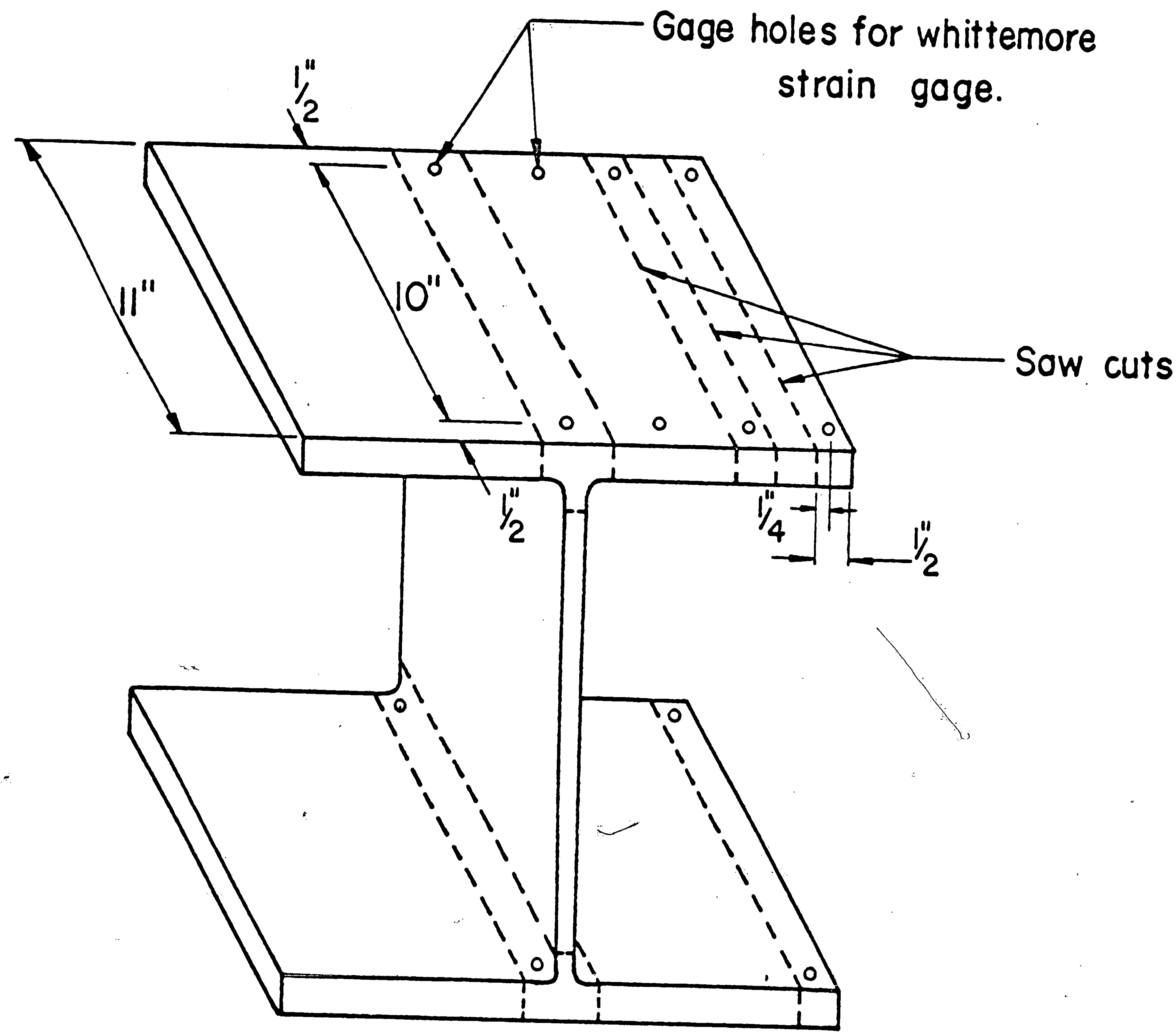


Fig. 8

Method of Sectioning

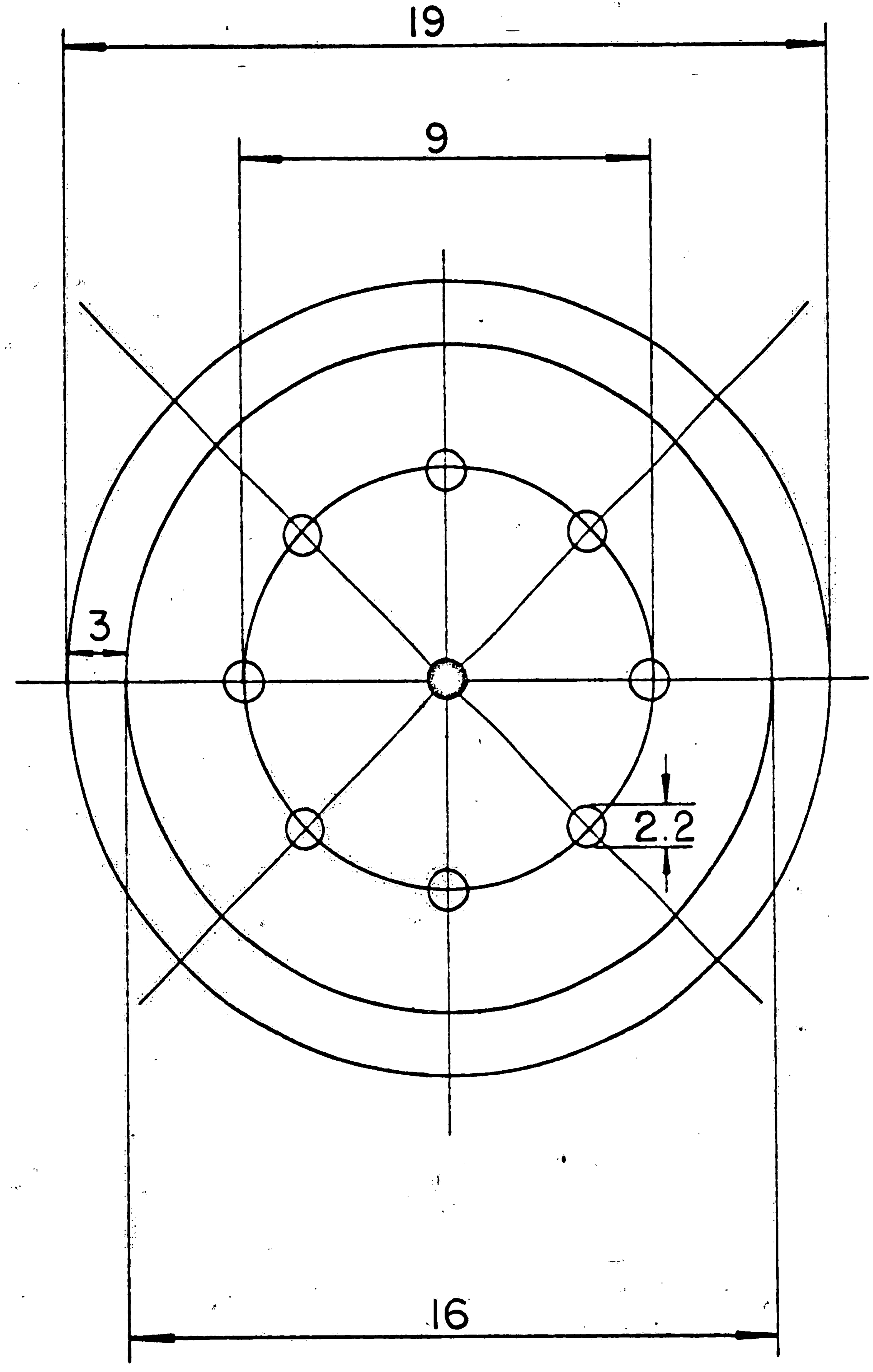


Fig. 9

Gunnert's Method

VII. REFERENCES

1. Heyn, E.
   INTERNAL STRAINS IN COLD-WROUGHT METALS, AND SOME TROUBLES CAUSED THEREBY, Journal, Institute of Metals (London), v. 12, p. 3, 1914

2. Durelli, A., Ekstein, H., Jacobson, R. and Tsao, C.
   RESIDUAL STRESS SURVEY, Armour Research Foundation, Project No. 2-937J, 1951

3. Sachs, G., Smith, C., Lubahn, J., Davis, G., Ebert, L.
   NONDESTRUCTIVE MEASUREMENT OF RESIDUAL AND ENFORCED STRESSES BY MEANS OF X-RAY DIFFRACTION, The Welding Journal, v. 11, p. 400s, 1946

4. Barrett, C.
   A CRITICAL REVIEW OF THE VARIOUS METHODS OF RESIDUAL STRESS MEASUREMENT, Soc. Exp. Stress Anal., v. 2, n. 1, p. 147, 1944

5. Lynch, J.
   MEASUREMENT OF RESIDUAL STRESSES, Residual Stress Measurements, American Society for Metals, Cleveland, p. 42, 1951

6. Heindlhofer, K.
   EVALUATION OF RESIDUAL STRESS, Metallurgy and Metallurgical Engineering Series, McGraw-Hill, 1948

7. Treuting, R.
   THE NATURE, ORIGIN, AND EFFECTS OF RESIDUAL STRESSES, Residual Stress Measurements, American Society for Metals, Cleveland, p. 1, 1951

8. Wishart, H.
   RESIDUAL STRESSES IN METALS, Residual Stress Measurements, American Society for Metals, p. 97, 1951

9. Baldwin, Jr., W.
   RESIDUAL STRESSES IN METALS, Twenty-third Edgar Marburg Lecture, Proc. ASTM, v. 49, p. 539, 1949

10. Baker, R., Rieksecker, R., Baldwin, Jr., W.
    DEVELOPMENT OF RESIDUAL STRESSES IN STRIP ROLLING, Trans., Am. Inst. of Mining and Metallurgical Engineers, v. 175, p. 337, 1948

11. Hawkes, G.
THE MEASUREMENT AND EFFECT OF RESIDUAL STRESS IN ENGINEERING COMPONENTS, Journal, Institute of Engineers (Australia), v. 33, p. 335, September 1961

12. Yang, C., Beedle, L., Johnston, B.
RESIDUAL STRESS AND THE YIELD STRENGTH OF STEEL BEAMS, The Welding Journal, v. 31, p. 205s, 1952

13. Huber, A., Beedle, L.
RESIDUAL STRESS AND THE COMPRESSIVE STRENGTH OF STEEL, The Welding Journal, v. 33, p. 589s, 1954

14. Beedle, L., Tall, L.
BASIC COLUMN STRENGTH, Proc. ASCE, v. 86(ST7), p. 139, 1960

15. Tall, L., Nagaraja Rao, N.
RESIDUAL STRESSES IN WELDED PLATES, The Welding Journal, v. 40, p. 468, 1961

16. Estuar, F., Tall, L.
EXPERIMENTAL INVESTIGATIONS OF WELDED BUILT-UP COLUMNS, The Welding Journal, v. 42, p. 164s, 1963

17. Gunnert, R.
RESIDUAL WELDING STRESSES, Almqvist and Wiksell, Stockholm, 1955

18. Greene, T.
EVALUATION OF EFFECT OF RESIDUAL STRESSES, The Welding Journal, v. 28, p. 193s, 1949

19. Spraragen, W.
RESIDUAL STRESSES IN WELDING, Residual Stresses in Metals and Metal Construction, edited by W. Osgood, Reinhold Publishing Co., p. 85, 1954

20. Boyd, G.
EFFECTS OF RESIDUAL STRESSES IN WELDED STRUCTURES, The Welding Journal, v. 34, p. 216s, 1955

21. Richards, D.
RELIEF AND REDISTRIBUTION OF RESIDUAL STRESSES IN METALS, Residual Stress Measurements, American Soeiety for Metals, p. 129, 1952

22. Kalakoutzky, N.
THE STUDY OF INTERNAL STRESSES IN CAST IRON AND STEEL, St. Petersburg, 1887 (Russian); also London, 1888, (from Ref. 4)

23. Howard, J.
INTERNAL STRAINS IN SECTION OF HARVEYIZED STEEL BAR, Report 5992 of Tests of Metals, Watertown Arsenal, pp. 285 and 532, 1893

24. Heyn, E., Bauer, O.
ON STRESSES IN COLD DRAWN METALS, Internationale Zeitschrift fur Metallographic, v. 1, p. 16, 1911, (from Ref. 9)

25. Mesnager, M.
METHODS DE DETERMINATION DES TENSIONS EXISTANT DANS UN CYLINDRE CIRCULAIRE, Comptes Rendus hebedaires des Seances de l'Academie des Sciences, v. 169, p. 1391, 1919, (from Ref. 9)

26. Sachs, G.
EVIDENCE OF RESIDUAL STRESSES IN RODS AND TUBES, Zeitschrift fur Metallkunde, v. 19, p. 352, 1927, (from Ref. 51)

27. Buehler, H.
Mitt. Ver. Stahlwerke, v. 2, p. 149, 1931, (from Ref. 4)

28. Stäblein, F.
STRESS MEASUREMENTS ON BILLETS QUENCHED FROM ONE SIDE, Stahl und Eisen, v. 52, p. 15, 1932

29. Sachs, G., Espey, G.
RESIDUAL STRESSES IN SUNK CORTRIDGE BRASS TUBING, Trans., Am. Inst. of Mining and Metallurgical Engineers, v. 147, p. 74, 1942

30. Laszlo, F.
A NEW METHOD OF MEASURING RESIDUAL STRESSES IN BRASS TUBES, Stahl und Eisen, v. 45, p. 1609, 1925

31. Lester, H., Aborn, R.
THE BEHAVIOR UNDER STRESS OF THE IRON CRYSTALS IN STEEL, Army Ordance, v. 6, 1925-26

32. Sachs, G., Weerts, J.
A NEW METHOD FOR THE X-RAY PRECISION MEASUREMENT OF LATTICE PARAMETERS, Ann. der Phys., v. 60, p. 481, 1930, (from Ref. 3)

33. Sachs, G., Weerts, J.
ELASTIC MEASUREMENTS BY MEANS OF X-RAYS, Zeitschrift fur Physik, v. 64, p. 344, 1930

34. Barrett, C., Gensamer, M.
STRESS ANALYSIS BY X-RAY DIFFRACTION, Physics. v. 7, January, 1936

35. Haskell, R.
X-RAY DIFFRACTION AS APPLIED TO DETERMINATION OF STRESS CONDITIONS IN GUN STEEL, Master's Thesis, M.I.T., 1934

36. Glocker, R.
X-RAY MEASUREMENT OF ELASTIC STRESS, Zeitschrift fur Metallkunde, v. 27, p. 196, 1935, (from Ref. 5)

37. Hatfield, W., Thirkell, G.
SEASON CRACKING, Journal, Institute of Metals (London), v. 22, p. 67, 1919

38. Anderson, R., Fahlman, E.
A METHOD FOR MEASURING INTERNAL STRESSES IN BRASS TUBES, Journal, Institute of Metals (London), v. 32, p. 367, 1924

39. Anderson, R., Fahlman, E.
THE EFFECT OF LOW-TEMPERATURE HEATING ON THE RELEASE OF INTERNAL STRESS IN BRASS TUBES, Journal, Institute of Metals (London), v. 34, p. 271, 1925

40. Crampton, D.
INTERNAL STRESSES AND SEASON CRACKING IN BRASS TUBES, Trans., Am. Instit. of Mining and Metallurgical Engineers, v. 89, p. 233, 1930

41. Pinkerton, A., Tait, W.
SEASON CRACKING IN ARSENICAL COPPER TUBES, Journal, Institute of Metals (London), v. 36, p. 233, 1926

42. Krecek, A.
Zeitschrift fur Metallkunde, v. 23, p. 175, 1931

43. Treuting, R., Read, Jr., W.
A MECHANICAL DETERMINATION OF BIAXIAL RESIDUAL STRESS IN SHEET MATERIALS, Journal of Applied Physics, v. 22, p. 130, 1951

44. Buchholtz, H.
RESIDUAL STRESSES IN STRUCTURAL MEMBERS, Welding Industry, v. 3, pp. 267 and 237, 1936

45. Siebel, E., Pfender, M.
STRAINS AND RESIDUAL STRESSES IN WELDED ASSEMBLIES, Archiv. fur das Eisenhuttenwesen, v. 7, p. 407, 1933-34, (from Ref. 9)

46. Bierett, G.
Zeitschrift Ver Deut. Ing., v. 78, p. 709, 1934

47. Mies, O.
TESTS OF THE DISTRIBUTION OF SHRINKAGE IN WELDED PLATES OF MILD STEEL, Die Warme, v. 57, p. 113, 1934, and v. 58, p. 97, 1935, (from Ref. 9)

48. Jamieson, R.
SOME MEASUREMENTS OF RESIDUAL STRESS IN ARC-WELDED STEEL PLATES, The Welding Journal, v. 13, p. 17, 1934

49. Nitta, A.
ULTIMATE STRENGTH OF HIGH STRENGTH STEEL CIRCULAR COLUMNS, Fritz Engineering Laboratory Report No. 272.3, June, 1960

50. Mathar, J.
DETERMINATION OF INITIAL STRESSES BY MEASURING DEFORMATIONS AROUND DRILLED HOLES, Trans., ASME, v. 56, p. 249, 1934

51. Gadd, C.
RESIDUAL STRESS INDICATION IN BRITTLE LACQUER, Soc. Exp. Stress. Anal., v. 4, n. 1, p. 74, 1946

52. Rosenthal, D., Norton, J.
A METHOD OF MEASURING TRIAXIAL RESIDUAL STRESSES IN PLATES, The Welding Journal, v. 24, p. 295s, 1945

53. Soete, W., Vancrombrugge, R.
DETERMINATION OF RESIDUAL STRESSES BELOW THE SURFACE, Residual Stresses in Metals and Metal Construction, ed. W. Osgood, Reinhold Publishing Co., p. 331, 1954

54. Briggs, C.
INTERNAL STRESSES IN CASTINGS, The Welding Journal, v. 4, p. 22s, 1939

55. Tall, L.
RESIDUAL STRESSES IN WELDED PLATES--A THEORETICAL STUDY, The Welding Journal, v. 43, p. 105, 1964

56. Nadai, A.
PLASTICITY, McGraw-Hill Pub. Co., New York, 1931

57. Sachs, G. and Espey, G.
A NEW METHOD FOR DETERMINATION OF STRESS DISTRIBUTION IN THIN-WALLED TUBING, Am. Inst. of Mining and Metallurgical Engineers, v. 147, p. 348, 1942

58. Norton, J. and Rosenthal, D.
STRESS MEASUREMENT BY X-RAY DIFFRACTION, Soc. Exp. Stress Anal., v. 1, n. 2, p. 73, 1943

59. Meriam J., De Garmo, E., and Jonassen, F.
A METHOD FOR THE MEASUREMENT OF RESIDUAL WELDING STRESSES, The Welding Journal, v. 25, p. 340s, 1946

60. Luxion, W. and Johnston, B.
PLASTIC BEHAVIOR OF WIDE FLANGE BEAMS, The Welding Journal, v. 27, p. 538s, 1958

61. Riparbelli, C.
A METHOD FOR THE DETERMINATION OF INITIAL STRESSES, Soc. Exp. Stress Anal., v. 8, n. 1, p. 173, 1950

62. Suppiger, E., Riparbelli, C., and Ward, E.
THE DETERMINATION OF INITIAL STRESSES AND RESULTS OF TESTS ON STEEL PLATES, The Welding Journal, v. 30, p. 91s, 1951

63. Letner, H.
APPLICATION OF OPTICAL INTERFERENCE TO THE STUDY OF RESIDUAL SURFACE STRESSES, Soc. Exp. Stress Anal., v. 10, n. 2, p. 23, 1953

64. Mark, M.
A QUALITATIVE STUDY OF RESIDUAL STRESSES IN WELDS BY PHOTOELASTICITY, The Welding Journal, v. 32, p. 374s, 1953

65. Waisman, J. and Phillips, A.
SIMPLIFIED MEASUREMENT OF RESIDUAL STRESSES, Soc. Exp. Stress Anal., v. 11, n. 2, p. 29, 1954

66. Gunnert, R.
METHOD FOR MEASURING THE RESIDUAL STRESSES IN THE INTERIOR OF A MATERIAL, Welding Research Abroad, v. 6, p. 10, 1960

67. Kurkin, S., Fishkis, M., Vinokurov, V., and Gazaryan, A.
THE MEASUREMENT OF DEFORMATIONS AND STRESSES WHEN WELDING VERY THICK ST.3 STEEL PLATES, Welding Research Abroad, v. 6, n. 6, p. 2, 1960

68. Frommer, E. and Lloyd, L.
THE MEASUREMENT OF RESIDUAL STRESSES IN METALS BY THE X-RAY BACK REFLECTION METHOD, Journal Institute of Metals, v. 70, p. 91, 1944

69. Tall, L.
STUB COLUMN TEST PROCEDURE, International Institute of Welding Document X-282-61, prepared by Working Group (H. Louis, M. Marincek, and L. Tall), Annual Conference, Oslo, July 1962

VIII. ADDITIONAL REFERENCES

70. Jasper, T.
THE CALCULATION OF QUENCHING STRESSES IN STEEL BY USING DIRECT MEASUREMENTS, Engineering (London), 1924

71. Hoyt, S.
STRESSES IN QUENCHED AND TEMPERED STEEL, Trans., Am. Soc. for Steel Treating, v. 11, 1927

72. Crook, L.
STRESSES IN FLAT STEEL PLATES DUE TO A WELDED BEAD ALONG ONE EDGE, The Welding Journal, v. 7, 1928

73. Portevin, A.
SUR LA DETERMINATION DES EFFORTS INTERNES DANS LES CYLINDRES CIRCULAIRES METALLIGUES, Comptes Rendus, v. 186, 1928

74. Aksenow, G.
MEASUREMENT OF ELASTIC STRESS IN A FINE-GRAINED MATERIAL BY THE DEBYE-SCHERRER METHOD, Journal of Applied Physics (U.S.S.R), 6, 1929

75. Klein, H.
TURNED THIN RINGS FROM THICK WALLED TUBING TO MEASURE RESIDUAL TANGENTIAL STRESSES RESULTING FROM COLD WORKING, Mitt. Kaiser-Wilhelm Inst. Eisenforsch, v. 11, 1929

76. Siebel, E.
TRANSVERSE SLICES CUT FROM ROLLED TUBING AND SLICES BORES OUT TO DETERMINE RESIDUAL TANGENTIAL STRESSES, Mitt. Kaiser-Wilhelm Inst. Eisenforsch, v. 11, 1929

77. Greene, O.
ESTIMATION OF INTERNAL STRESSES IN QUENCHED HOLLOW CYLINDERS OF CABON TOOL STEEL, Trans., Am. Soc. for Steel Treating, v. 18, 1930

78. Davidenkov, N.
CALCULATION OF RESIDUAL STRESSES IN COLD-DRAWN TUBES, Zeitschrift fur Metallkunde, v. 24, 1932

79. Buhler, H. and Lohmann, W.
BEITRAG ZUR SCHWEISS-SPANNUNGEN III EIGENSPANNUNGEN, bei der Fleckschweissung Elektroschev, v. 5, 1934

80. Buchholtz, H. and Buhler, H.
COMPARISON OF METHODS FOR DETERMINING RESIDUAL STRESSES BY TEMPERING, Stahl und Eisen, v. 52, 1932

81. Barrett, C.
INTERNAL STRESSES, Metals and Alloys, v. 5, 1934

82. Reeve, L.
INTERNAL STRESSES IN WELDING AND THEIR DETERMINATION, Welding Industry, v. 4, 1936

83. Spararagen, W. and Claussen, G.
SHRINKAGE STRESSES IN WELDING--A REVIEW OF THE LITERATURE OF JANUARY 1937, The Welding Journal, v. 16, 1937

84. Rodgers, O. and Fetcher, J.
THE DETERMINATION OF INTERNAL STRESSES FORM THE TEMPERATURE HISTORY OF A BUTT-WELDED PLATE, The Welding Journal, v. 17, 1938

85. Sachs, G. and Espey, G.
THE MEASUREMENT OF RESIDUAL STRESSES IN METALS, Iron Age, v. 148, Sept. 18 and Sept. 25, 1941

86. Isenburger, H.
BIBLIOGRAPHY OF STRESS ANALYSIS BY MEANS OF X-RAY BACK REFLECTION METHOD, The Welding Journal, v. 23, 1944

87. Norton, J.
X-RAY METHODS IN THE FIELD OF RESIDUAL STRESSES, Soc. Exp. Stress Anal. v. 2, n. 6, 1944

88. Horger, O., Neifert, H. and Regen, R.
RESIDUAL STRESSES AND FATIGUE STUDIES, Soc. Exp. Stress Anal., v. 1, n.1, 1943

89. Horger, O. and Neifert, H.
CORRELATION OF RESIDUAL STRESS IN THE FATIGUE STRENGTH OF AXLES, Trans., ASME, v. 64, 1942

90. McPherson, A.
MEASUREMENT OF RESIDUAL STRESSES IN A MAGNESIUM CASTING, Soc. Exp. Stress Anal., v. 2, n. 1, 1944

91. DeForest, A. and Stern, F., Jr.
STRESSCOAT AND WIRE STRAIN GAGE INDICATIONS OF RESIDUAL STRESSES, Soc. Exp. Stress Anal., v. 2, n. 1, 1944

92. Suppiger, E.
THE DETERMINATION OF STRESSES FROM STRAINS MEASURED ON THREE INTERSECTING GAGE LINES, Air Corps Technical Report No. 4822, 1942

93. Spaulding, R.
ARC WELDING WITHOUT RESIDUAL SHRINKAGE STRESSES, The Welding Journal, v. 20, 1941

94. Bellenrath, F., Hauk, V. and Osswald, E.
RESIDUAL STRESSES IN PURE TENSION REVEALED BY X-RAY DIFFRACTION METHOD, The Welding Journal, v. 21, 1942

95. Norton, J. and Rosenthal, D.
APPLICATIONS OF THE X-RAY DIFFRACTION METHOD OF STRESS MEASUREMENT TO PROBLEMS INVOLVING RESIDUAL STRESSES IN METALS, Soc. Exp. Stress Anal., v. 1, n. 2, 1943

96. Sachs, G. and Espey, G.
RESIDUAL STRESSES IN SUNK CARTRIDGE BRASS TUBING, Trans., Am. Inst. of Mining and Metallurgical Engineers, v. 147, 1942.

97. Sachs, G.
PRACTICAL METALLURGY, American Society for Metals, Cleveland, 1940

98. Norton, J. and Rosenthal, D.
AN INVESTIGATION OF THE BEHAVIOR OF RESIDUAL STRESSES UNDER EXTERNAL LOAD AND THEIR EFFECT ON SAFETY, The Welding Journal, v. 22, 1943

99. Thomas, D.
THE MEASUREMENT OF STRESSES BY X-RAYS, Journal of Scientific Instruments, v. 18, 1941

100. Ford, H.
SYMPOSIUM ON INTERNAL STRESSES IN METALS AND ALLOYS, The Institute of Metals, 1948

101. Safoglu, R.
CONTRIBUTION TO THE METHODS OF MEASURING STRESSES BELOW THE SURFACE, Ph.D. Thesis, Massachusetts Institute of Technology, 1949

102. Norton, J. and Rosenthal, D.
RECENT CONTRIBUTIONS TO THE X-RAY METHOD IN THE FIELD OF STRESS ANALYSIS, Soc. Exp. Stress Anal., v. 5, n. 1, 1947

103. Wilson, W. and Hao, C.
RESIDUAL STRESSES IN WELDED STRUCTURES, Bulletin No. 361, University of Illinois, 1946

104. Weck, R.
RESIDUAL STRESSES DUE TO WELDING, The Welding Journal, v. 28, 1949

105. Wood, W.
STUDY OF INTERNAL STRESSES IN A METAL BY X-RAY DIFFRACTION, Proceedings, Institution of Mechanical Engineers, v. 152, 1945

106. N.A.C.A.
NONDESTRUCTIVE MEASUREMENT OF RESIDUAL AND ENFORCED STRESSES BY MEANS OF X-RAY DIFFRACTION: Correlated Abstracts of the Literature, NACA Tech. Note 986, Sept. 1945, Some Applications to Aircraft Problems, NACA Tech. Note 987, Nov. 1945

107. Erker, A.
RESIDUAL STRESS AND DISTORTION AND THEIR EFFECT ON THE SUITABILITY OF STRUCTURES IN SERVICE, Welding Research Abroad, June-July 1962.

108. Ryan
PHOTOELASTIC MODELS REVEAL WELDING STRESSES, Welding Engineer, v. 32, 1947

109. Fuchs, H. and Mattson, R.
MEASUREMENT OF RESIDUAL STRESSES IN TORSION BAR SPRINGS, Soc. Exp. Stress Anal., v. 4, n. 1, 1946

110. Hasio, C.
THE DISTRIBUTION OF RESIDUAL STRESSES IN THE ROLLING PROCESS, Soc. Exp. Stress Anal., v. 6, n. 2, 1948

111. Soete, W.
MEASUREMENT AND RELAXATION OF RESIDUAL STRESSES, The Welding Journal, v. 28, 1949

112. Soete, W. and Vancrombrugge, R.
HET METEN VAN ERGENSPANNINGEN IN DIEPTE, Revue de la Soudure, n. 1, 1948

113. Soete, W. and Vancrombrugge, R.
EEN QUASI NIET--DESTRUCTIVE WERKWIJZE VOOR HET BEPALEN VAN ERGENSPANNINGEN, Revue de la Soudure, n. 4, 1947

114. Kournossov, D. and Jakutovich, M.
THE MEASUREMENT OF RESIDUAL STRESSES BY MEANS OF DRILLING HOLES, The Engineer's Digest, v. 5, n. 5, 1948

115. Ryan, J.
PHOTOELASTIC MODELS REVEAL WELD STRESSES, Welding Engineer, v. 32, 1947

116. Milbrandt, K.
RING METHOD FOR DETERMINING RESIDUAL STRESSES, Soc. Exp. Stress Anal., v. 9, n. 1, 1951

117. Henrikses, E.
RESIDUAL STRESSES IN MACHINED SURFACES, Trans., ASME, v. 73, 1951

118. Read, W., Jr.
FORMULAS FOR THE DETERMINATION OF RESIDUAL STRESS IN WIRES BY LAYER REMOVAL METHOD, Journal of Applied Physics, v. 22, 1951

119. Soete, W. and Vancrombrugge, R.
AN INDUSTRIAL METHOD FOR THE DETERMINATION OF RESIDUAL STRESSES, Soc. Exp. Stress Anal., v. 8, n. 1, 1950

120. Horger, O.
RESIDUAL STRESSES, Handbook of Experimental Stress Analysis, John Wiley and Sons, 1950

121. Treuting, R., Lynch, J., Wishart, H., and Richards, D.
RESIDUAL STRESS MEASUREMENTS, American Society for Metals 33rd National Metal Congress, 1952

122. Demorest, D. and Leeser, D.
A STUDY OF RESIDUAL STRESSES IN FLAT BEAMS BY ELECTROPOLISHING METHODS, Soc. Exp. Stress Anal., v. 11, n. 1, 1953

123. Hanslip
RESIDUAL STRESSES IN SURFACE--HARDENED OIL FIELD PUMP RODS, Soc. Exp. Stress Anal., v. 10, n. 1, 1952

124. Leaf, W.
TECHNIQUES IN RESIDUAL STRESS ANALYSIS, Soc. Exp. Stress Anal., v. 9, n. 2, 1951

125. Tokarcik, A. and Polzin, M.
QUANTITATIVE EVALUATION OF RESIDUAL STRESSES BY THE STRESSCOAT DRILLING TECHNIQUE, Soc. Exp. Stress Anal., v. 9, n. 2, 1951

126. Jenks, B., Jr.
A PRACTICAL METHOD FOR THE DETERMINATION OF INITIAL STRESSES IN STEEL PLATES, M.S. Thesis, Princeton University, June 1950

127. Hanstock, R.
THE NON-DESTRUCTIVE TESTING OF METALS, Institute of Metals Monograph and Report Series Number 10, The Institute of Metals, 1951

128. Rosenthal, D.
MEASUREMENT OF RESIDUAL STRESS, from Residual Stresses in Metals and Metal Construction edited by W. R. Osgood, Reinhold Publishing Co., 1954

129. Boiten, R. and TenCate, W.
A ROUTINE METHOD FOR THE MEASUREMENT OF RESIDUAL STRESSES IN PLATES, Applied Scientific Research, v. 3, Section A, n. 2, 1952

130. Masubushi, K.
ANALYTICAL INVESTIGATION OF RESIDUAL STRESSES AND DISTORTIONS,

131.
BIBLIOGRAPHY ON RESIDUAL STRESSES, Supplement No. 1, SAE Paper No. SP-167, Feb. 1959

132. Durelli, A., Ekstein, H., Jacobson, R. and Tsao, C.
RESIDUAL STRESS SURVEY, Armour Research Foundation, Project No. 2-937J, 1951

133. Weiss
RESIDUAL STRESS IN CYLINDERS, Soc. Exp. Stress Anal., v. 15, n. 2, 1958

134. Miller, M., Mantel, E., and Coleman, W.
AN EVALUATION OF THE X-RAY DIFFRACTION METHOD OF STRESS MEASUREMENT WITH A COMPARISON TO DISSECTION METHODS OF RESIDUAL STRESS MEASUREMENT IN HARDENED STEEL, Soc. Exp. Stress Anal., v. 15, n. 1, 1957

135. Fujeta, Y.
THE MAGNITUDE AND DISTRIBUTION OF RESIDUAL STRESS, Fritz Engineering Laboratory Report 220A.20, 1955

136. Kelsey, R.
MEASURING NON-UNIFORM RESIDUAL STRESSES BY THE HOLE DRILLING METHOD, Soc. Exp. Stress Anal., v. 14, n. 1, 1956

137. Huber, A.
RESIDUAL STRAIN MEASUREMENT, Fritz Engineering Laboratory Report 220A.17, 1955

138. Kurkin, S. and Vinokurov, V.
TRI-AXIAL WELDING STRESSES IN HEAVY SECTION BUTT JOINTS, Doklady Vysshei Shkoly (Russian), n. 1, 1958

139. Schwaighofer, J.
DETERMINATION OF RESIDUAL STRESSES ON THE SURFACE OF STRUCTURAL PARTS, Experimental Mechanics, v. 4, February 1964

VITA

The author was born the second son of Elizabeth and Benjamin Seaman in Hershey, Pennsylvania, July 6, 1940.

He graduated from M. S. Hershey Jr.-Sr. High School in Hershey, Pennsylvania in May, 1958 and then attended Hershey Junior College, Hershey, Pennsylvania from September, 1958 to June, 1960. He was awarded the degree of Bachelor of Science from Lafayette College which he attended from September, 1960 to June, 1962.

In June, 1962 he joined Berger Associates, Inc., of Harrisburg, Pennsylvania and was employed as a junior bridge engineer until September, 1962.

The author enrolled in the Graduate School, Department of Civil Engineering at Lehigh University, in September, 1962, and was appointed the Lawrence Calvin Brink Research Fellowship in Civil Engineering, and later to a research assistantship in February, 1963. He has been associated with the Welded and Rolled Column Project in the Structural Metals Division of Fritz Engineering Laboratory, Lehigh University since September, 1962.