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FINAL REPORT

RESIDUAL STRESS OF DIFFUSION BONDED ALUMINUM-TO-STAINLESS STEEL JOINS

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MASTER

Materials and Devices Research Group

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by

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ABSTRACT

An X-ray method for determination of residual stress as a function of surface position on a metal sample is described. This method is capable of spatial resolution on the order of 0.040 inch (1 mm) and precision positioning of the sample along three orthogonal axes to better than 0.001 inch. A high precision sample holder was designed and fabricated for this purpose. Apparent residual stress was found to be a strong function of sample position with respect to the axis of rotation of the diffractometer circle. This relationship is on the order of 400 to 500 Kpsi/inch for aluminum. The high precision sample holder allowed careful centering of the sample providing true (rather than apparent) residual stress measurements in the range of low stresses (less than 10 Ksi). Comparison was made between applied stress values obtained with strain gage output and those obtained by X-ray diffraction. Correlation was good with the accuracy of stress measurements being approximately ± 500 psi. Computer methods were devised for data reduction using Fortran and the BASIC II languages.

The capabilities of this X-ray method would make it possible to monitor the quality of diffusion bonds between dissimilar metals. The experimental demands and the inability to monitor internal interfaces limits this from being a routine production test. The high precision sample holder does make mapping of residual stress patterns on planar surfaces (such as silver-coated substrates prior to diffusion bonding) a more practical nondestructive inspection.

ACKNOWLEDGEMENTS

This work was funded by Research Grant No. 5631109 from the Lawrence Livermore National Laboratory. Special thanks are extended to Donald Walmsley for his generous support of this project. As in most research, whatever was accomplished was built upon prior work done by others in the field. In addition to the specific reference citations and the general materials in the bibliography, essential background was developed in several mechanical engineering senior projects. The work of Robert B. Zegarski, Maurice Dickerson and Duke M. Wong is gratefully acknowledged. Professor E. B. Evans of the University of the Pacific very generously provided important background material from his extensive experience in the measurement of residual stress in metals.

Essential support was provided by the faculty and staff of the Mechanical Engineering Department. Specific thanks are offered to Marija Morala for expert handling of fiscal and budget matters; to Brian Brown for his generous contribution of the TRS-80 computation program; and to George Yancey for his expert and generous help in the machine shop. Gil Parra provided the drafting services for the charts and graphs and Lesa Havert accomplished the formidable task of typing and organizing this manuscript. The photographic work was done by Steve Rita of Illustration Services.

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INTRODUCTION

Background

Residual stress determination by X-ray diffraction depends upon the fact that the spacing of the atomic planes in a crystalline material is altered by stress. The spacing of the atomic planes can be determined by measurement of a diffraction angle and the change in their spacing is then used to calculate the associated stress. It is clear that residual stress is not measured directly by X-ray diffraction, rather the strain is measured from which stress is calculated using some assumed, or otherwise determined, elastic constants for the material.

Stress-strain relationships. According to the theory of elasticity, Hooke's Law states that stress (σ_y) is related to strain (ϵ_x) by the modulus of elasticity (E):

$$\sigma_y = E \epsilon_x \quad (1)$$

The force in the x-direction producing the strain ϵ_x also produces strain in the transverse directions perpendicular to x.

The ratio of this transverse strain to the strain ϵ_x is called Poisson's Ratio (ν) and:

$$\epsilon_y = \epsilon_z = -\nu \epsilon_x = -\frac{\nu}{E} \sigma_y \quad (2)$$

In general, for a triaxial system the strain along any axis is due to the stress along that axis and to the strains superimposed by the Poisson effect from the stresses along the other two axes. This leads to equations for the principal strains $\{\epsilon_i\}$: (Figure 1)

$$\epsilon_1 = \frac{1}{E} \left[\sigma_1 - \nu (\sigma_2 + \sigma_3) \right] \quad (3a)$$

$$\epsilon_2 = \frac{1}{E} \left[\sigma_2 - \nu (\sigma_3 + \sigma_1) \right] \quad (3b)$$

$$\epsilon_3 = \frac{1}{E} \left[\sigma_3 - \nu (\sigma_1 + \sigma_2) \right] \quad (3c)$$

In the case of a surface where residual stress is to be determined, the normal stress (σ_3) is taken to be zero since stress cannot act across a free surface. The above strain relationships then become:

$$\epsilon_1 = \frac{1}{E} (\sigma_1 - \nu \sigma_2) \quad (4a)$$

$$\epsilon_2 = \frac{1}{E} (\sigma_2 - \nu \sigma_1) \quad (4b)$$

$$\epsilon_3 = \frac{\nu}{E} (\sigma_1 + \sigma_2) \quad (4c)$$

X-ray Strain Analysis. Since X-ray diffraction measurements are considered to be confined to the surface, plane stress conditions are assumed. Only two principal stresses are considered which lie in the plane of the surface, i.e., σ_3 is considered to be zero (Figure 1). The strain normal to the surface is usually not equal to zero. The general expression for strain along a particular direction from the surface is given as [2]:

$$\epsilon_\phi^s = \frac{1}{E} \left[\sigma_\phi^s (1 + \nu) \sin^2 \phi - \nu (\sigma_1 + \sigma_2) \right]. \quad (5)$$

The difference between the strain in the normal direction (ϵ_3) and the strain along the inclined direction (ϵ_ϕ^s) is obtained by subtracting Equation (4c) from Equation (5). Thus:

$$\epsilon_\phi^s - \epsilon_3 = \frac{\sigma_\phi^s}{E} (1 + \nu) \sin^2 \phi. \quad (6)$$

Figure 1. Surface Stresses

It is assumed that the elastic properties of the material are isotropic. The above equation shows that the differences between two strains in a stressed specimen depends only upon the stress acting in the plane of the two strains. If the strains in Equation (6) are expressed as relative changes in the spacing of atomic planes in the crystal lattice, then we have:

$$\frac{d_i - d_o}{d_o} - \frac{d_n - d_o}{d_o} = \frac{\sigma_\phi}{E} (1 + \nu) \sin^2 \psi \quad (7)$$

where

d_i = spacing of planes normal to beam incident at angle ψ ,

d_n = spacing of planes parallel to surface,

d_o = spacing of unstressed planes.

Since d_i , d_n , and d_o are nearly equal to one another, $d_i - d_n$ is small compared to d_o . The unknown spacing d_o can then be replaced by either d_n or d_i with negligible error. Equation (7) can then be written [2]:

$$\sigma_\phi = \frac{E}{(1 + \nu) \sin^2 \psi} \left(\frac{d_i - d_n}{d_n} \right) \quad (8)$$

Thus, it is possible to calculate stress in any chosen direction by measuring the d spacings from two-directions in a plane normal to the surface containing the stress.

The Diffractometer Method

The X-ray technique for determination of lattice spacings involves a precise determination of the angle of diffraction. Since only particular values of λ , d and θ can satisfy the Bragg Equation:

$$n\lambda = 2d \sin \theta \quad (9)$$

where

λ = wavelength of radiation,

n = an integer,

d = plane spacing,

θ = diffraction angle.

A monochromatic source of X-rays can produce diffraction only when

$$d = \frac{\lambda}{2 \sin \gamma}, \quad \lambda = \text{constant} \quad (10)$$

and the d spacing is calculated from the measured angle θ where diffraction occurs. A typical diffractometer arrangement for measurement of residual stress is shown in Figure 2. Since this method provides a direct measurement of the angle 2θ it is more convenient to express the residual stress as a function of diffraction angle rather than of d spacing. Differentiation of the Bragg Equation (9) gives an expression for unit strain:

$$\frac{\Delta d}{d} = - \cot \theta \left(\frac{\Delta 2\theta}{2} \right) \quad (11)$$

Combining this expression with Equation (8) for stress σ_ϕ gives:

$$\sigma_\phi = \frac{E \cot \theta (2\theta_n - 2\theta_i)}{2(1 + \nu) \sin^2 \phi} \quad (12)$$

In this equation all of the terms except the measured values of 2θ are known so that a simplified form may be written:

$$\begin{aligned} \sigma_\phi &= K (2\theta_n - 2\theta_i) \\ \sigma_\phi &= K (\Delta 2\theta) \end{aligned} \quad (13)$$

Figure 2. The Two Angle Method

The constant K is called the stress constant and is fixed by the material and the angles ψ and θ .

In practice a specimen is set up at the axis of the diffractometer circle and the diffraction angle 2θ is determined for two different plane spacings, usually for $\psi = 0^\circ$ and $\psi = 45^\circ$. The line shift $\Delta 2\theta$ is determined and σ_ψ is calculated from Equation (13) above. This is often called the two-exposure or two-angle method.

Practical Considerations

The method for determination of a residual stress by X-ray diffraction is, theoretically at least, a simple, straight-forward procedure. In practice, several complicating considerations arise which often lead to a certain ambiguity in the stresses reported. The numerical value for the stress is obtained by multiplying the angular shift of the diffraction peak by the stress constant K . Essentially, then, the diffractometer measures the shift in diffraction line position due to stress as the angle ψ is changed. Accordingly, errors in angular measurement and errors in determination of the stress factor K must be considered.

Angular errors. An example given by Cullity [3] is a good illustration of the necessity for accurate determination of the shift in 2θ . The example involved the diffraction of CrK_α radiation from the (211) planes of steel with $\theta = 78^\circ$. The value of ψ was chosen to be 45° and elastic constants were assumed; $E = 30,000$ psi, $\nu = 0.29$; the corresponding value for K was 86.3 KSI/deg $\Delta 2\theta$. If the standard deviation for the angular measurements of 2θ equal to 0.02° , then the standard deviation of the stress σ_ψ is 2.4 KSI.

Instrument misalignment can also lead to significant errors in the angular data. This can be verified by control measurements on a stress-free sample, e.g., a finely powdered polycrystalline metal. A discrepancy of 2θ greater than 0.1° for $\psi = 0^\circ$ and $\psi = 45^\circ$ generally indicates the need for better instrument alignment [2]. The specimen surface must lie very exactly on the diffractometer axis so that it does not shift as the angle ψ is changed. James and Cohen have concluded that sample displacement is the largest single source of error associated with the X-ray measurement of residual stress [4].

In addition to the problem of instrument accuracy and precision there exists the necessity for determining the center lines of the diffraction peaks. The position of these lines cannot be determined with adequate precision from the usual chart recording. The method in common use involves selecting specific positions on the peak and determining a count rate for each with a scaler. Various mathematical methods are then used to force-fit a parabola through the selected points. The axis of the parabola is taken as the center line of the diffraction peak [3]. Recently, several computer-controlled stress measurement techniques have been developed. James and Cohen [4] have described a complete computer controlled method for measuring residual stress and have reported standard deviations below 200 psi for some samples of low carbon steel.

Stress Factor. Since K is a product of the known quantities θ and ψ and an unknown elastic constant of the material it becomes necessary to select an appropriate value for this material parameter.

One approach is to assume that the strains measured for individual crystals are the same as for the bulk material. The values for E and ν may then be found in handbooks and applied directly to Equation (13). The second method does not assume isotropic behavior and uses elastic constants obtained from single-crystal experiments. These values are applied to the particular crystallographic directions for the diffracting planes chosen in the residual stress experiment. The third and most direct, if not most convenient, method is to experimentally measure the normal and oblique diffraction line shifts at particular applied stresses. The points are then plotted with 2θ against the applied stress and the slope of this line is the value of K .

Selected Bibliography

The preceding section served as a general introduction to the key topic of this work, viz., X-ray diffraction measurement of residual stress. Appendix C contains an extensive bibliography for this project. The emphasis is on residual stress measurement and not on particular applications. There were three key sources. First, the SAE Handbook Supplement SAE J784a is the definitive guide to practical experimental measurements of the type performed. Second, NTAC publication 76-2 is the summary of a state-of-the-art review of the field made in 1975. Third, a computer search was made covering subsequent work (1975 to present) using information retrieval services of the American Society of Metals (Metadex and Testing and Control Digest).

EXPERIMENTAL WORK

While the general experimental technique for residual stress characterization by X-ray diffraction is well documented (see Item 1 in Bibliography) there are some key features which required special consideration in order to obtain the required accuracy of position and translation.

Fixturing

A special positioning fixture was needed to locate precisely the test specimens at the axis of rotation of the goniometer. This fixture must provide for accurate movement of the specimen along both of its axes, as well as for translation along the beam axis. Following are some specific design criteria.*

1. The fixture must permit simple but accurate positioning of the sample along the beam axis (referred to as the "z" coordinate).
2. There must be some way to displace the specimen by small measured increments of distance for each stress determination so that an accurate plot of stress distribution along its "x" and "y" axes can be made.
3. The sample stage must be compatible with the G.E. XRD-6 diffractometer and must not interfere with the necessary angular and radial movement of the detector slide assembly.
4. The base of the fixture must be designed to interchange with the present residual stress kit so that the fixtures may be removed and replaced without loss of registration or compromising the diffractometer alignment.

A precision specimen stage was designed and fabricated which can be adjusted to an accuracy of 0.0001 inch for sample position with regard to focusing. The stage also incorporates micrometer positioning of the sample along x and y axes so that a region of sample area

*Developmental design work was aided greatly by D. M. Wong, and reported in his senior research project: ME 124 Report, UC Davis, June 22, 1979.

10 x 10 mm may be "mapped" as required. Assembly drawings are shown in Figures 3 & 4. The completed fixture is illustrated in Figure 5.

Spatial Resolution

In routine stress measurements the area of inspection is rather large. This is acceptable when a typical plate geometry is under study with uniform stress over a broad area. A typical inspection area is a square of 1/2-inch on a side.

To monitor changing stress levels over small areas on a sample surface, a 1 mm² inspection area is desirable. For the usual diffractometer arrangement with a flat sample the length of the irradiated region is given approximately as [2],

$$L_0 = \frac{1}{2} \frac{R}{\sin \theta}$$

where

L_0 = length of irradiated region,

θ = primary beam divergence,

R = diffractometer radius.

When this geometry is altered by inclining the sample by an angle ψ , the irradiated region of the sample is changed. For a flat sample the length of this region is given by:

$$L = \frac{1}{2} \frac{R}{\sin (\theta + \psi)}$$

For samples with a stress gradient it is important to measure the diffracted beam energy from equivalent areas for $\psi = 0^\circ$ and for $\psi = 45^\circ$. This may be achieved by choosing a primary beam divergence angle to maintain the condition where $L_0 = L_{45}$. The very small beam size, of course, leads to much reduced intensities at the detector with attendant long counting times.

Figure 3

Figure 4

Figure 5 Precision Specimen Stage with Calibration Sample in Place

An additional complication would be caused by curved surface geometry of the test samples. A curved surface causes focusing aberrations since the left and right hand sides of the specimen produce different sized focusing circles, especially when tilted at an angle γ . A perfect focusing point is not obtained at the detection slits. This problem can be minimized by having the smallest possible beam projected on the sample. It would be necessary to conduct trial runs with cylindrical samples in order to define the beam projection requirements for meaningful stress distribution measurements. Successful measurements on 1-inch diameter steel ball bearings* using similar equipment (a G.E. XRD-5) indicate that the experiment should be practical.

Collimation

In order to evaluate the practical limits of spatial resolution several experiments were made using the standard collimating slits supplied for the general electric XRD-6 diffractometer. Photographic images were made on standard dental X-ray film packets using the three available medium resolution (MR) seller slit assemblies. These had specified beam divergence angles of 0.5° , 1.0° and 3.0° , respectively. The results are reproduced as Figure 6. The film packets were fastened to the specimen stage at $2\theta = 139^\circ$ and $\gamma = 0^\circ$. It will be seen that the 0.5° slit "illuminates" an area approximately 0.5 mm wide and about 13 mm high. This resolution was considered to be very good for mapping along the "x" axis of the specimen. Translation of the specimen holder at 2 mm intervals produced the result shown in Figure 7a.

*E. Evans, private communication.

a) 3.0° Slit

b) 1.0° Slit

c) 0.4° Slit

Figure 6 Film Images of X-ray Beam Spot (Shown Approximately 7.5X Full Size)

Since the goal is to obtain a beam spot of small size in both dimensions, i.e., about 1 mm square or circular, several attempts were made to mask the rectangular beam produced by the standard soller slit. Small pieces of lead foil were fastened onto the front, on the back and onto both front and back of the standard slit assemblies with poor results. Scattering from edge effects produced a diffused beam which lead to ambiguous diffraction angles and meaningless residual stress data.

What was needed was a collimating tube similar to the one used in the Debye-Scherrer cameras discussed by Cullity, p. 165 [2]. Accordingly, an adapter was designed to allow the collimator from the Debye-Scherrer camera to be used on the XRD-6 diffractometer. The images shown in Figure 7b were made by exposing the film at 2 mm intervals of x and y movement of the specimen stage. It will be seen that the spot size produced is about 1 mm wide and somewhat more than 1.5 mm high. The collimator assembly is shown mounted in front of the X-ray tube in the XRD-6 diffractometer illustrated in Figure 8.

Computer Analysis of X-ray Data

The experimental precision required for these measurements makes rather tedious data analysis necessary. Since small shifts in X-ray diffraction peaks must be observed, the exact peak position must be known. Angular dependent intensity corrections (the Lorentz-polarization-absorption factor) must be applied to an X-ray intensity value made at any given diffraction angle (2θ). In addition, dynamic scanning of a diffraction peak leads to experimental errors. As a result, step scanning is preferred. Three intensity measurements are

a) 0.4° Slit ≈ 2 mm Intervals

b) Collimator ≈ 2 mm Intervals

Figure 7 Translated Beam Images (Shown Approximately 7.5X Full Size)

Figure 8 Precision Stage and 1.0 mm Collimator
in Place in XRD-6 Diffractometer

made at different 2θ positions near the expected peak location. The "true" peak position is defined as the axis of the parabola best-fit through the three data points. A computer program to provide both intensity corrections and curve-fitting is shown in Appendix A.* It is currently available for use on the campus Burroughs 6700 computer.

A program for computation of stress and 2θ peak positions has also been prepared for use on the TRS-80 Level II microcomputer located in the X-ray laboratory.** This program computes Lorentz polarization and absorption correction factors for each of the three data points collected at $\psi = 0^\circ$ and at $\psi =$ "selected angle." The program documentation is in Appendix B. It was found to provide a very significant improvement in computation efficiency. It has the advantage that only the six values for 2θ with their related intensity data are required. There is no need for tables or other supplemental calculations. It is only required to enter the parameters of Young's modulus, Poisson's ratio, selected angle, and selected interval. The six data pairs are then entered and the result is immediately available on the display screen. The results are obtained in such a form that they can be stored or transmitted to a plotter if desired.

Survey of Operating Parameters and Functions for XRD-6 X-ray Diffractometer

A sample of "Permaquartz" was used for preliminary set-up and calibration of the goniometer and chart recorder. Permaquartz is General Electric X-ray's name for a permanent sample of novaculite

*From work by R. B. Zegarski and M. Dickerson for Senior Project (ME-124), University of California, Davis, December 13, 1978.

**Coded by Brian D. Brown, P.O. Box 975, Davis, CA 95616

for use in the flat sample holder in the diffractometer. Novaculite is a very fine-grained quartzose rock. The sample is described along with a typical recording of intensity versus angle 2θ in General Electric X-ray direction 12414A. The sample is shown installed in the diffractometer in Figure 9.

A large number of chart recordings were made for this specimen using chromium K_{α} radiation at 40 KV tube voltage and 10 mA current. Scans were made using a variety of scanning rates and chart speeds in order to optimize resolution for a single diffraction peak. The peak at $2\theta = 40.1^{\circ}$ was chosen as a typical example to be used for preliminary point counting experiments. A series of intensity measurements were made at small increments of 2θ in order to locate the peak maximum. Some typical data are shown in Table 1. It will be seen that agreement with the chart recorder data ($2\theta = 40.1^{\circ}$) is good. In practice a best-fit parabola is defined as the peak location. Small shifts in peak location may be detected this way, which would not be apparent from the chart record of a continuous scan. This concluded the preliminary equipment check-out and familiarization. The next step was to examine diffraction patterns for aluminum powder.

Development of Diffraction Pattern of Aluminum Powder

The first step in the preliminary work with aluminum was to obtain a continuous scan of 2θ versus intensity using aluminum powder (325 mesh). Chart recordings were made in the range of $2\theta = 50^{\circ}$ to $2\theta = 150^{\circ}$ using chromium K_{α} radiation. A particular peak was then chosen to be used for model stress determinations. It was decided to use the 311 peak (d spacing = $1.221\text{\AA}$) at $2\theta = 139.36^{\circ}$

Figure 9 Permaquartz Sample in XRD-6 Diffractometer

TABLE I

Permaquartz

Scalar Counting for 100 Seconds Chromium

 K_{α} Radiation @ 40 KV and 10 mA

2 θ°	Intensity versus Angle 2 θ Counts in 100 Seconds			
	1	2	3	4
39.0	8,150	8,130	8,190	8,120
39.2	8,010	8,030	8,080	8,120
39.4	8,170	8,030	8,110	8,160
39.6	8,780	8,630	8,720	8,570
39.8	11,450	11,760	11,460	11,860
40.0	74,530	80,520	77,380	81,150
40.2	66,370	60,910	61,720	57,950
40.4	9,270	9,220	9,000	9,050
40.6	8,240	8,050	8,090	8,070
40.8	7,860	7,880	7,900	7,890
41.0	7,760		7,770	7,680

since this is a high angle peak often used for residual stress measurements. An expanded trace of the selected peak was made using a slow scanning rate ($0.4^\circ/\text{min}$) with a chart speed of 1.0 inch/min . This resulted in a trace with a broad base and a double peak, probably a resolved K_α doublet. Point counting experiments were then made at 0.01° increments in the range of $2\theta = 139.30^\circ$ to 140.00° . The time to accumulate 10,000 counts was recorded at each increment of 2θ . Analysis of this data resulted in experimental positions for the K_{α_1} peak of chromium at 139.45° and the K_{α_2} at 139.90° . The theoretical 2θ angles for this doublet would be at 139.36° and 139.90° using $\lambda = 2.290\text{\AA}$ for the K_{α_1} radiation and $\lambda = 2.994$ for the K_{α_2} .

Residual Stress in Aluminum Plate Specimens

At this point the General Electric X-ray residual stress kit was installed in the diffractometer. A series of experiments was then conducted to develop familiarity with residual stress measurement methods. Aluminum powder was used in the as-received condition for this first set of measurements. Point count data were obtained at angles of $\psi = 0^\circ, 15^\circ, 30^\circ$, and 60° . Best-fit parabolas were then computed for each data set and the shift of the diffraction peak was obtained. Apparent residual stress was calculated using the form of the stress equation recommended in Sec. 16.4 of Ref. 2, as follows:

$$\sigma = \frac{E}{(1 + \nu) \sin^2 \psi} \left(\frac{\sin \theta_n}{\sin \theta_i} - 1 \right)$$

where

E = modulus of elasticity

ν = Poisson's ratio,

θ_n = diffraction angle at $\psi = 0^\circ$,

θ_i = diffraction angle at $\psi = \psi$ (e.g. 45°).

Values for E and ν were assumed to be 9×10^6 psi and 0.29, respectively [6].

The data are summarized in Table 2. It will be seen that an average of nearly 16 ksi compressive stress was obtained for the as-received aluminum powder.

The aluminum powder was then annealed in air for 2 hours at 375°F . Residual stress measurements were made on the annealed powder giving an average stress of about 13 ksi in compression (see Table 2). Samples of aluminum plate were run concurrently with the powder samples with residual compressive stress levels measured at 16 ksi and 20 ksi for the as-received and annealed conditions, respectively.

These values of high compressive stress for the annealed aluminum powder samples were considered anomalous and cast suspicion upon the accuracy of radial movement of the detector slide, in particular. Accordingly, an exhaustive examination of the accuracy of radial movement of the slide was carried out. It was found that the slide was skewed with respect to the true radius of the diffractometer by about 0.10° over the range of movement used in the measurement of peak shift from $\psi = 0^\circ$ to $\psi = 45^\circ$. The slide was realigned to an accuracy of true radial movement of better than 0.01° over the desired range. This was judged to be the practical limit of accuracy

TABLE 2
Aluminum Powder

ϕ	Summary of Apparent Residual Stress Data					
	2 θ Peak		$\Delta 2\theta$		Stress (psi)*	
	As-received	Annealed	As-received	Annealed	As-received	Annealed
0	139.48	139.48	---	---	---	---
15	139.52	139.52	0.04	0.04	14,346	14,346
30	139.66	139.59	0.18	0.07	17,262	10,560
45	139.83	139.75	0.35	0.27	17,215	13,024
60	139.94	139.84	0.46	0.36	14,642	11,414
AVERAGE					15,866	12,336

*All Stress values are compressive.

for this equipment and indeed can only be achieved with a good deal of tedious effort. Accurate work will require instrumental precision at least as good as conventional machine tools. This is not available now.

The annealed aluminum powder was run again to confirm the hypothesis that the high apparent stress values measured were due to instrument error. The result was not what was hoped for but was instructive. The stress was 8 ksi compression in this case, a reduction of nearly 4 ksi from the previous result of 12 ksi but still not zero. At this point it was decided that it would be advisable to abandon the aluminum powder for a time and concentrate upon obtaining a zero stress calibration using chromium powder (as used in the standard method reference - SAE Handbook Supplement J784a).

Calibration of Diffractometer Using Annealed Chromium Powder

Annealed Chromium powder is often used as a calibration standard for zero residual stress (see SAE Information Report J784a, Sec. 8). This material is reported to yield a 0 - 1 ksi value using a flat specimen and a 1° beam divergence angle.

Chromium powder of reagent grade (99% pure) was obtained and sieved down to <325 mesh. It was then annealed at 820°C for 3 hours in argon. It was cooled overnight with argon flow and apparent residual stress was measured using a standard flat sample holder. It was considered to be possible that the radial slide alignment had shifted and this was checked. Alignment was found to be in error by a small positive amount at both slide positions but still less than 0.01° and less at all intermediate positions of slide movement. This is as good as can be obtained and no improvement was attempted.

The remaining source of possible error was then examined. Sample location with respect to the axis of rotation of the residual stress stage can influence test results by introducing focusing aberrations. The residual stress kit as supplied by General Electric X-ray provides for sample location by means of a fixed gage pin. There is no provision for verifying accuracy of this system except by indirect mechanical measurement outside of the goniometer. Errors in this locating system can lead to anomalous test results.

As a preliminary check on sample positioning accuracy it was decided to introduce shims between the gage pin and the sample. The sample was first shimmed back 0.027 inch. Apparent residual stress measured was 6.5 ksi tensile. Next, a shim of 0.021 inch was used giving 0.5 ksi tensile stress. These results, although very preliminary, suggested that the measured apparent residual stress for annealed chromium powder changes about an order of magnitude when the sample location is changed 0.006 inch. Confirmation of this relationship implies a high degree of sensitivity to location errors -- in the range of 1000 psi/.001 inch (about 39 ksi/mm). This emphasizes the need for accuracy in locating and positioning fixtures. Accordingly, it was decided to conduct a preliminary experiment to determine the relationship between apparent stress and sample position with respect to the goniometer axis.

A series of shims was used to locate the annealed chromium powder sample in the range of 0.000 to 0.030 inch displacement. Residual stress was measured at 0.003 inch intervals using the standard residual stress kit. The experimental data were obtained using CrK_α radiation at 40 kV and 10 mA. The following data

represent apparent residual stress as calculated from measured line shift using an assumed Young's modulus of 30×10^6 psi and Poisson's ratio of 0.35. Increase in shim thickness moves the sample "away" from the source/detector location.

TABLE 3 (ANNEALED CHROMIUM POWDER)

displacement (inch)	Apparent residual stress (psi)
0.000	-9630
0.003	-8158
0.006	-6932
0.009	- 599 (- 169)
0.012	-1065 (-2900)
0.015	-1707
0.018	0
0.021	+2733 (+2240)
0.024	+4583
0.027	+6698 (+6525)
0.030	+14425 (+6028)

Values of stress marked (-) are compressive; those marked (+) are tensile. The values in parentheses are re-runs to confirm values that appeared to lie outside of the general trend. These data points are plotted in Figure 10. It will be seen that the data are clustered along a line of approximately 570 ksi/inch of slope with zero stress near the .018 inch position. The data points for .009 inch and for .030 inch do appear anomalous and were re-run as shown in the preceding table. The re-run at .009 inch confirmed the original value and the re-run for .030 inch fell much closer to the data trend. The techniques for locating the sample with shims is not a refined one, which may be responsible for some of the data scatter. The precision stage is intended to provide accurate and repeatable sample movement which should reduce the scatter substantially.

Figure 10. Annealed Chromium Powder (Plot of Apparent Residual Stress vs. Sample Displacement)

Calibration with Annealed and As-received Aluminum

A sample of as-received aluminum plate was used to obtain stress data for various sample displacements using the shim method described above. The method used was identical. The test data are summarized below.

TABLE 4 (ALUMINUM PLATE)

displacement (inch)	residual stress (psi)
0.000	-9977
0.003	-7707
0.006	-7686
0.009	-7866
0.012	-4706
0.015	-2987
0.018	-2027
0.021	-2099
0.024	- 232
0.027	+2419
0.030	+2635

These data are plotted in Figure 11. The reduced scatter when compared to data for chromium is probably due to improvements in operator skill. The apparent residual stress data for as-received aluminum are seen to fall along a line of approximately 470 ksi/inch slope with zero stress at about 0.024 inch displacement. If the annealed chromium powder is accepted as a zero stress standard then the aluminum plate has compressive stress in the range of 2000 to 3000 psi. This seems a reasonable value in light of typical plate rolling processes.

The next series of measurements was carried out with annealed aluminum powder with the following results:

Figure 11. Aluminum Plate (Plot of Apparent Residual Stress vs. Sample Displacement)

TABLE 5 (ALUMINUM POWDER (annealed))

displacement (inch)	residual stress (psi)
0.000	-4468
0.003	-4278
0.006	-2345
0.009	-2495
0.012	-1795
0.015	+2273
0.018	+1700
0.021	+1819
0.024	+5373
0.027	+5183
0.030	+9623

The data for aluminum powder (see Fig. 12) cluster around the 430 ksi/inch line with zero near 0.018 inch. This is consistent with the zero stress location for the chromium powder and is also nearly identical in slope to the aluminum plate data.

It should be emphasized that the data for apparent residual stress are calculated from shifts in diffraction line position, i.e., a change in the 2θ (Bragg) angle for diffraction. The line position for each experimental measurement is obtained by a mathematical method which assumes a parabolic shape for the diffraction peak. The method locates the parabolic axis based upon three selected angles near the peak. In order to evaluate the effect of choosing slightly different values for the pre-selected data points several duplicate points were analyzed. This analysis is summarized in Tables 6, 7 and 8.

Figure 12. Annealed Aluminum Powder (Plot of Apparent Residual Stress vs. Sample Displacement)

TABLE 6
ALUMINUM PLATE, .024 in DISPLACEMENT, $\psi = 0^\circ$

pre-selected $2\theta^\circ$	computed peak location	difference
139.25 139.35 139.45	69.658 $^\circ$	0.01%
139.20 139.25 139.35	69.651 $^\circ$	

TABLE 7
ALUMINUM PLATE, .024 in DISPLACEMENT, $\psi = 45^\circ$

pre-selected $2\theta^\circ$	computed peak location	difference
139.25 139.35 139.45	69.657 $^\circ$	0.005%
139.20 139.30 139.40	69.653 $^\circ$	

TABLE 8
ALUMINUM PLATE, .030 in DISPLACEMENT, $\psi = 45^\circ$

pre-selected $2\theta^\circ$	computed peak location	difference
139.15 139.25 139.35	69.636 $^\circ$	0.00
139.20 139.30 139.40	69.636 $^\circ$	

It is clear that small changes in the actual data points selected for measurement have little or no effect upon peak position when calculated by the best fit parabola method.

The significance of the slope of the residual stress versus sample displacement line needed further investigation. Preliminary examination of the geometry of sample displacement and the related change in apparent residual stress suggested that it may be possible to obtain elastic property data by suitable stress vs. displacement experiments.

The foregoing experimental work suggested several preliminary conclusions. Among these were:

- 1) Apparent residual stress as measured by X-ray diffraction methods is a very strong function of sample positioning errors. This relationship is approximately linear and is in the range of 400-500 ksi/inch.
- 2) The slope of the plot of stress versus displacement data is related to elastic constants for the material, viz., Young's modulus and Poisson's ratio, as well as to the spacing of the planes of metal lattice.
- 3) Accurate measurement of low stress levels, i.e., less than 1000 psi will require very precise positioning of the sample surface with respect to the diffractometer axis. The ultimate precision possible using the present diffractometer should be established by use of the modified stress kit stage.

At this point the precision sample positioning stage was completed and was installed in the goniometer in place of the General Electric standard stress kit (see Figure 8).

Precision Specimen Stage

Calibration of the focusing micrometer was performed using the sample of annealed chromium powder from previous experimental work. Apparent stress was calculated from point count data taken in the full range of sample position using $\psi = 30, 40, 50, \text{ and } 60$ degrees.

The data are summarized in Table 9 and are shown as plots of apparent stress vs. sample position in Figures 13 through 16.

It will be seen that the data are not linear. The average slope in the region of zero stress, however, may be estimated and compared with the data taken previously with $\psi = 45^\circ$. These data had an average slope of the apparent stress vs. displacement curve of 570 KSI/inch. The average slopes calculated for the four selected angles are summarized below.

<u>Selected Angle (ψ)</u>	<u>Average Slope</u>
30 $^\circ$	430 KSI/inch
40 $^\circ$	450 " "
45 $^\circ$	570 " "
50 $^\circ$	650 " "
60 $^\circ$	950 " "

It should be stressed that these "average slopes" do not describe a functional relationship. They are intended only as an aid for estimating the dependence of apparent stress upon sample positioning errors. They do confirm the conclusion that stress measured by X-ray diffraction is a very strong function of sample position. It is interesting that this dependence increases greatly as the selected angle (ψ) is increased from 30 $^\circ$ to 60 $^\circ$. This is illustrated in Figure 17.

Statistical Survey of Experimental Method

A preliminary statistical evaluation of selected raw data was undertaken. The majority of the stress data reported in this work were recalculated from point count data collected for 40 seconds at each selected 20 interval. Typical data points comprise approximately 35,000 to 45,000 counts obtained during the 40-second period.

TABLE 9
APPARENT STRESS vs DISPLACEMENT (ANNEALED CHROMIUM POWDER)

Sample Position	Apparent Stress* (PSI)			
	$\psi = 30$	$\psi = 40$	$\psi = 50$	$\psi = 60$
("Z" inch)				
.300	-101,730	-114,770	-158,350	--
.325	- 90,840	-103,660	-143,150	--
.350	- 73,510	- 90,410	-121,850	--
.375	- 63,520	- 78,000	-109,240	-146,280
.400	- 57,350	- 67,410	- 93,280	-127,300
.425	- 43,080	- 52,390	- 76,260	-102,180
.450	- 39,360	- 44,930	- 61,900	- 81,580
.500	- 17,620	- 17,450	- 24,990	- 33,440
.525	- 8,381	- 7,849	- 11,070	- 9,533
.550	+ 7,471	+ 6,008	+ 4,588	+ 19,123
.575	+ 28,510	+ 7,100	+ 27,950	+ 50,860
.600	--	+ 32,301	+ 39,380	+ 63,390
.625	+ 49,400	+ 46,900	+ 61,590	+ 99,670
.650	+ 51,910	+ 55,840	+ 77,130	+123,540
.675	+ 53,431	+ 62,960	+ 91,780	+146,590
.700	+ 64,500	+ 75,540	+104,250	+ 84,410

* (+) = tensile, (-) = compressive

Figure 13. Apparent Stress vs. Displacement
(Annealed Cr Powder) $\psi = 30^\circ$

Figure 14. Apparent Stress vs. Displacement
(Annealed Cr Powder) $\psi = 40^\circ$

Figure 15. Apparent Stress vs. Displacement
(Annealed Cr Powder) $\psi = 50^\circ$

Figure 16. Apparent Stress vs. Displacement
(Annealed Cr Powder) $\psi = 60^\circ$

Figure 17. Average Slope of Stress vs. Displacement Curves Plotted Against Selected Angle = ψ (Annealed Cr Powder)

This provides a relatively rapid technique for stress evaluation. It was necessary to validate this technique in order to assume statistical reliability of the individual data points. Accordingly, a series of data was collected for several positions of 2θ angle without moving the goniometer setting. Values for the mean, standard deviation (of experimental data), and probable error (50% confidence limit) were computed and are presented in Table 2. It will be seen that the standard deviations amount to about 300 to 500 counts in 40,000 with probable error values somewhat less. This is considered to be within acceptable experimental limits.

TABLE 10

STATISTICAL EVALUATION OF POINT COUNT DATA FOR $\psi = 20^\circ$
(counts in 40 sec. for 10 data points at each 2θ angle)

Selected 2θ Angles

	153.60°	153.65°	153.70°	153.75°	153.80°	153.85°	153.90°
m	44,040	45,360	46,230	46,600	46,570	45,960	45,200
s	302	359	412	484	512	536	553
p.e.	215	255	293	344	364	381	394

m = average of the 10 data points

s = standard deviation of experimental data

p.e. = probable error at 50% confidence limit [7]

In addition, the time to accumulate one million counts was recorded at three selected values of 2θ to see if a larger number of counts would result in different computed values of peak 2θ . The result of this work is shown in Table 11. It is clear that the 2θ values are essentially identical. It was concluded that counting for 40 seconds (about 40,000 counts) at each point gives acceptable data and that counting as many as a million events does not change the result in any important way.

TABLE 11

COMPARISON OF TWO METHODS FOR OBTAINING 2θ (PEAK)

1) Counting for 40 seconds:

2θ	Counts	2θ peak
153.70	46230	153.772°
153.75	46600	
153.80	46570	

2) Timing for 10^6 counts:

2θ	Time (sec.)	2θ peak
153.65	880.42	153.771°
153.70	855.91	
153.75	866.35	

Correlation of Stress Measurement by XRD with Strain Gage Data

A simplified test specimen was devised to allow direct comparison of XRD results with strain gage output. The specimen is a flat metal plate reduced in the center to resemble a small standard tensile

testing coupon. Various loads may be applied to produce strains in the gage length by means of small screws at each end. Stress is computed from the strain gage output and compared with the result obtained by X-ray diffraction. The gage length may be tapered or stepped to produce non-uniform strain fields under a constant load. The precision sample stage may be used to traverse the test area to obtain a map of stress as a function of position along the sample. The standard specimen is 1.35 in long x 0.50 in wide with a reduced center section 0.65 in long x 0.50 in wide x 0.62 in thickness.

The specimen is shown with strain gage bonded in place in Figure 18. The loading fixture is shown with specimen installed in Figure 19. Figures 20 and 21 show the assembly as set up for calibration loading using a dead weight system. The weights used are from an Instron calibration set used for verification of universal testing machines.* They are certified to National Bureau of Standards for class C laboratory weights. The strain gages are SR4** type FAE-25-12-S13 foil gages with gage factor of 2.07. The bridge-amplifier-meter used was a BAM-1 from Ellis Associates; Pelham, New York.

The calibration of meter reading as a function of applied stress (dead weight) was accomplished by the following procedure.

- 1) Obtain tare weight of specimen and weight support assembly

$$W_T = 2.29 \text{ lb}$$

- 2) Install specimen assembly in support fixture and add calibration weights in 10 lb increments.
- 3) Record the computed stress (σ_c), meter reading (M), and dead weight in increments (W), where $\sigma_c = W/A$ (A = cross-sectional area of specimen).

*Available from Instron Corporation, Canton, Mass.

**SR4 gages available from BLH electronics, 42 Fourth Ave., Waltham, Mass. 02154

Figure 18 Specimen with Strain Gage

Figure 19 Specimen in Loading Fixture

Fig. 20 Dead Weight Stress Calibration of Specimen/Fixture Assembly

Figure 21 Close-up View of Specimen Under
Load for Strain Gage Calibration

The following data are for the particular aluminum specimen that was used in the subsequent X-ray diffraction study:

<u>dead wt. (W) lb</u>	<u>stress (σ_c) psi</u>	<u>meter reading M</u>
22.38	794	140
32.38	1148	180
42.38	1503	210
52.38	1857	240
62.38	2212	260
72.38	2567	290
82.38	2921	310
92.38	3276	345
102.38	3630	360

tare weight (W_t) = 2.38 lb

cross-sectional area (A) = 0.028 in²

The calibration data that was developed in the previous section were used to provide specific strain increments. The specimen was installed in the loading fixture and mounted on the precision stage in the diffractometer (Fig. 5). Loads were then applied to produce strains by tightening the tension screw at the end of the loading fixture. These strains were monitored with the strain gage/bridge amplifier meter. At each of several values of applied stress, X-ray stress measurements were made. The results are plotted against the applied stress data in Figure 22.

Although the data shows considerable scatter, it does show that externally applied stress produces changes in the XRD data in the correct sense, i.e. an increase of 1 ksi in the tensile direction. The intercept of the best fit line with the zero applied stress line

Figure 22. Strain Gage vs. Stress Data

indicates a residual stress in the unstressed tensile specimen surface of approximately 2 ksi compressive (consistent with the results for the aluminum plate (p. 33)).

There are several things which may be responsible for the scatter of the data. Among these are:

- 1) Focusing errors. The small collimating tube was used to obtain a one millimeter spot size which results in very low energy at the detector slit. A small misalignment here would have a relatively large effect on the angular shift when going from $\psi = 0^\circ$ to $\psi = 45^\circ$.
- 2) Non-uniform application of external loads. The method of applying loads to the specimen can produce torsional loading as the screw is tightened. This would result in ambiguous strain gage readings.
- 3) Misalignment of specimens. Slight errors of positioning of the specimen surface with respect to the axis of the diffractometer leads to inaccurate stress data. It has been shown that this effect is in the range of 400 to 500 ksi/inch.

In general, the method of comparing applied stress measured by strain gage output with that determined by X-ray diffraction can provide useful information for calibration purposes. The method requires very high mechanical precision in order to obtain consistent results. This precision is available for sample movement with the precision specimen stage described in this work. The present diffractometer, however, does not have the necessary precision with respect to: detector movement, detector and collimator alignment or goniometer movement. These problems are of particular concern when measuring low stress levels in the range of a few thousand psi, for example.

Figure 22 shows that, over the low stress region evaluated, stress measurements by XRD were reproducible within less than ± 1 ksi. Considering that the strain gage method contributed some unknown

amount to data scatter, it seems fair to say that measurements of low levels of residual stress made with the currently available (GE XRD-6 diffractometer with custom-designed residual stress fixture) are accurate to approximately ± 500 psi.

RECOMMENDATIONS FOR FUTURE WORK

The work described herein can provide a basis for applications to residual stress determination in several areas. The method described provides a means for determination of residual stress as a function of location on a specimen with resolution of approximately one millimeter. Specimen positioning accuracy of better than 0.001 inch in 3 axes is useful for "mapping" of surfaces where residual stress as a function of position is of interest. Among these applications are the following:

- 1) Quality of the diffusion bonding of dissimilar metals

When an assembly of the dissimilar metals to be bonded is heated to induce diffusion each of the components expands according to its individual coefficient of thermal expansion. After diffusion has occurred the assembly is cooled and each component tends to recover its original dimensions. Since the interface is now restrained by the diffusion bond, stresses are set up in the adjacent areas because of the unequal thermal expansion and contraction that has taken place. The distribution of these stresses is complex and depends upon the geometry of the structure, the modulus of elasticity for each component in the assembly, and the quality of the join. It is suggested that measurement of these stresses can lead to characterization of the quality of the diffusion bond. A bond of high strength should set up higher local stresses when cooled from the processing

temperature than would a bond which would permit stress relaxation. These stresses can be thought of as similar to the residual stresses set up by other metal forming processes such as rolling, grinding or shot peening and they can be analyzed by X-ray diffraction techniques. Correlation of the residual stresses near the bond interface with physical test results would lead to a potentially useful nondestructive method for evaluation of bond quality. Results of the current study indicate that this residual stress could be measured within approximately ± 500 psi. Finite element code analyses of the problem of residual stress aluminum-to-stainless joins (produced by diffusion bonding with silver as the diffusing species) indicate that stresses on the order of 5,000 psi are expected [8]. Therefore, the use of this XRD technique can be expected to be successful in monitoring bond quality.

Several points of caution are necessary. While residual stress variations are within measurable limits, this study has shown that extreme care in fixturing of the test piece is required. The use of cylindrical or other non-planar geometries would increase the demands on experimental technique. State-of-the-art X-ray diffraction hardware [4] would be desirable to minimize experimental error. Even optimal experimental equipment (e.g., the custom-designed specimen holder of this study) would not make this inspection a routine production test. In addition, this XRD method is "surface sensitive" and could not give direct characterization of interior interface quality. Since a primary concern in diffusion bonding is the quality of the silver coating prior to joining, a substantially easier inspection would be the mapping of residual stress in the vapor deposited silver coating on the planar interface prior to joining. This application is described below.

2) Stress in vapor deposited films

A primary concern in many vapor deposited film applications is the quality of the bond between the substrate and the film. This method could be used to evaluate the level of residual stress in the deposited film, which might be correlated with bond quality. The assumption is that contamination on the substrate surface leads to poor silver adhesion leading eventually to poor diffusion bonding [9]. Preliminary data has been generated for residual stress of a silver coating on stainless steel.* The experiment was carried out by making a series of residual stress measurements at various points across an area of the substrate that was only partially cleaned. The results show a good correlation with this processing history. The stress level dropped gradually as the "de-bond" area was approached and fell sharply as it was traversed. These are very preliminary results but they suggest a promising area of research.

3) Weld zone stresses

In many welding applications the stress condition in the heat affect zone is of great interest. A plot of a residual stress as traversed from outside the weld area, across the heat affected zone and near the weld itself could provide useful information for the design of welding processes. These weldment residual stress levels can be included in stress analyses for joined components. Some preliminary work has been done in our laboratory in this area with the result that the method appears to have potential as a useful nondestructive test.

*T. Nishikawa, Senior Project Report (ME-124), UC Davis, Winter 1980.

4) Surface texture

Many production processes produce surface stresses in metals which are functions of direction. Among these are grinding, rolling, and heat treatment. These stresses can be evaluated by making plots of residual stress vs. position for several directions along the sample surface. Appropriate collection and display of these data would lead to a "map" which would describe the stress condition anywhere on the sample surface.

REFERENCES

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- [7] L. C. Parratt, Probability and Experimental Errors in Science, Dover Publication Inc., New York, 1961, p. 173.
- [8] A. Harral, Lawrence Livermore National Laboratory, private communication.
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APPENDIX A

B6700 FORTRAN COMPILATION MARK STRESS

RESIDUAL STRESS BY X-RAY DIFFRACTION TECHNIQUE
READ THE DATA VALUES

READ (5, 100) XK

100 FORMAT (1F10.0)

READ (5,100) X11, X12, X13, THET, DTHET

110 FORMAT (5F10.0)

READ (5,120) X14, X15, X16, THETP, DTHETP, PSI

120 FORMAT (6F10.0)

C
C COMPUTE CORRECT INTENSITY WITH LORENTZ-POLARIZATION-ADSORPTION
FACTOR

PL= (1+ COS(THET)**2)/(SIN(THET/2)**2)*8

PLA= ((1+ COS(THETP)**2)/(SIN(THETP/2)**2)*8)*(1- (TAN(PSI)/(TAN(1THETP/2)))

T1= X11/4*PL

T2= X12/4*PL

T3= X13/4*PL

T4= X14/4*PLA

T5= X15/4*PLA

T6= X16/4*PLA

C COMPUTE THE PEAK TWO THETA ANGLE USING PARABOLIC CURVE FITTING

A= T1- T2

B= T3- T2

C= DTHET/2

AP= T4- T5

BP= T6- T5

CP= DTHETP/2

THETV= THET+ C*((3*A+ B)/(A+ B))

THETVP= THETP+ CP*((3*AP+ BP)/(AP+ BP))

C COMPUTE RESIDUAL STRESS

C

STRESS= XK*(THETVO- THETVP)

C

C WRITE HEADING

WRITE (6,130)

130 FORMAT("1", 15X, "RESIDUAL STRESS BY X-RAY DIFFRACTION
TECHNIQUE"/1//)

C

C WRITE DATA AND RESULTS

WRITE (6,140) PSI, X11, X14, X12, X15, X13, X16, THETVO, THETVP,
X 1K, STRESS

140 FORMAT (15X,"THE 3 INVERSE INTENSITIES AT", 22X,

1"THE 3 INVERSE INTENSITIES AT"/, 15X,

2"ANGLE PSI EQUALS ZERO DEGREES ARE:", 15X, "ANGLE PSI EQUALS ",

312, " DEGREES ARE:"//, 28X, F5.1, 43X, F5.1//, 28X, F5.1, 43X,

AFS.1//, 28X, F5.1, 43X,

4F5.1///, 18X, "THE TWO THETA PEAK ANGLE IS:", 24X,

5"THE TWO THETA PEAK ANGLE IS:"//, 26X, F7.3, 42X, F7.3////////,

615X, "USING THE STRESS FACTOR, K= ", 1PE9.2,

7" POUNDS/SQUARE INCH/DEGREE,"/, 15X, "THE RESIDUAL STRESS IS ",

81PE9.2, "POUNDS/SQUARE INCH.")

END

APPENDIX B

BASIC/RS (05/07/80)

```

100 'TITLE: RESIDUAL STRESS CALCULATION
200 'PURPOSE: CALCULATES RESIDUAL STRESS FROM X-RAY DATA
300 'VERSION: 1.0A
400 'DATE: 07 MAY 1980
500 'CODING: BRIAN D. BROWN
600 ' P.O. BOX 975
700 ' DAVIS, CA 95616
800 'SOURCE: ROB STROUD
900 ' MECHANICAL ENGINEERING, UCD
1000 ' DAVIS, CA 95616
1100 '
1200 '*RESIDUAL STRESS
1300 'BEGIN
1400 GOSUB 1900
1500 'LOOP
1600 GOSUB 3400
1700 END
1800 '
1900 '*BEGIN: RESIDUAL STRESS
2000 'GREETING
2100 CLS
2200 PRINT "RESIDUAL STRESS CALCULATION"
2300 PRINT
2400 'GET GLOBAL PARAMETERS
2500 PRINT "ENTER THE FOLLOWING:"
2600 INPUT "YOUNG'S MODULUS"; YM
2700 INPUT "POISSON'S RATIO"; PR
2800 INPUT "SELECTED ANGLE "; SA
2900 INPUT "SELECTED INTERVAL"; C
3000 'INITIALIZE DEGREE-TO-RADIANS CONSTANT
3100 DR = 3.1415926 / 180
3200 RETURN
3300 '
3400 '*LOOP: RESIDUAL STRESS
3500 'DISPLAY GLOBAL PARAMETERS
3600 GOSUB
3700 'GET EXPERIMENTAL PARAMETERS
3800 GOSUB 6300
3900 'CALCULATE X(I), I = 1,2,3
4000 GOSUB 7500
4100 'CALCULATE X(I), I = 4,5,6
4200 GOSUB 8300
4300 'CALCULATE A,B,D,E
4400 GOSUB 8900
4500 'CALCULATE THETA-N
4600 TN = TH(1) + C/4.0 * (3.0*A + B) / (A + B)
4700 'CALCULATE THETA-I
4800 TI = TH(4) + C/4.0 * (3.0*D + E) / (D + E)
4900 'CALCULATE RESIDUAL STRESS
5000 GOSUB 9600
5100 'PRINT OUT RESULTS
5200 GOSUB 10100
5300 GOTO 3400
5400 '
5500 '*DISPLAY GLOBAL PARAMETERS
5600 CLS
5700 PRINT "YOUNG'S MODULUS", YM

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5800 PRINT "POISSON'S RATIO",, PR
5900 PRINT "SELECTED ANGLE",, SA
6000 PRINT "SELECTED INTERVAL", C
6100 RETURN
6200 '
6300 '*GET EXPERIMENTAL PARAMETERS
6400 PRINT
6500 PRINT "ENTER THE FOLLOWING:"
6600 FOR J = 1 TO 6
6700     PRINT "2 * THETA("; RIGHT$(STR$(J),1); ")",
6800     INPUT T
6900     TH(J) = T / 2.0
7000     PRINT "INTENSITY"; J,
7100     INPUT IN(J)
7200 NEXT J
7300 RETURN
7400 '
7500 '*CALCULATE LP'S
7600 FOR I = 1 TO 6
7700     T = DR * TH(I)
7800     T2 = 2.0 * DR * TH(I)
7900     X(I) = IN(I) * 8.0 * SIN(T) / (1.0 + COS(T2))
8000 NEXT I
8100 RETURN
8200 '
8300 '*ADD AF TO X(I), I = 4,5,6
8400 FOR I = 4 TO 6
8500     X(I) = X(I) * 2.0 / (1.0 - TAN(DR*SA)/TAN(DR*TH(I)))
8600 NEXT I
8700 RETURN
8800 '
8900 '*CALCULATE A,B,D,E
9000 A = X(2) - X(1)
9100 B = X(2) - X(3)
9200 D = X(5) - X(4)
9300 E = X(5) - X(6)
9400 RETURN
9500 '
9600 '*CALCULATE RESIDUAL STRESS
9700 S2 = SIN(DR*SA) ^ 2
9800 RS = YM / (1.0+PR) / S2 * (SIN(DR*IN)/SIN(DR*TI)-1.0)
9900 RETURN
10000 '
10100 '*PRINT OUT RESULTS
10200 CLS
10300 PRINT , " 2 * THETA", " INTENSITY"
10400 FOR I = 1 TO 6
10500     PRINT I, 2.0*TH(I), IN(I)
10600 NEXT I
10700 PRINT
10800 PRINT "THETA-N",, TN
10900 PRINT "THETA-I",, TI
11000 PRINT "RESIDUAL STRESS",, RS
11100 PRINT
11200 PRINT "HIT ENTER WHEN READY FOR NEXT DATA SET"
11300 LINEINPUT L$
11400 RETURN
11500 '

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APPENDIX C

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