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A GENERAL PURPOSE RESIDUAL STRESS ANALYZER

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MATERIALS CHARACTERIZATION DIVISION

JANUARY 1983

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This project has been accomplished as part of the U. S. Army Materials Testing Technology Program, which has for its objective the timely establishment of testing techniques, procedures or prototype equipment (in mechanical, chemical, or nondestructive testing) to insure efficient inspection methods for materiel/material procured or maintained by DARCOM.

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ABSTRACT

An X-ray diffraction system (Rigaku Strainflex) for measuring residual stresses in both the laboratory and in the field, utilizing the same X-ray head, has been evaluated for Army applications. Procedures have been developed with assorted Army materiel for determining the residual stress levels in steel, aluminum, and uranium alloys. Standard calibration samples of steel and aluminum have been fabricated and tested for ensuring the accuracy of measurements on systems in the future. Recommendations have been made for improved X-ray devices to meet Army needs. This work was performed on a project under the same title, as part of the U.S. Army Materials Testing Technology Program at the Army Materials and Mechanics Research Center.

CONTENTS

INTRODUCTION

Early in 1977 the demands for determining the residual stress profile of various U.S. Army materiel components were increasing at an alarming rate, both at AMMRC and at other installations. Failures of projectiles (M735, GAU8A, M392) and missile cases (LAW, etc.) resulted in several residual stress analyses using outdated X-ray procedures and equipment. The need for an expanded residual-stress measurement capability was clearly indicated.

The basic needs in X-ray residual stress capability seemed to be:

1. a general purpose system with the latest attainable precision,
2. flexibility in maneuverability to measure any size or shape component,
3. portability for field application,
4. speed in measurements, and
5. accuracy of the residual stress measurements with good correlation with mechanical measurements.

The approach toward achieving these ambitious goals contained several aspects. First, a study of the manufacturers state-of-the-art was conducted. This entailed visiting industrial laboratories with similar problems (General Electric Co., Schenectady, N.Y., 28 September 1976; Bethlehem Steel Co., 26 January 1977, T.O. #1-67). Manufacturers of X-ray residual stress equipment were also contacted, and a survey was conducted.

Secondly, the need for a high-speed portable X-ray device resulted in a contract with the Denver Research Institute by MERADCOM to develop such apparatus to measure residual stresses in aluminum (Al) assault bridges. Liaison was established by AMMRC with MERADCOM and DRI so that a cooperative effort would ensure a capability in X-ray residual stress analysis until such time that an advanced system of the DRI type would be available to the Army. Tests were conducted on the DRI system on 1-3 March 1978 on steel, and again on 3-9 August 1980 on aluminum.

Thirdly, the experimental method and specific procedures on particular items of Army hardware became a part of the ongoing 6.1 program, X-Ray Characterization of U.S. Army Weapon Systems. This research work provided valuable support for the eventual applications of the project, which is the subject of this report.

On 12 April 1977, a presentation by C. P. Gazzara was made to the Materials Testing Technology Division on the needs for an MTT program to meet the U.S. Army requirements for X-ray diffraction equipment to measure residual stress with an emphasis on automatic operation, portability, accuracy, versatility, adaptability to specimen size and shape, adaptability to procedural changes, resolution, and the development of steel and Al calibration standards. An MTT contract (A General Purpose Residual Stress Analyzer) was awarded and commenced on 1 October 1977. An allocation of $100,000 was made with $75,000 allocated for equipment and the balance for execution of the project. The original and most recent milestones are given in Tables 1 and 2, respectively.

Table 1. ORIGINAL MILESTONE CHART

Element	Date Work Was/Will Be Initiated	Finalized	Percentage of Total Effort
Evaluation of Methods, Equipment, Procurement	1 Oct 77	1 Jun 78	5
Purchase and Installation of Equipment	1 Jun 78	1 Aug 78	50
Evaluation and Testing of Equipment	1 Aug 78	1 Nov 78	4
Field Testing Equipment	15 Sep 78	20 Sep 78	1
Standards and Computer Program Development	1 Oct 78	1 Apr 79	10
Development of Procedures	1 Oct 78	1 Oct 79	20
Write-up of Procedures	1 Sep 79	1 Dec 79	10

Table 2. RECENT MILESTONE CHART

Element	Date Work Was/Will Be Initiated	Finalized	Percentage of Total Effort
Modification and Testing of Residual Stress Analyzer - Complete	1 Jun 79	1 Aug 79	10
Fielding Testing Equipment - Complete	15 Jan 80	1 Oct 80	2
Standards and Computer Program Development and DRI Test - Complete	1 Jul 79	1 Sep 80	22
Development of Procedures - Complete	1 Jul 79	1 Oct 80	44
Write-up of Procedures	1 Oct 80	1 Dec 80	22
Revised Write-up of Procedures	1 Jan 81	1 Mar 81	

Table 3. POSTURE REPORT TABLE

	Rigaku	Fast Stress	DRI	GE/DIANO	Siemens	"PARS" (J.B. Cohen)	Wvlt.
Portability	Yes	No	?	No	No	Yes	No
Specimen Adaptability	Flexible	Flexible	Flexible	Not Flexible	Flexible	Flexible	Flexible
Line-up Adaptability	Excellent	Good	Fair	Fair	Fair	Excellent	Fair
Resolution	$<0.01^\circ$	$<0.01^\circ$	0.05°	$<0.01^\circ$	$<0.01^\circ$	$\sim 0.05^\circ$	$<0.01^\circ$
Availability	Yes	Yes	No	?	Yes	?	Custom Made
2θ Range	140-170°	-	155-175°	0-165°	-	?	115-160°
Reading Time	10 min.	2 min.	20 sec.	20 min. 2 hrs	10 min.	~20 sec.	15 min. 1 hr.
Setting Angles	Automatic	Automatic	Manual	Manual	Manual	Automatic	Automatic
Specimen Surface	Large 16mm	Small 7mm	v. small 1mm	v. lge. 30mm	-	-	Variable
Tube Power	300 watts			1000 watts	1000 watts	150 watts Air Cooled	700 watts

As a result of the evaluation of X-ray diffraction equipment, a report entitled Posture Report on a residual Stress Analyzer was written on 8 November 1977, giving comparative results of equipment up to that point in time. Table 3 from that analysis is presented here.

Since the beginning of this project, a chronology of significant and relevant events are as follows:

1-3 March 1978	A trip to DRI to inspect and test the solid-state X-ray analyzer using steel standard.
10 August 1978	Residual stress measurements on leaking "Weteye" bombs using parallel beam optics. (Performed at General Electric Co., Schenectady, N.Y.).
8 September 1978	Rigaku Strainflex installed in AMMRC.
23 August 1979	Request by MERADCOM to assist with residual stress measurements on bridging.
25-26 September 1979	Evaluation of Al-graphite composite and 2024 Al sheets with Rigaku determined the existence of a texture problem.
15-24 March 1980	Trip to MERADCOM to determine residual stress needs (T.O. #3-43). Agreed to (1) set up Al standards (with Rigaku and MERADCOM materiel), and (2) use standards to test DRI X-ray instrument.
June 1980	Initial work on stress measurements on uranium (U) penetrators in cooperation with ARRADCOM and Battelle-Northwest.
3-9 August 1980	Tested DRI analyzer with Al standards developed on this project.
August 1980	Report was written on Al standards.
2 October 1980	Field tested Rigaku at Ft. Devens.
15 October 1980	Submitted article to Army R&D Magazine entitled X-Ray Measurements of Residual Stress in Army Weapon Components outlining work on this project.
3 November 1980	Stress measurements made with Rigaku on train axle supplied by Massachusetts Bay Transit Authority.

January 1981 — Report was written on texture effect on X-ray residual stress measurements with Rigaku.[1]

EQUIPMENT

General

The X-ray diffraction system is a Rigaku Strainflex MSF/PSF system. (MSF stands for "manual" strainflex and PSF means "portable" strainflex.) The same X-ray tube and goniometer assembly are employed in both cases. When used in the PSF configuration, the goniometer-X-ray tube assembly is unbolted from the MSF head and fixed on a steel tripod. Ten meters of high-voltage cable enable placement of the detection tripod to the limits of the cable reach. Also, the portable system has somewhat limited control from a panel that allows for specific scan modes (1,2,3), but oscillation of the head is still available. A separate portable recorder presents the data on a chart in the form of a diffractogram. Other features of this system include standardization of the inclination angle, the Bragg angle 2θ with the recorder head and the control console (MSF) whenever the system is energized. A Cr X-ray tube is the source of the K_α filtered radiation utilized and operates at a fixed 30 kV and 10 mA; however, other targets are available. A standard 1^o divergence beam and receiving slit with a built-in collimator, provide the specified "parallel beam" optics.

The X-ray geometry illustrating the optical variables is shown in Figure 1. N_s is the specimen normal, whereas the diffraction system normal is N_R. The angular displacement between N_s and N_R is denoted by δ, and is ideally equal to 0. ψ'_o is the experimental inclination angle and equals $\psi_o+\delta$, where ψ_o is the corrected inclination angle. ψ'_o (or ψ_o, if $\delta=0$) is the notation for the inclination angle built into the Rigaku Strainflex, whereas ψ is the notation that is standard in X-ray residual stress calculations. The angle η is defined as $90-\theta$.

During an X-ray "2θ scan", this X-ray system is designed so that the scintillation detector rotates through the $2\theta_{hkl}$ reflection, while the beam slit and specimen remain stationary. In this case, the value of ψ_o and ψ changes at half the rate as that of 2θ.

The position of the diffraction peak maximum was obtained from the recorded chart diffractogram with the side slope method. It was found that the parabolic fitting and the midpoint (when sufficient background data was recorded) methods gave consistently similar results but that the side slope method was more convenient to work with. Another feature of the Rigaku Strainflex is that the X-ray data can be introduced into a computer, in a step-scan mode, and the diffraction peak position automatically computed with a 3-point/5-point parabolic fitting or midpoint program.

1. GAZZARA, C. P. The Measurement of X-Ray Residual Stress in Textured Cubic Materials, AMMRC TR 83-3, January, 1983.

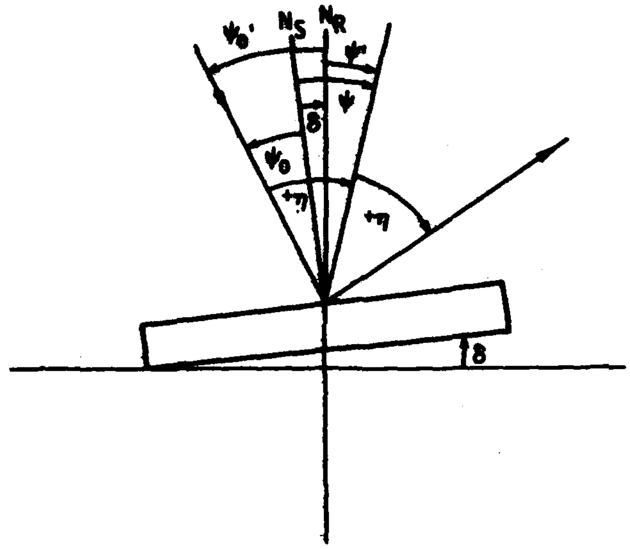

Figure 1. Schematic drawing of X-ray diffraction geometry for the Rigaku Strainflex system.

Pertinent specification data follow:

1. Goniometer

   a. focus-sample distance, 10 cm (setting with marked jig)
   b. soller slits 1°
   c. scanning range 139.5° to 170.5° 2θ with safety switches
   d. electric safety shutter (shuts X-rays off after each scanning operation)
   e. ψ_o setting - manual with PSF
      - automatic or manual with MSF
   f. standardization of ψ_o - 30° (MSF)
   g. standardization of 2θ - 156°
   h. height adjustment

2. Controller

   a. PSF
      - ratemeter range - 1,2,5,10,20,50,100,200,500,1000 cps
      - time constant - 0.5,1,2,5,10,20 sec
      - oscillation - ± 3,6°
      - scan modes:
        1. 165 to 148° 2θ
        2. 170 to 140° 2θ
        3. 156 to 140° 2θ
      - scanning speeds - 1/4,1/2,1,2,4,8,16 °/min
      - electromagnetic safety shutter
   b. MSF
      - 2θ - ψ link
      - oscillation - ±3, ±5, ±7 (ψ_o) 96 /min

- ψ_o settings - 0,5,10,15,20,25,30,35,40,45°
- upper and lower limit setting switches of 2θ angle (nearest integer)
- quick scan switch (± 2θ) 50°/min
- digital display of ψ_o (integer) and 2θ (to 0.01°)
- quick ψ_o scan ±
- start switch for automatic operation
- increment settings for step-scan mode (must be employed for computer operation) 0.1,0.2,0.5,1,2,5° 2θ

c. Detector/Counter Control (MSF)
- high-voltage scintillation counter supply 1100 to 1600 V @ 250 μA
- pulse height control/variable
- time constant - same as PSF
- ratemeter range 100,1000,10K,100K, cps x1,x2,x4,x8
- preset times - 1,10,100,1000 x1,x2,x4,x8
- scaler display - counts/time

d. Recorder; MSF
- chart; speeds; 2.5,5,10,20,40,80 mm/min
- input range; 10 mV
- pen speed; 0.5 sec, full-scale, ink
- automatic synchronization (2θ)
- event marker - every 1°2θ

e. Recorder; PSF
- chart; 120 mm (folding type)
- chart speed; 16, 80 mm/min
- pen; felt

f. Power Supply
- AC stabilizer range 85 to 130 V
- output; 100 V @ 10 A
- stability; ±1.5%
- portable high-voltage transformer
- heat exchanger capacity ~ 5.2 kcal/min @ 25°C

g. Computer
- Wang 600 desk top computer
- residual stress tapes for automatic operation of ψ-2θ controller and least-squares computer program for four ψ_o settings - 0°, 15°, 30°, 45° to compute the residual stress
- CrK_α, αFe (211) midpoint
  3-point parabola
  5-point parabola
- CrK_α, Al (222) midpoint
  3-point parabola
  5-point parabola
- CrK_β, γFe (311) midpoint
  3-point parabola
  5-point parabola

h. portable power supply
i. electropolishing system
j. instruction manuals, schematic drawings

OPERATION OF EQUIPMENT

The detailed sequence of operation of the Rigaku Strainflex is carefully outlined in the instruction manuals. The general approach in the determination of residual stress will be considered here. Then, specific cases (i.e., an Army system) will be discussed with the pertinent special considerations.

MSF; Semi Automatic

1. Warm-up period - All components of the Rigaku Strainflex system, including filament power to the X-ray tube, should be operated for at least one half-hour prior to taking X-ray measurements.

2. Operating settings of equipment parameters - Normally, the settings for a diffraction scan are:

Scan speed 4^{o}/min, chart speed 40 mm/min, and time constant 1 sec. The ratemeter is set so that the most intense diffraction peak, for a particular setting, is not above 80% of full scale. The 2θ limits are set such that the diffraction peak has decreased in intensity to background for at least $1^{o}2\theta$, on both sides of the diffraction peak. For the (211) CrK_{α} peak of αFe, for example, the peak position is approximately at 156^{o} 2θ. Normally, setting at 2θ upper = 161^{o} and 2θ lower at 151^{o} is sufficient to record the complete diffraction peak.

3. Surface conditions - It must be determined if the surface finishing of the piece to be examined has obliterated the surface residual stresses by introducing plastic strain (i.e., polishing, grinding, sand blasting, etc.). Therefore, before a procedure is established for the type of material examined, an electrolytic polish, or a carefully-performed mechanical polish, is done prior to X-ray examination. In some cases, it is possible to take X-ray measurements in the as-received condition, but this choice cannot be taken for granted.

4. Determination of diffracted peak position - Several options are available for establishing the exact position of the diffracted peak maximum.

   a. Midpoint method - The Rigaku Company recommends this technique; simply find the half-maximum peak height above background, then bisect a line drawn parallel to background at half maximum that intersects the diffraction peak. The 2θ position of the bisector is taken to be the 2θ peak position.

   b. Parabolic fitting - Defining a parabola analytically can be simply achieved by taking one point at peak maximum and either two points (3-point method) or four points (5-point method) just below peak maximum. Now, a fitting procedure can be used to determine the parabola that best describes the diffraction peak (near maximum).

   c. Side slope method - This method is, simply stated, to draw a straight line through the ascending and descending section of the diffraction peak that is best described by a straight line. The intersection of the two lines is the 2θ peak position.

In cases where residual stress is to be computed and the computer cannot be employed; i.e., when more than four ψ_o values are necessary, or a computer program does not exist (as with U specimens), then the diffraction peak 2θ positions must be obtained from the recorder diffractogram.

The procedure recommended for graphically obtaining the 2θ peak position (unless otherwise stated for a specific application) has been found to be the side slope method with one provisional supplement; namely, that several lines parallel to the background be drawn close to peak maximum and that the bisectors form a curve that intersects the diffraction peak near the peak maximum. The 2θ peak positions determined both ways should be compared and agree within the experimental error limits, before proceeding on with more measurements. When a sufficient degree of confidence has been developed, with one type of material or a specific application, the side slope method has been found to be sufficiently accurate for most applications. If, however, agreement with both methods is not achieved, the cause should be determined (i.e., multiple peaks, skewing of diffraction peaks due to stacking faults, etc.) before meaningful data can be taken.

Calculation of Residual Stress

Once the 2θ peak positions have been determined and corrected for the Lorentz Polarization and Absorption Factor,[2] the residual stress, σ, can be calculated from the equation:

$$\sigma = \frac{E}{1+\nu}\cot\theta \; \frac{(2\theta_{\psi} - 2\theta_{\psi=o})}{2\sin^2\psi} = \frac{E}{1+\nu}\cot\theta \; \frac{\Delta 2\theta}{2\sin^2\psi} \qquad (1)$$

or $\sigma = K\,\Delta 2\theta/2\sin^2\psi$.

E = Elastic Modulus
ν = Poisson's Ratio

The values of K commonly used are:

	CuKα		CrKα
Aluminum (422) $2\theta=138^o$	3.1	Aluminum (222) $2\theta=157^o$	1.58
Tungsten (400) $2\theta=154^o$	10.0	$Steel_\alpha$ (211) $2\theta=156^o$	4.98
Tungsten (321) $2\theta=131^o$	20.5	$Uranium_\alpha$ (133) $2\theta=166^o$	2.61
Uranium (154,313) $2\theta=141.5^o$	7.22		

2. Residual Stress Measurement by X-Ray Diffraction, SAE J784a, SAE Inc., 400 Commonwealth Drive, Warrendale, PA, 15096, 1971.

Using Equation (1) and performing a linear least-squares analysis of $\Delta 2\theta$ vs. $\sin^2\psi$ a value of σ can be calculated automatically with one of the tapes included in the computer package. An alternative often used is to plot $\Delta 2\theta$ vs. $\sin^2\psi$ and extrapolate to $\sin^2 \psi = 1$ to obtain the value of σ. (Such plots are made up from graphs, which are part of the laboratory inventory, to facilitate computations.)

MSF; Automatic

The instructions for operating the strainflex in the completely automatic mode are given in Instruction Manual for MSF-WANG 600 System Manual #ME201BE3.

When operating in this mode, care should be exercised so that the 2θ position being counted and the position registered in the computer are synchronous. Also, when feeding in the program tape, care should be exercised to assure that the readings are reproducible and accurate. This can be accomplished by measuring a standard bar first for consistency or by repeating the first measurement taken. The procedure of reading in the tape is subject to error in that the sensing head or tape may be dirty, with the introduction of noise, etc. It is good policy to record the diffraction peaks simultaneously with the recorder and check the 2θ peak positions determined manually with those calculated with the computer.

The usual operating procedure is to set the ψ_o switches to 0, 15, 30, and 45°, the scaler F.T. mode with the count time set for 10 sec, and the step width at 0.5° 2θ. It is preferred that the 2θ scanning speed be set at 8°/min.

Texture Problem - In order to avoid serious errors due to the presence of texture, the following procedure should be followed: (1) Compare the peak height of the diffraction peaks on the recorder trace at ψ_o = 0, 15, 30, and 45°, and if any of the peak heights is greater than the others by more than 50%, (2) repeat the runs after translating the specimen in the plane direction and observe if the ratios change significantly. If they do, then the problem is one of particle size and the oscillator ±3, ±5, and ±7° should be employed (the greater the grain size, the greater the oscillation), and (3) if the ratios are the same, the problem is one of texture and the procedure outlined in Reference 2 should be followed.

PSF

In order to operate in the portable mode, the goniometer mounting bolt is unscrewed, and the X-ray head and goniometer are removed by sliding the mount off the track. This procedure is reversed in mounting the head to a portable tripod fixture. This tripod [shown in Applications PSF (Steel)] is placed against the material to be examined and the X-ray tube focal spot is positioned in the same manner as with the MSF application, which is described in the Rigaku instruction manual.

The components that make up the PSF system are: the PSF controller (which replaces the MSF controller), the same high-voltage transformer, the same voltage regulator and water recirculator, and the PSF portable recorder. All switches and electrical connections that indicate transfer from MSF to PSF are made in accordance with the instructions. The system comes equipped with a portable electric power supply (gasoline engine) but should not be used when 115 Vac is available. The operation of the PSF system is identical to the MSF system except that the recordings of the diffraction scans are obtained at the lower recorder speed and the diffraction peak position is obtained by the twofold recommended graphical procedure and subsequent evaluation described earlier.

It is noted that in field applications, the arrangement of experimental devices is so varied, that the probability for dangerous X-ray scattering is enhanced. In these cases, therefore, necessary precautions must be taken, i.e., increased shielding, careful monitoring of stray X-radiation, and removal of personnel from area of irradiation.

Calibration

It is usually implicitly assumed that a diffraction system can measure shifts in 2θ angles at various ψ angles and from such data accurate values of σ can be calculated. If the equipment has not been disturbed after calibration this assumption is usually valid. However, in the final analysis, measuring a level of stress on a body whose stress level is known insures the accuracy of the system. Such specimens are obtained and maintained for such a purpose and are called "standards". Formerly, another type of standard consisted of a stress free sample, usually in powder form, whose lattice constant was well known. If a camera technique or a goniometer were used, the powder was selected so that a 2θ reflection was present near the 2θ high angle diffraction peak of the material whose residual stress was to be measured. The 2θ position of the stress free sample afforded a "reference" 2θ level for calibrating the unknown 2θ value. This technique is still employed in some laboratories but it necessitates different powders for different materials applications, decreases the X-ray intensity of the diffraction peak of the material under investigation, and is considered "messy." An alternative is to produce a specimen under stress (e.g., weld plates introduces measurable stresses) and carefully determine the stress at a conveniently remeasurable location. This procedure was followed in this work for a steel specimen. Another technique is to elastically flex a specimen of special geometry, measuring the elastic strain with strain gauges and with X-rays. This procedure was followed for producing Al calibration bars.

Steel Standard

A bar of rolled mild steel was cut so that a sample of convenient size for X-ray diffraction analysis was produced. This specimen was investigated with a "Faststress" residual stress analyzer at TARADCOM and found to contain high residual stresses.* Subsequent X-ray measurements (Glocker 2ψ method) yielded conflicting results, and subsequent X-ray diffraction measurements with a Diano divergent beam system revealed a non-linear relationship of $\Delta 2\theta$ vs. $\sin^2\psi$ employing values of $\psi = 0, 15, 30,$ and 45^o. A decision was made to : (1) cut all six faces

*Thanks are extended to Dr. P. Fopiano for furnishing this specimen, and to S. Catalano for initial measurements.

of the steel specimen nearly orthogonal, (2) Produce surfaces that would be free from cold work (especially those due to grinding). A technique developed by the metallographic group at AMMRC[3] for mechanically producing a flat strain-free surface in metallographic specimens was used to yield six strain-free surfaces on the steel specimen. This technique involves initially polishing the surfaces with polishing papers and finally polishing with a slurry on a vibratory automatic polisher. The loading is critical in such an operation. A testimony to this method is the ability to polish β-titanium (transage alloy) without producing a martensitic structure.[4] Normally, a 5% reduction in the β-titanium will convert this alloy to martensite, and (3) X-ray residual stress measurements were performed on all surfaces with the Diano (divergent beam) X-ray system in two directions on each face. The X-ray measurements were repeated with the Rigaku MSF system. Figure 2 shows a schematic drawing of the "steel standard" with the resultant X-ray stress measurements listed in Ksi. In spite of the fact that most faces produce a $\Delta 2\theta$ vs. $\sin^2\psi$ plot that is non-linear, the calculated stress readings are reproducible within ±5%.

Face 5 has been found to be most linear and with the highest residual stress readings. Therefore, this face has been used as a reference face on the "steel standard." This specimen has been tested at General Electric Co., Schenectady, N.Y., with a Rigaku system on 28 September 1976, and at the Denver Research Institute on 1-3 March 1978, using a position sensitive detector. The strain measurements were well within the acceptable limits (<10%). This specimen is maintained at AMMRC as a "steel standard" and is available for calibration of other X-ray systems.

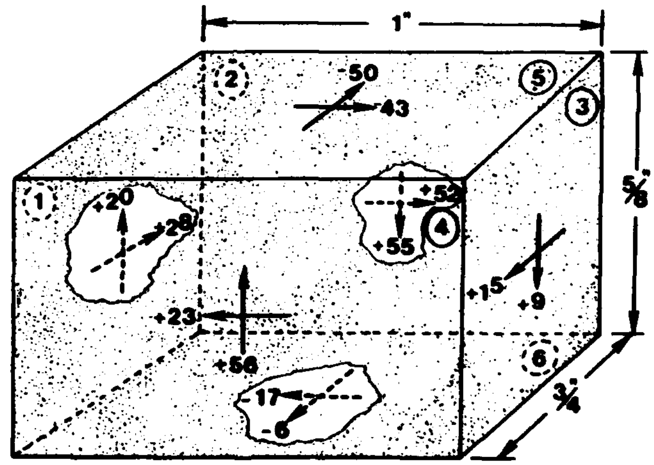

Figure 2. Schematic drawing of steel standard with faces, stress levels, and stress directions identified.

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3. FOPIANO, P. J., and ZANI, A. J. Metallographic Preparation of Two-Phase Titanium Alloys for Replica Electron Microscopy, Metallography, v. 3, no. 2, 1970, p. 209.
4. MIDDLETON, R. M., and HICKEY, C. F. Transformation Characteristics of Transage Ti 129, Titanium and Titanium Alloys - Scientific and Technological Aspects, J. C. Williams and A. F. Belov, eds., Plenum Press, N.Y., 1981.

Aluminum Standards

To develop an Al standard in a similar fashion to the steel standard is not feasible due to the problem of creep in Al, i.e., any residual stress would not remain constant with time.

It was, therefore, decided to make up specimens of Al alloys in the shape of bars that could conveniently be elastically deformed with reproducible stress levels. The alloys employed were: 2024 T3, 5052 H32, 6061-T6, and 7005 channel, bars 12" long by 1" wide by 0.250" thick (except for 2024 which was 0.090" thick).

A cantilever beam arrangement was purchased and modified to deform the bars as shown in Figures 3a and 3b.* The specimens were tested with strain gauges, mounted beneath, and calculations of the stress values were made. The bars were marked off every inch so that bar positions could be located for X-ray measurements. This work was conducted by a summer employee, Nora L. Horning, MIT 1982, as a part of the effort on this project, and the results are contained in a special report.[5]

Figure 3a. X-ray residual stress measurements (MSF) of an elastically bent aluminum alloy (7005) standard bar. Notice the strain gauge test arrangement for simultaneous X-ray and mechanical stress measurements.

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*The Mechanics and Engineering Laboratory of AMMRC, in particular B. Parker and D. Oplinger, assisted with the strain fixture and the strain gauge measurements.

5. HORNUNG, N. L. X-Ray Stress Analysis Development of Aluminum Standards, Special AMMRC Report, to be published.

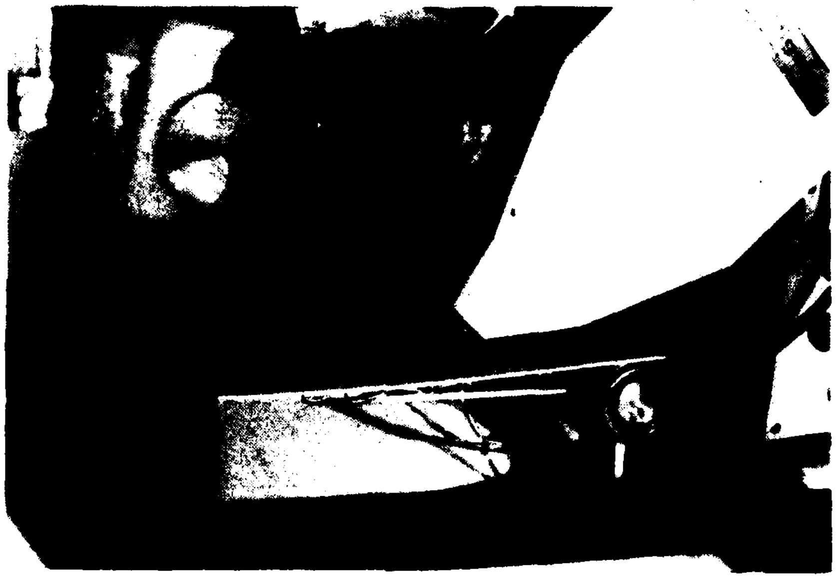

Figure 3b. Close-up of aluminum bars (with attached strain gauges) in cantilever bending fixture.

The greatest problem encountered with the Al standards is that of large grain size, and it was found necessary to oscillate the X-ray head up to ±7° in order to minimize the effects of grain size. In the case of the 5052 and 6061 Al bars, oscillating ±7° was even insufficient to yield accurate stress readings. The results of the measurements on the Al standard bars are given in Table 4. The DRI results were obtained in August 1980 with the solid-state X-ray residual stress analyzer (see AMMRC Trip Report, 20 August 1980 - T.O. #7-44). In this case the cantilever fixture and Al standards were taken to DRI and the measurements were made, indicating the utility of these Al standards. The DRI instrument proved to be more sensitive to the effects of large grain size as can be seen from Table 4. (Notice that readings were unobtainable from alloy 7005.)

The cantilever and Al standards are maintained at AMMRC for calibration purposes.

Table 4. RESIDUAL STRESS VALUES (KSI) OF ALUMINUM ALLOY BARS

Alloy 2024 T3 - 0.090" Thickness

Bar Position	Theoretical Stress	Stress (Strain Gauge)	Rigaku(222)CrKα X-Ray ±3° Oscill TC=1 Sec (Auto Mode)	Rigaku(222)CrKα ±7° Oscill TC=10 Sec (Graph)	DRI 333/511 CuKα
4	7.0	5.6	6.9 (11) σ=±1.7* S.D.	9.0	10.0
7	4.5	3.4	7.1 (7) σ=±1.4 S.D.	6.0	(Scatter Too Large)
10	1.9	1.1	3.0 σ=±1.2 S.D.	3.0	3.0

Alloy 7005 (750°F, 3 Hours, Furnace Cool) 0.250" Thickness

Bar Position	Theoretical Stress	Stress (Strain Gauge)	(Graph)	(Graph)	
4	15.7		13±2†	14±2	
7	9.6		10±2	9±2	
10	3.5		5±2	5±1.5	

*σ = Standard Deviation. Based on Number of Measurements (11) of S.D. Residual Stress.

†Error in Residual Stress Based on Uncertainty of Diffraction Peak Position Only.

Iron Stress Free Sample

An iron (Fe) sample was developed in a stress free condition with a surface free of cold work using the polishing technique previously described with a grain size of approximately 10μM. This sample was obtained in 1967 by raising and lowering the temperature of the cold worked iron sample above and below the recrystallization temperature in a controlled fashion*.

This fine-grained annealed iron specimen yields a very sharp X-ray diffraction peak and is highly useful for correcting for systematic errors in $\Delta 2\theta$. This specimen is also maintained at AMMRC for standardization in performing residual stress measurements.

APPLICATIONS

A group of special applications on specific Army materiel is presented.

*This technique was developed by Dr. E. P. Abrahamson while employed at AMMRC.

Uranium Penetrators (MSF)

The problem of measuring X-ray residual stresses in U penetrators was initially addressed early in 1976. The two angle (ψ=0°, 45°) Glocker method was used to measure stresses in GAU8A stock. The (154, 313) CuK_α diffraction peak was examined at approximately 141.5° 2θ with the Diano focussing beam diffractometer. An annealed U specimen (heat treated at 500°C for 6 hr) made it possible to correct for instrumental aberrations. Tensile stresses as high as 30 ksi were observed but the scatter in data was greater than ±10%.

In May 1980, a need to measure residual stresses in straightened DU bar stock,[6] with a nominal composition of U-3/4 Ti, which would be fabricated into XM833 penetrators was expressed by ARRADCOM and Battelle Pacific Northwest Laboratories. Measurements were made with the Rigaku MSF (Glocker) employing recorder tracings only. The (133) CrK_α diffraction peak (∿166° 2θ) gave a very low peak to background ratio and it was determined that a better surface treatment was necessary to give worthwhile residual stress results. By October 1980, Mr. H. Kjarmo from Battelle Northwest (working at AMMRC) had developed a method for electropolishing the U bars that doubled the peak to background ratio. It was decided, however, that in order to measure residual stresses in U, a higher energy X-ray source would have to be applied, such as a CuK_α source. This is due to the extremely high degree of absorption of X-rays in U, which provides a very shallow layer of material for diffraction. Hence, the oxidized layer "robs" an increasingly amount of radiation available for diffraction, with an increase in time, lowering the precision of the residual stress measurement. A harder or higher energy radiation increases the penetration of X-rays in U. Additional problems, such as grain size, texture, substructure with subsequent line broadening, and twinning, indicate that more research effort is necessary before a reliable accurate X-ray procedure can be effected to measure residual stresses in U.

It should be noted, however, that preliminary X-ray results show that X-ray residual stresses of high magnitude, approximately 50 ksi (both compressive and tensile), are present, justifying further work. Secondly, a system such as the Rigaku (MSF) can be employed on the U bars directly, without the need for cutting (which changes the stress distribution in the bars).

6. Proceedings of the High Density KE Alloy Penetrator Materials Conference (U), CONFIDENTIAL AMMRC MS 82-2, April 1982, the following unclassified papers:

   POLSON, C. E., and LEVY, L. M. Vacuum-Water Production Heat Treatment of XM774 and XM833 Depleted Uranium - 0.75% Titanium Penetrators National Lead Company of Ohio, p. 459.

   MORRIS, C. J., and FOREMAN, S. J. Nondestructive Testing and Evaluation of XM774 Depleted Uranium-Penetrators, Battelle Pacific Northwest Laboratories, p. 519.

   ZABIELSKI, C. V., and LEVY, M. Fracture Toughness and Stress Corrosion Cracking Resistance of the Depleted Uranium-3/4 Ti Alloy, AMMRC, Watertown, MA 02172, p. 325.

Steel (MSF)

1. Maraging Steel Sheath for M735 Tungsten Penetrator (See Figure 4)

In October 1977, measurements using the (211) CrK_α diffraction peak (Diano-focussing system) were begun with the testing of many steel sheaths. The results of the tests are presented in a report.[7] With the acquisition of the Rigaku MSF, similar measurements in the automatic mode confirmed the results obtained with the manual Diano system. The only practical problem with this penetrator is the surface preparation of the steel sheath. It was concluded that, due to the thin wall of the sheath, any chemical or electropolishing would remove too much material, destroying the sheath and changing the stress profile. Sufficient valuable stress information is obtained in the as-received condition. (Indeed, tensile stresses up to 65 ksi were often observed in the steel sheath.) No special texture or grain size effects necessitated special treatment with the M735 steel sheath.

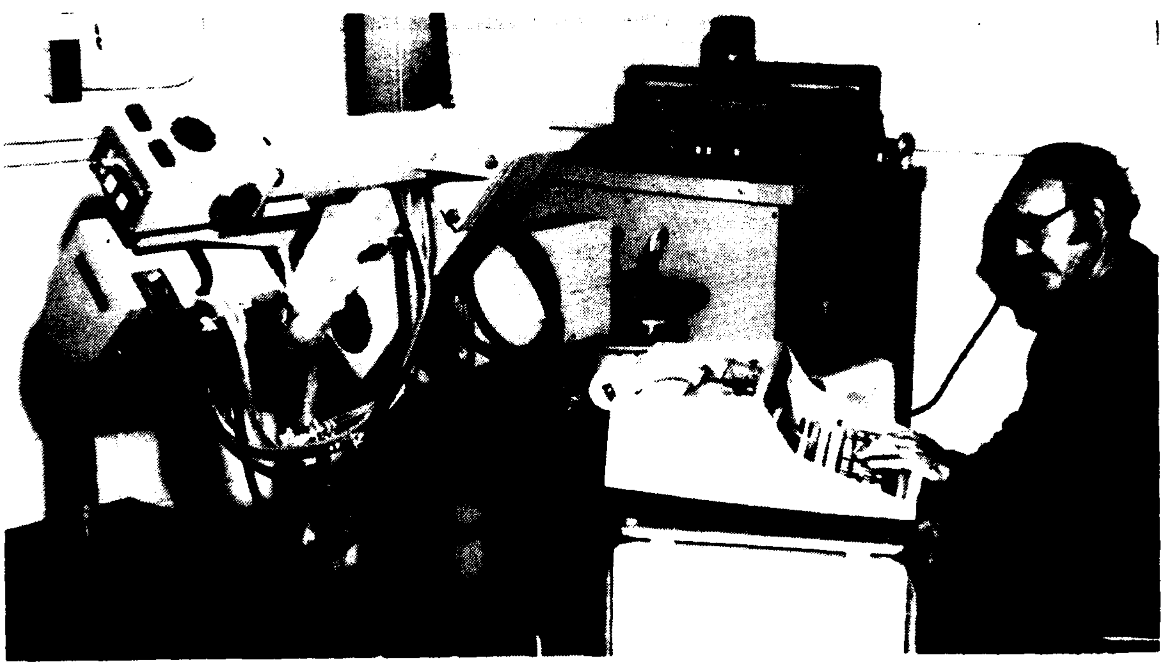

Figure 4. Residual stress measurement of M735 penetrator with computerized laboratory X-ray system (Rigaku, MSF).

7. DE LAI, A. J., and DESISTO, T. Evaluation and Characterization of the M735 Projectile, AMMRC TR 82-46, August 1982.

2. M437A2 HE 175-MM (4140 Steel)

In November 1979, MSF Auto mode (ψ_o = 0, 15, 30, 45°) measurements were performed on this shell at the nose and at the rotating band (longitudinal and hoop). Results revealed tensile stresses at the nose of 50 to 75 ksi. The size of this shell presented no problem in measuring stresses. (See Reference 8 for details on failure analysis).

Recommendations:

a. The need exists for a versatile shell holder, whereby the shell can be moved and positioned conveniently for rapid X-ray measurements.

b. A procedure for electropolishing in situ is necessary to prepare the surface, although the one shell examined showed no problem in this respect. In fact, X-ray measurements performed in another laboratory on this shell showed reproducible measurements within ±5%.

3. M329A2 4.2" Artillery Shell

On 29 November 1979, Auto mode measurements (ψ_o = 0, 15, 30, 45°) similar to those performed on the 175-mm shell revealed very high tensile stresses (up to 100 ksi). No special problems were observed in performing measurements.

4. M114 TOW Motor Case

In October 1980, Auto mode (ψ = 0, 15, 30, 45°) measurements were made on a maraging steel cylindrical missile case before and after electropolishing. Significant tensile stresses were found above the inside threaded end. The MSF was applied to two other TOW motor cases and a stress profile along the motor case was determined. This work was concluded in February 1980. In this application, a potentially useful NDT process is feasible (with the MSF) for testing the TOW motor case in the as-received condition. The results of this application of the MSF are presented in a report.[9]

DOT (Department of Transportation)/MBTA (Mass. Bay Transit Authority) LRV Axle

On 9 May 1980 AMMRC was requested to assist DOT/MBTA with a problem involving catastrophic failure of steel axles. Attempts by the MBTA and consulting engineering firms failed to reveal any commercial laboratories that could/would measure residual stresses on the axles.

8. WITT, F., LEE, F., and RIDER, W. A Comparison of Residual Stress Measurements Using Blind Hole Drill/Abrasive Jet/Trepan Ring, Proc. Spring Mtg. SESA, Dearborn, Michigan, 2 June 1981.
9. HICKEY, C. F., HATCH, H., and GAZZARA, C. P. Residual Stress Analysis Relative to TOW Rocket Motor Case Failures, AMMRC LR. RPT., August 1981.

The MSF (Auto mode, ψ_o = 0, 15, 30, 45°) determined X-ray stress profiles around the axles at two locations, before and after electropolishing and etching (see Figure 5). A letter report was sent out on 3 November 1980 and another is pending. The results of this investigation were presented to the Department of Transportation.[10]

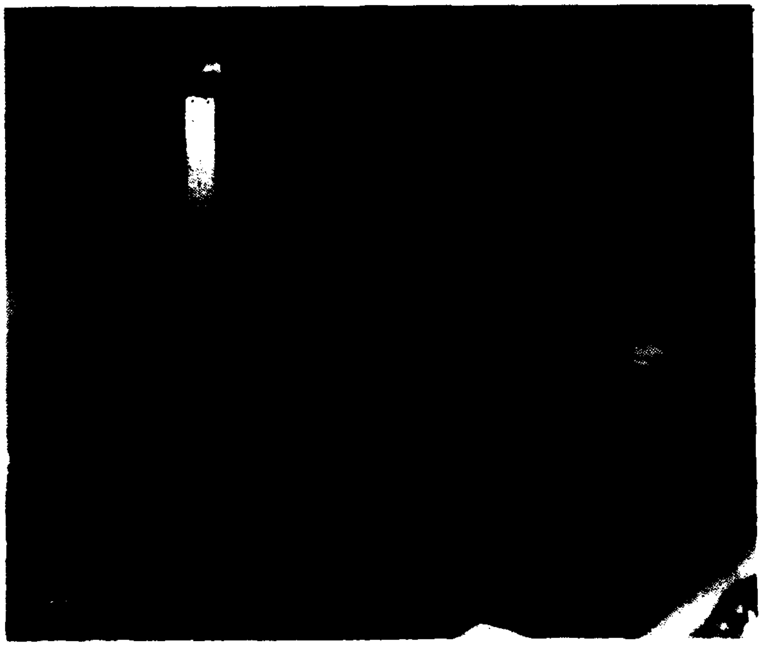

Figure 5. Residual stress laboratory measurements of an MBTA axle with computerized laboratory X-ray system (Rigaku, MSF).

The irregularity in the stresses around the axle (the reproducibility of the results is good) and the presence of tensile stresses indicate the value and potential usefulness of the MSF system for this application.

Aluminum (MSF)

1. LAW Rocket Motor Casings (7001-T6 Aluminum)

The initial X-ray residual stress work on these casings began in March 1976 with the Diano system. The (422) CuK_α diffraction peak was employed. Results showed that error levels were too high for the results to be useful due to (a) an anodized surface which reduced the X-ray intensity to too low a level, (b) the presence of cold work and line broadening, and (c) the presence of a large grain size.

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10. GAZZARA, C. P. X-Ray Diffraction Method for Measurement of Residual Stresses, Proc. of Symp. on NDT Measurement of Wheel/Axle Residual Stress, Cambridge, Mass., 16 - 17 June 1981, p. 2.9.1.

2. "Weteye" Bomb Casing

On 2 and 3 August 1978, a Rigaku MSF was employed at General Electric, Schenectady, N.Y., to measure residual stresses. The CrK_α (311) diffraction peak was recorded and the stresses manually determined using the midpoint and side slope techniques to determine the diffraction peak position. The results of this study showed the potential for the MSF Auto mode, but revealed potential problems in working with Al that were further substantiated in developing the Al standards, discussed previously.

3. Aluminum-Graphite (Al-C) Composite

On 25 and 26 September 1979 an Al-C plate was examined with the MSF system in both the automatic and manual mode. This plate was brought to AMMRC by Mr. H. Horner, MERADCOM, and examined using the CrK_α (222) reflection ($157.5^o 2\theta$). The results showed that a severe texture problem exists rendering the stress readings meaningless without texture corrections (see Reference 1). It is recommended that in order to perform X-ray residual stress measurements on materials of this nature, further research work is necessary and is planned.

Other Aluminum Applications

When samples of Al are to be examined, the MSF auto mode system can be employed if care is exercised in checking for texture, grain size, and cold work. If texture is severe, special procedures are necessary (see Reference 1) and are currently being investigated. If grain size is a problem, the enlistment of the oscillator is necessary with corresponding increases in time constants. Where cold work, anodizing, corrosion, etc., is present, electropolishing or chemical polishing can be usefully performed.

General Applications

Many applications of the MSF are now routinely made, i.e., exploding steel tubes (3 February 1981), steel armor plate, shells, etc. with acceptable results.

Applications PSF (Steel)

On 2 October 1980 the PSF system was transported to Ft. Devens for tests on existing Army field systems with potential problems. Two systems were singled out: (1) an M88 tank retriever with a section at the base of the crane (high stress area) where multiple welds exist, and (2) the knuckle of a D7 bulldozer, although this is the area of failure on other similarly designed bulldozers.

The (211) CrK_α diffraction peak was used in the Glocker manual mode (ψ_o = 0, 45^o) and measurements taken (see Figures 6 and 7). The recorder scans were read with the parabolic and the side slope methods. Stress levels in both cases revealed compressive levels at 30 to 40 ksi.

Figure 6. Residual stress field measurements of welds in steel on the M88 tank retriever with portable X-ray system (Rigaku, PSF).

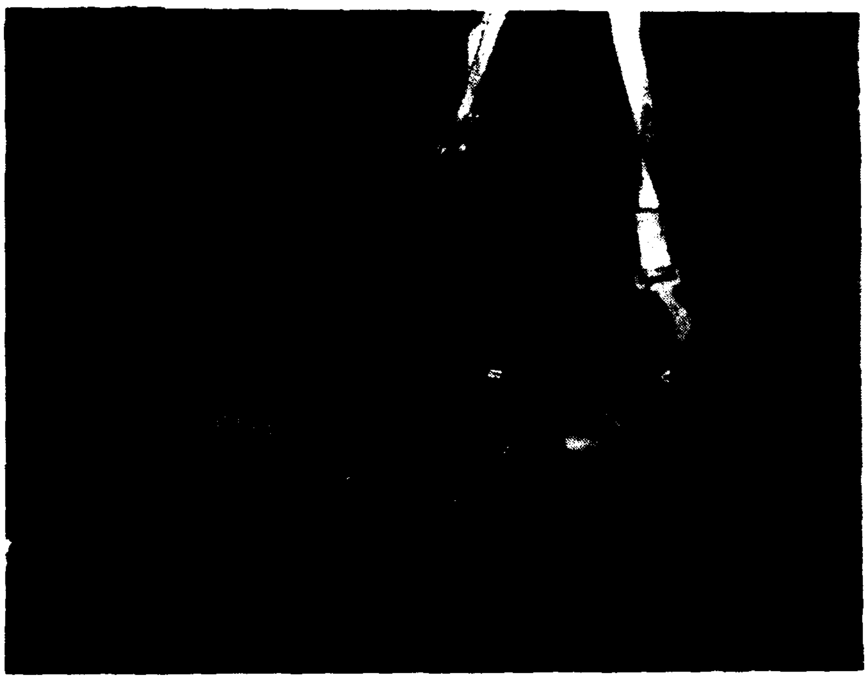

Figure 7. Residual stress field measurements on a steel knuckle of a D-7F Bulldozer with portable X-ray system (Rigaku, PSF).

The disadvantages with this mode of operation were: (1) the tripod was not flexible enough to get into some difficult positions on either device and (2) one must exercise great caution when operating the system in ever changing environs that excessive radiation exposure not occur to personnel.

Recommended Implementations

1. Equipment Performance

a. Some of the computer tape programs for the auto mode computations were found to be faulty, i.e., 5-point parabolic fitting, midpoint (steel and Al). The system must be checked out to ensure that the operation is accurate and reproducible. Periodic checks with the employment of the standards is advisable.

b. Total systems responsibility - With this system a Wang computer is included with split responsibility for operation and maintenance between Rigaku and The Wang Corporation. This is a poor arrangement, due to the fact that when problems occur, particularly with errors in the automatic mode, delegation of responsibility is very difficult.

c. Reproducibility - In some cases, the first determination of the peak position in the automatic mode has been found to be erroneous. This is determined by comparing the computer readout with the recorder chart data. In this case, the run must be performed again.

d. In some cases a drift in the chart speed and the 2θ goniometer drive has been noted. This can be corrected because of the existence of the 2θ angle marker, but some inconvenience is involved.

e. The inking system is subject to leaking and improper operation requiring additional attention. Also, the ink is a very-slow drying type that requires careful handling of the recordings. A felt pen, similar to that employed in the PSF recorder would, be a great improvement.

f. The portable tripod stand has already been commented on. A more versatile setup with more adjustments would be desirable.

g. The electropolishing kit was tested on steel and found to be inadequate, due to the buildup of reaction products on the surface and the tool. It was not possible to obtain a shiny electropolished or even clean matte surface.

h. The gas-powered portable power supply was found to be noisy and introduced small noise spikes on the recordings. These were found to affect the precision of measurement when the sensitivity range was increased (low range on ratemeter).

2. Radiation Hazard

Great care must be exercised when operating either the MSF or PSF system due to the potentially high radiation field, particularly in the back reflecting region. Radiation shields and the restriction of personnel near the apparatus are enforced at AMMRC. Better shielding systems would be helpful.

3. Technical Area

In some cases, the X-ray system described can not be usefully employed due to the absence (or lagging) of research. This is particularly true relative to the effect of texture. Follow-on research should be performed to increase the effectiveness of this and any other future systems to be developed.

4. Future Systems

During the course of this project, feedback to the Rigaku Corporation has already helped in the development of an improved second generation residual stress analyzer with the incorporation of a microprocessor. Lately, a third generation analyzer has been developed with a ψ rotation capability and a monochromator to improve peak to background ratios. This is further testimony to the usefulness of projects such as the one reported on.

In the near future, the incorporation of a solid-state position sensitive detector is envisioned which will provide for: (1) a lighter system more compatible with PSF applications, and (2) a faster system with measuring speeds in seconds, not minutes.

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A GENERAL PURPOSE RESIDUAL STRESS ANALYZER
Charles P. Gazzara

Technical Report AMMRC TR 83-4, January 1983, 25 pp - illus-tables, D/A Project M79 6350
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Army Materials and Mechanics Research Center
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A GENERAL PURPOSE RESIDUAL STRESS ANALYZER
Charles P. Gazzara

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AMCMS Code 5397

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Key Words

X-ray diffraction
Residual stress
Portable equipment
Test and evaluation

An X-ray diffraction system (Rigaku Strainflex) for measuring residual stresses in both the laboratory and in the field, utilizing the same X-ray head, has been evaluated for Army applications. Procedures have been developed with assorted Army materiel for determining the residual stress levels in steel, aluminum, and uranium alloys. Standard calibration samples of steel and aluminum have been fabricated and tested for ensuring the accuracy of measurements on systems in the future. Recommendations have been made for improved X-ray devices to meet Army needs. This work was performed on a project under the same title, as part of the U.S. Army Materials Testing Technology Program at the Army Materials and Mechanics Research Center.

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