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RESIDUAL STRESS REVERSAL IN HIGHLY STRAINED SHOT PEENED STRUCTURAL ELEMENTS

By

WILLIAM S. MITCHELL

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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Major: Mechanical Engineering

The purpose of this research was to further the understanding of a crack initiation problem in a highly strained pressure containment housing. Finite Element Analysis methods were used to model the behavior of shot peened materials undergoing plastic deformation. Analytical results are in agreement with laboratory tensile tests that simulated the actual housing load conditions. These results further validate the original investigation finding that the shot peened residual stress had reversed, changing from compressive to tensile, and demonstrate that analytical finite element methods can be used to predict this behavior.

CHAPTER 1
INTRODUCTION

Motivation for the Research

Compressive residual stresses in the shot peened surfaces of highly loaded structural elements may be subjected to stress reversal (compressive to tensile) when the bulk section of the structure is stressed beyond the elastic yield point of the material. This surface stress reversal could then lead to a significant reduction in the low cycle fatigue (LCF) life of the structure. LCF life is defined as the number of load - unload cycles necessary to initiate cracking of the material.

During the design of highly stressed structures such as pressure containment vessels, care must be used in specifying surface shot peen applications. In particular, structures that are acceptance proof pressure tested at higher than normal operating load conditions may require surface treatments such as shot peening, to be applied only *after* the proof pressure testing is completed!

The actual LCF life of the pressure containment vessel (also commonly referred to as "housing") shown in Figure 1 was found to be significantly lower than predicted by design analyses. The housing load-carrying ribs developed surface cracks in less than 13 applied load cycles; 5 proof pressure cycles plus 8 operational cycles. Design structural analysis for the rib location would predict the LCF life to be greater than 1500 cycles.

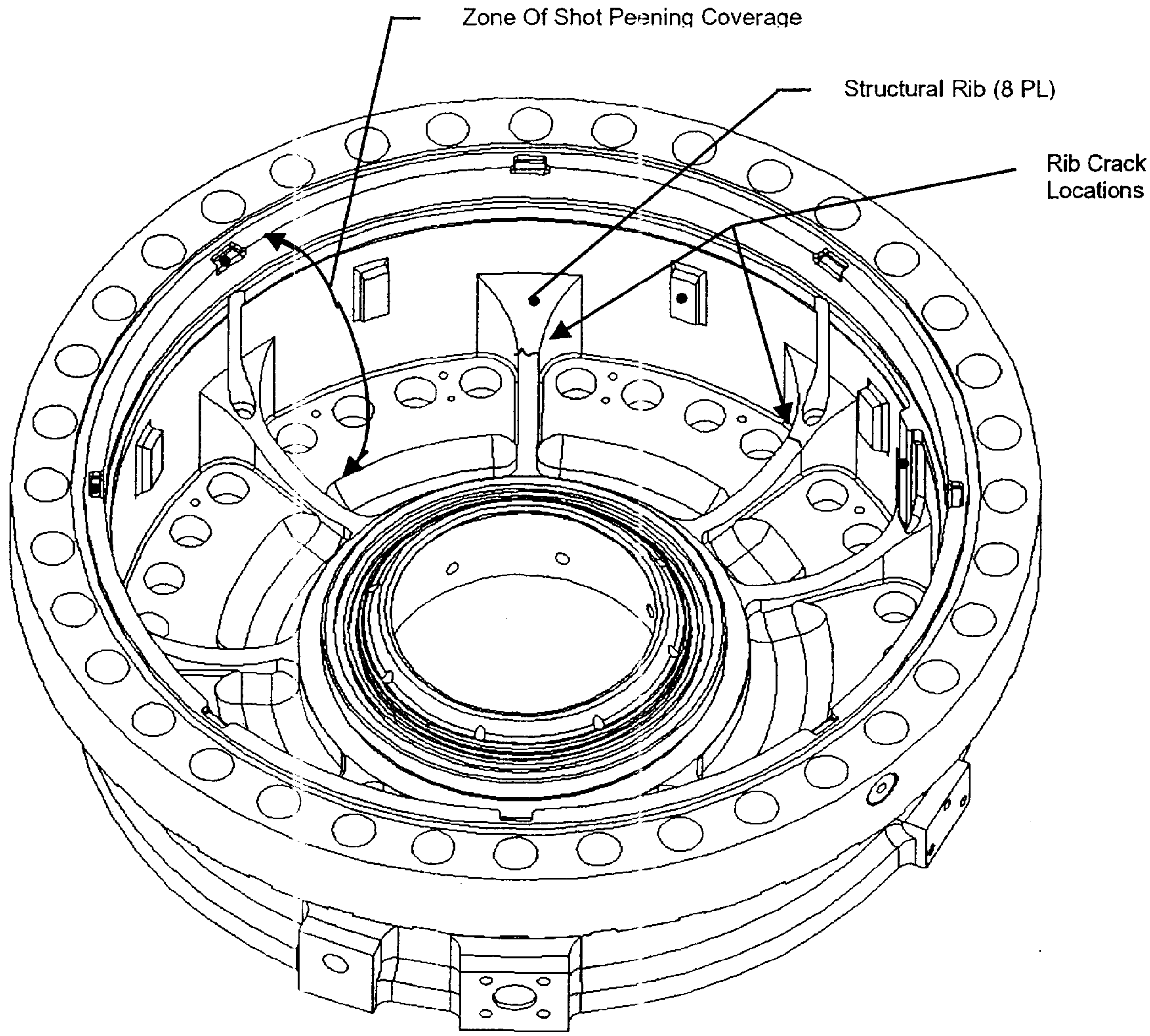

Figure 1. Housing Schematic

Correlation of post-test inspection data from several different housings showed that only housings that had been shot peened demonstrated low LCF life (cracking) at the rib locations. Four non-peened housings, tested up to a maximum of 43 pressure load cycles, were free of any cracks in the structural ribs. The two housings that had been shot peened were cracked in as few as 13 cycles, see Table I.

Table I - Housing Rib Inspection Summary

Unit #	Proof Cycles	Operating Cycles	Inspection Results
3	5	21	No rib cracks
5	5	10	No rib cracks
6	5	34	No rib cracks
7	5	38	No rib cracks
9*	5	11	1 of 8 ribs cracked
10*	5	8	4 of 8 ribs cracked

* shot peened prior to proof testing and operation

An Integrated Product Team (IPT) consisting of mechanical design, structural analysis, material, and manufacturing specialists along with government and academia experts was formed to investigate this rib cracking issue as well as cracking problems at other locations in the housings. This thesis will address only the rib crack initiation problem.

Background Information

Shot peening is used to impart compressive residual stresses at the surface of mechanical components such as disks, shafts, gears, etc. This surface residual stress improves the service life of these components by increasing the fatigue life of the metal as the compressive stresses induced by peening offset any machining induced or operational tensile stresses. The surface compressive residual stress is created by plastic deformation of the metal by bombarding the surface with either ceramic or steel shot peen particles.

When the high velocity shot particle impacts the metal surface it deforms the surface under high compressive loads that cause plastic yielding and permanent deformation of the surface layer metal. As this metal is deformed (compressed) in the normal direction (z), the metal is also forced to deform in the sideways (x, y) directions (in tension) due to poisson effects. However, when the shot particle rebounds the elastically stressed metal immediately sub-surface of the shot peen layer contracts. This applies a constraining load against the plastically yielded - tensile surface layer, forcing the surface metal into residual compression.

The plastic strain in the surface layers can be represented by the strain tensor ε_{ij}^{P} and defined as:

$$\varepsilon_{ij}^{P} = \begin{matrix} \varepsilon^{P}_{xx} & & 0 \\ & \varepsilon^{P}_{yy} & \\ 0 & & \varepsilon^{P}_{zz} \end{matrix}$$

As the material is plastically yielded in the normal direction (z) it also yields plastically in the surface directions x, y. Due to conservation of volume, the plastic strain in the x, y directions is ½ that in the z direction and opposite in sign $\varepsilon^{P}_{xx} = \varepsilon^{P}_{yy} = -\varepsilon^{P}_{zz} / 2$. The plastic strain ε^{P}_{xx} and ε^{P}_{yy} implies that the surface layers will change in length (δL). This is illustrated graphically in Figure 2a. The subsurface bulk of material at initial length L_o constrains the outer surface by imparting traction forces F in both the x and y directions as shown in Figure 2b. These imparted forces will cause residual compressive forces in the outer surface and residual tensile forces in the sub-surface. The high levels of compressive stress in the thin surface layer (smaller net area) is balanced out by low level tensile stress in the sub-surface metal (larger net area).

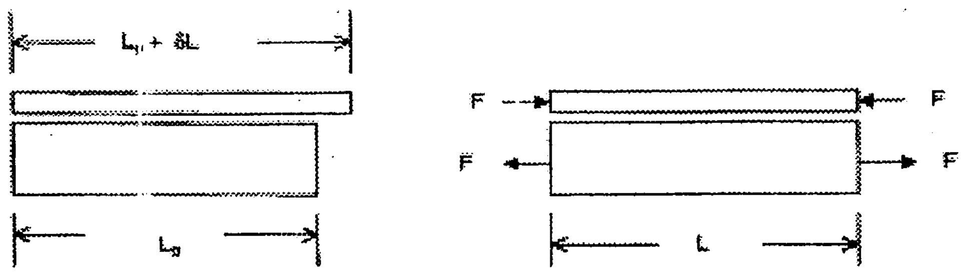

Figure 2a **Figure 2b**

Figure 2 Shot Peened Surface Layer Deformation and Constraint,
Figure 2a Surface Layer Deformation
Figure 2b Force Balance
(adapted from Ref [1] Figure 3.2 pg 49]

A typical shot peened subsurface radial stress distribution is illustrated in Figure 3. The stress at the extreme of the surface will generally be approximately half the yield strength of the work-hardened surface layer. It is possible that the residual stress will be higher than the original metal yield strength if sufficient work hardening occurs. The maximum compressive residual stress occurs below the metal surface at roughly two-thirds that of the work hardened metal yield strength. The depth of the compressive stress field will be approximately equal in magnitude to the diameter of the shot peen used. Larger shot will drive the compressive layer deeper. The overall depth of the compressive layer depends not only on the shot diameter, but also on the shot hardness, shot velocity, base metal hardness and the work hardening characteristics of the metal.

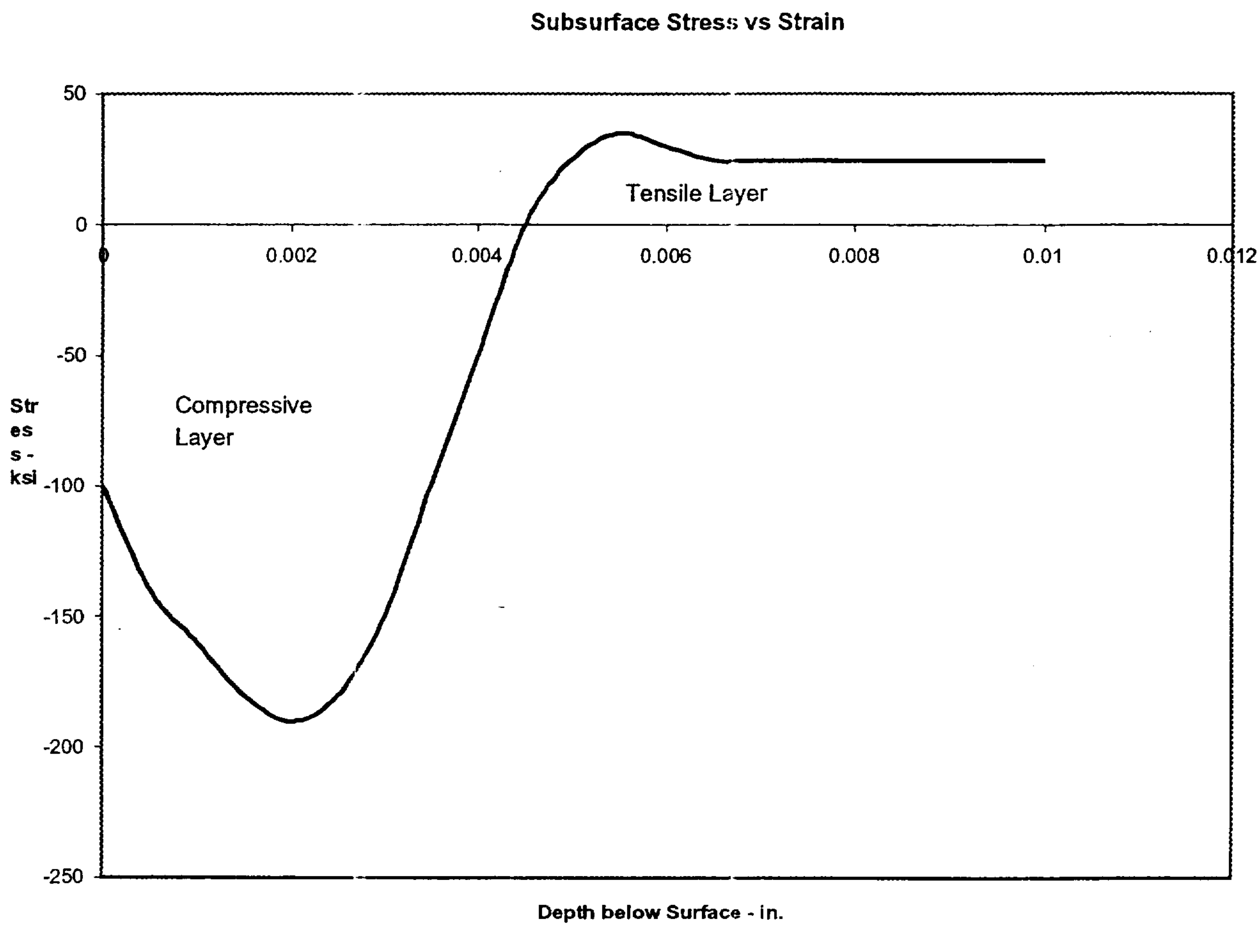

Figure 3. Shot Peen Radial Stress Profile – Typical (adapted from Ref [2] Figure 13 pg 355)

Figure 4 shows a typical stress strain curve for material as it undergoes plastic deformation to a strain of ε_3 at point A. When the material unloads to a point of zero stress A', it will retain the plastic strain $= \varepsilon_2$. The elastic component of strain at point A' is equal to the difference in strain, $\varepsilon^e = (\varepsilon_3 - \varepsilon_2)$[1].

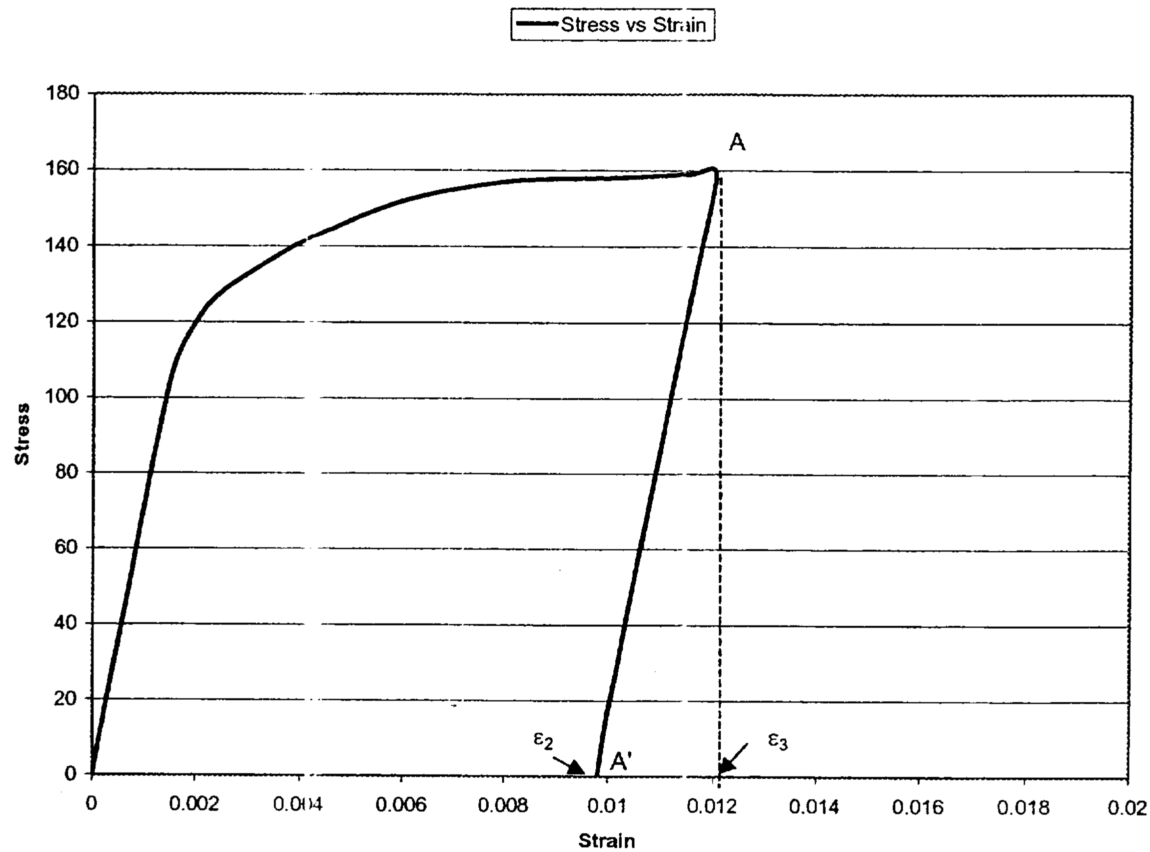

Figure 4. Stress Strain Profile
(adapted from Ref [1] Figure 2.18 pg 41)

Work hardening of the surface layer due to shot peening will change the elastic yield characteristics of the material. Figure 5 illustrates the stress – strain relationships for the shot peened surface metal and the core or bulk sub-surface metal that has not been work hardened. The amount of plastic strain retained in the metal after the stress is reduced is different. Stress reversal may occur in a component if it is subjected to high loads that cause the core material to yield.

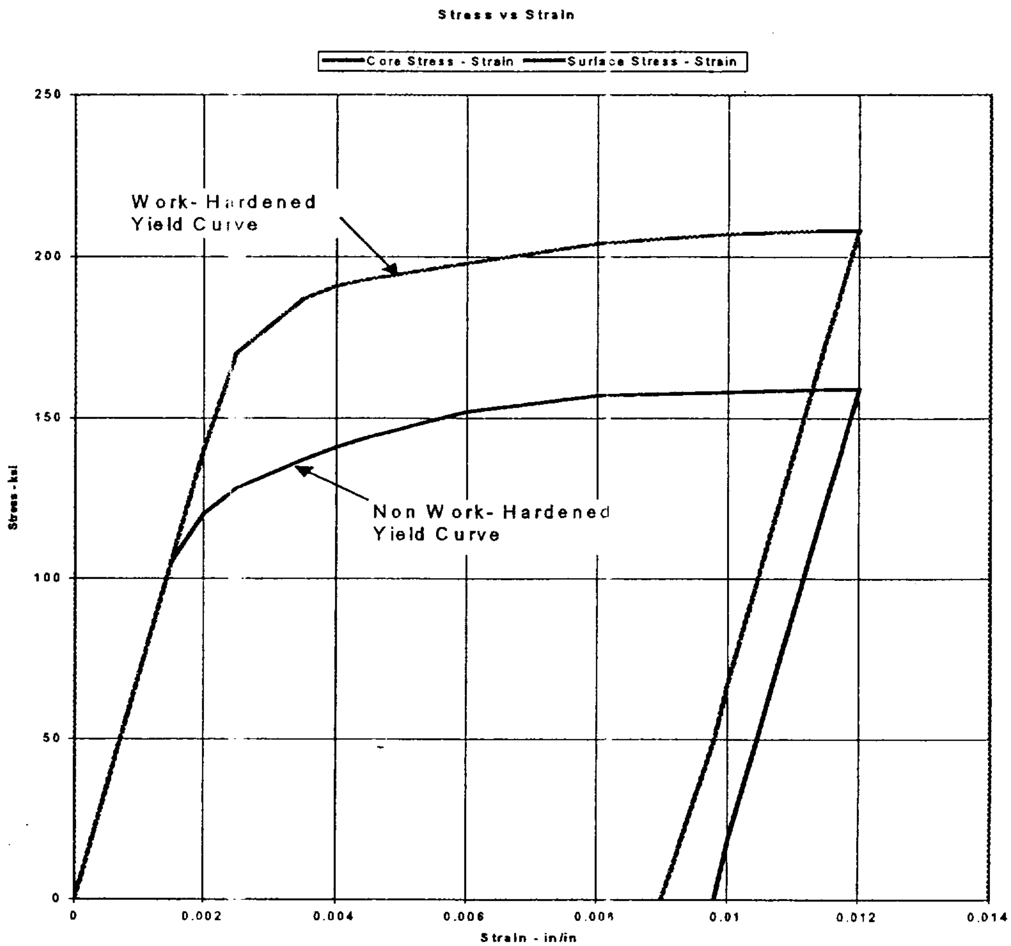

Figure 5. Work Hardened vs. Non Work Hardened Yield Curves

The physical explanation for the surface residual stress reversal, compressive to tensile, is related to the fact that the bulk or core section of the material is subjected to significant plastic yielding. On the surface, the shot peening cold works a thin layer of the material and increases the yield strength of the surface material. When the core material and the surface material are later strained beyond their elastic limits, they experience different levels of plastic strain. The core or sub-surface material will yield at a lower stress level and ultimately control the end-point strain level. The cold-worked surface material is held at the same end-point strain level and will be in tension. The end result is a tensile residual stress in the surface material as illustrated in Figure 6, for a typical stress vs. strain loading cycle.

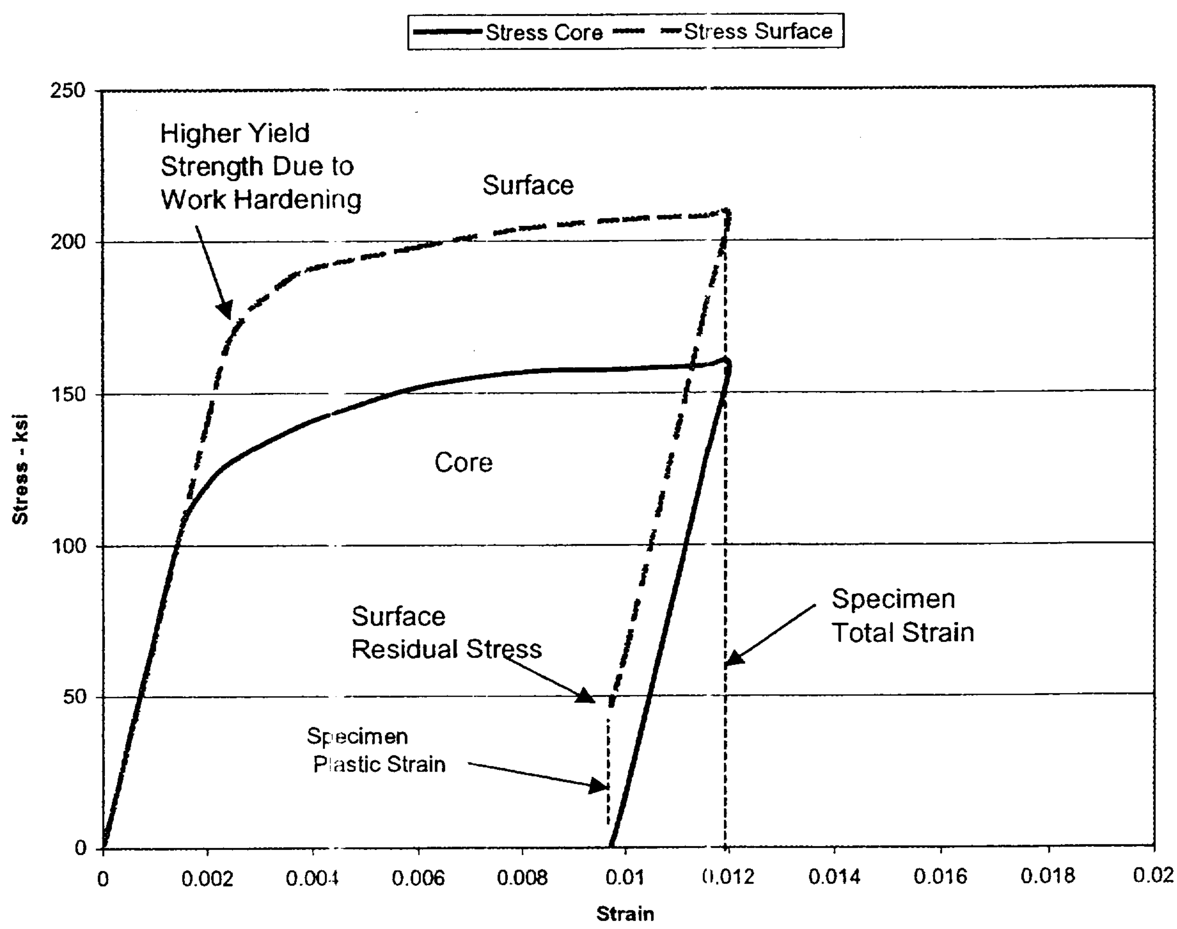

Figure 6. Stress vs. Strain Profiles - Typical

CHAPTER 2
ROOT CAUSE INVESTIGATION

Operation Review and Material Inspection Results

Initial IPT investigation review of the manufacturing and operational history of the housings that had developed the rib cracks was focused not on the shot peening, but rather on other related configuration changes, usage and operational differences. The original thought was that shot peening is normally expected to provide an improvement in LCF life; it was not expected to be a contributor to a reduction in life. Typical benefits of shot peening are shown in Figure 7. [X]

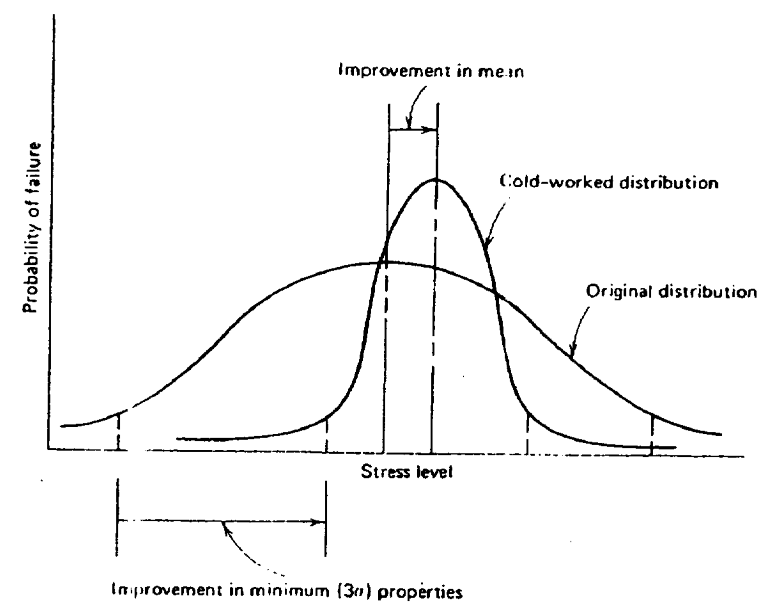

Illustration of improvement in minimum fatigue properties brought about by reduction in scatter through shot-peening or cold-rolling.

Figure 7 - Improved fatigues properties (adapted from Ref [3] Figure 7.45].

During the housing investigation IPT discussions about the rib cracking, it was suggested that perhaps the shot peening might be a key variable. One of the team members recalled that during his testing of various surface treatment effects on material LCF life, one of the shot peened specimens tested actually had a reduced LCF life. In reviewing this particular specimen, it was determined that the specimen had inadvertently been over-loaded during its initial setup in the tensile machine. The surface residual stress in the specimen was later found to be tensile rather than compressive. This suggestion led the housing IPT to measure (using x-ray diffraction techniques) the residual surface stress in the structural ribs. The surface residual stresses in the shot peened housing ribs were found to be tensile and not compressive as would normally be expected. Figure 8 illustrates the locations where the residual stresses were measured. Figure 9 shows the measured residual stress profile vs. the distance along the centerline of the ribs for a peened housing (Unit 9 build 1, designated Unit 9-1) and an un-peened housing (Unit 5 build 4, designated Unit 5-4) [4] These x-ray diffraction residual stress measurements were made using a two – angle sine – squared – psi technique per SAE J784a [5].

Also shown in Figure 9 is the measured percent cold work at various rib surface locations. The percent cold work is determined from the x-ray diffraction peaks (measured at psi = 0) and empirical correlations using specimens deformed to known levels of true plastic strain.

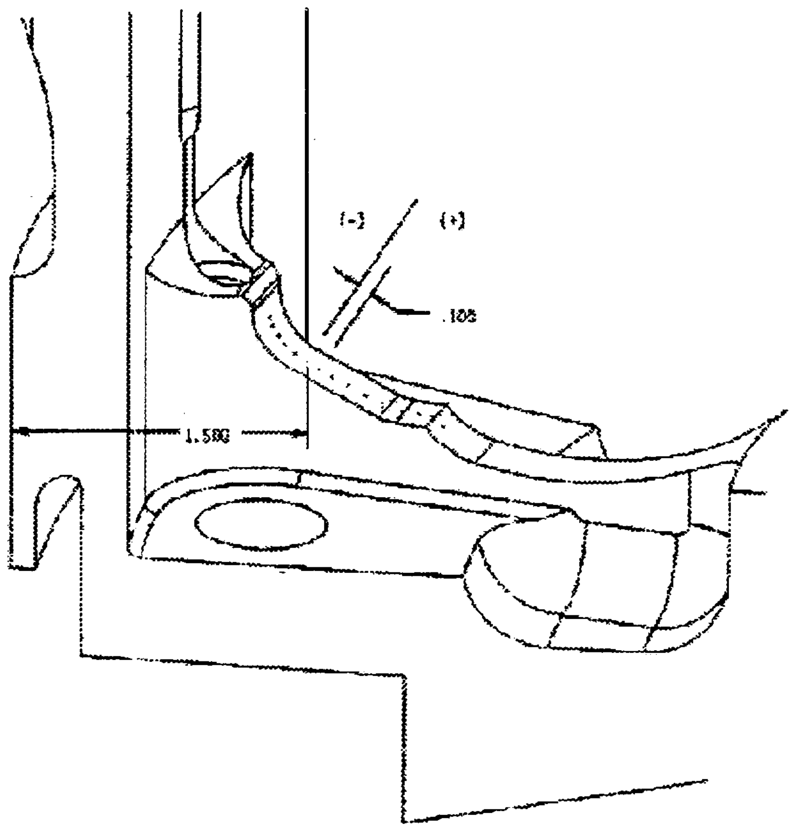

Figure 8. Rib Residual Stress Measurements Locations

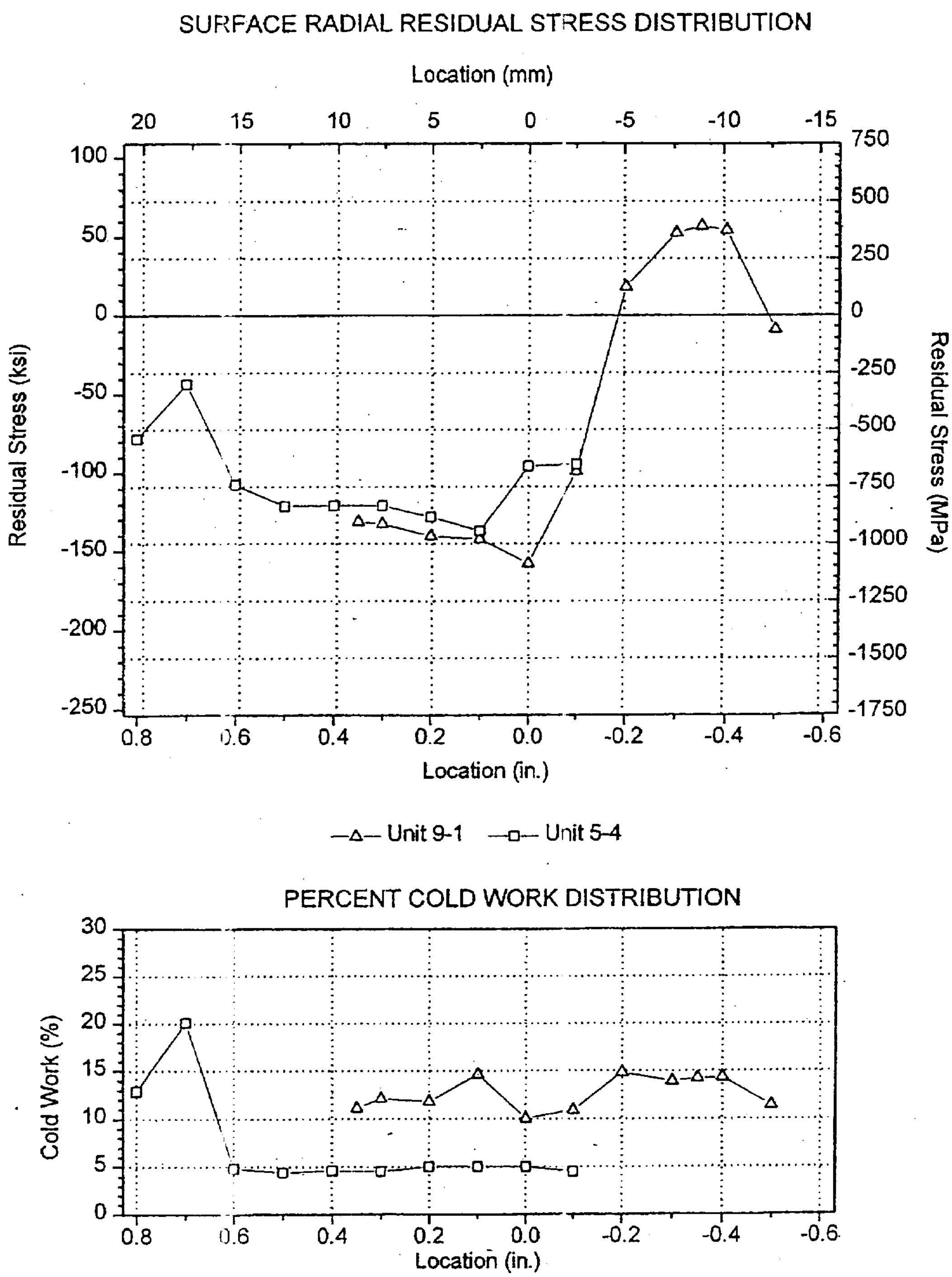

Figure 9. Residual Stress Profile

At two locations on the peened Unit 9 housing, radial profile measurements were conducted to determine the residual stress and percent cold work gradients. Figure 10 shows these radial profile gradients. Material was removed electrolytically for sub-surface measurements. The extent of the tensile stress is illustrated as well as the marked difference in the sub-surface stress profiles. However, the percent cold work profiles are similar [4].

The residual stress profile differences (sub-surface) suggest that each measurement location experienced different operational strains. At the negative 0.35 inch location, sufficient sub-surface yielding must have occurred to induce the high positive residual stress at the shot peened surface.

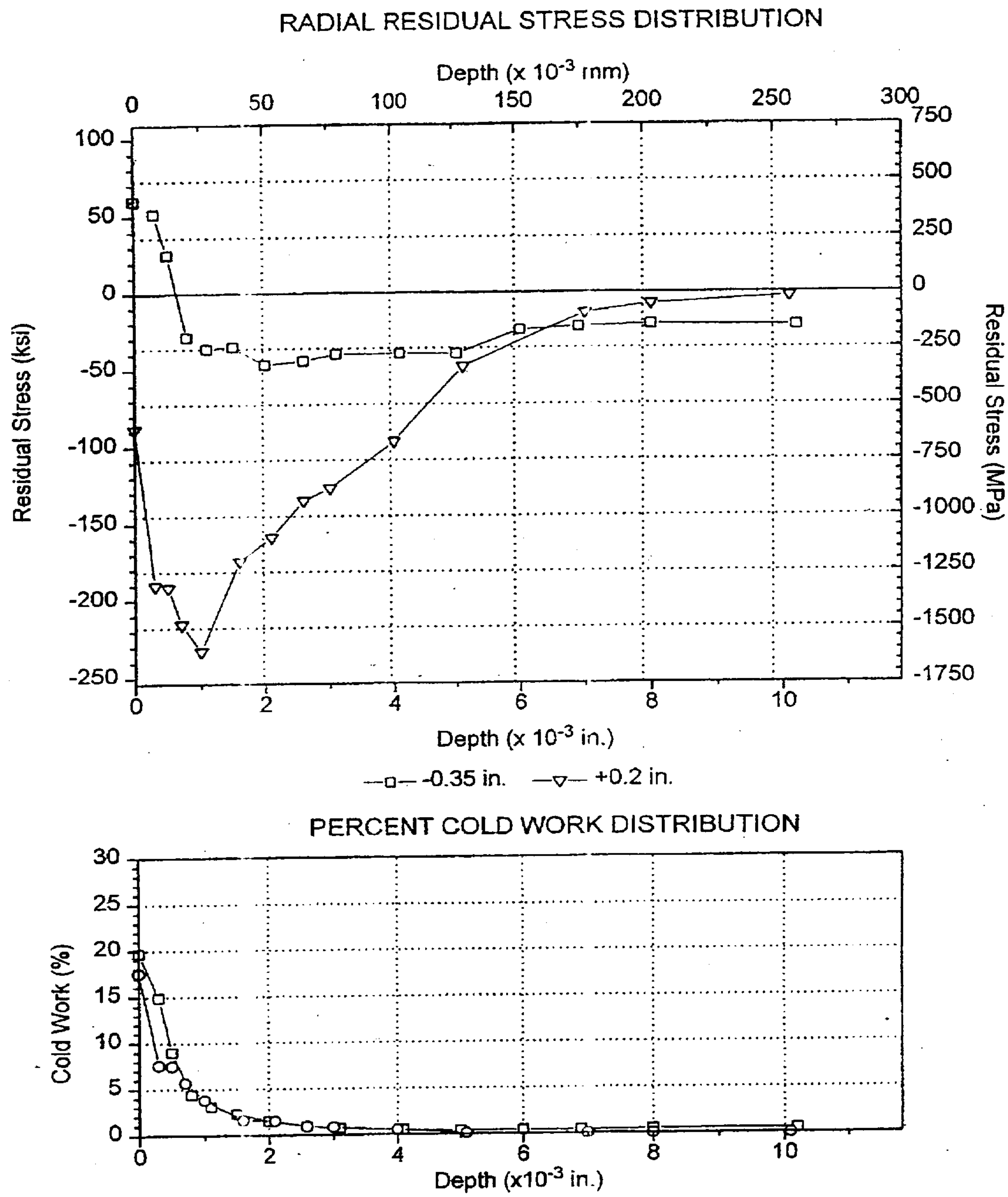

Figure 10. Radial Residual Stress Profiles

Design Analyses Validation

Rib strain measurements recorded during housing proof pressure testing show strains up to .67% are reached during the initial load cycle. This strain level is sufficiently high to cause some local yielding. The Incoloy IN100 housing material has a yield strength of 155ksi with a modulus of elasticity of 30.98 x 10**6 at room temperature. Figures 11 shows the rib strain gage locations and Figure 12 shows actual strain measurements recorded during proof pressure testing.

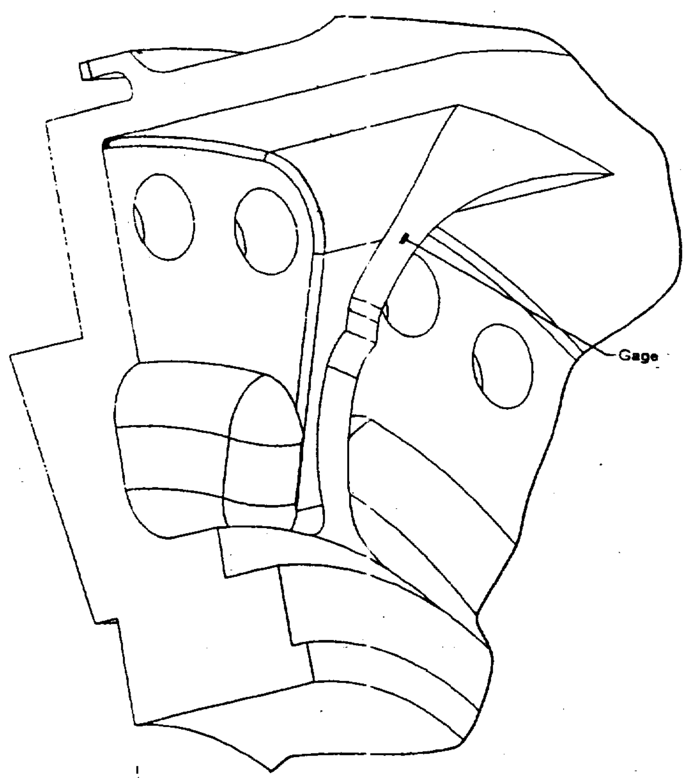

Figure 11. Rib Strain Gage # 23 Location

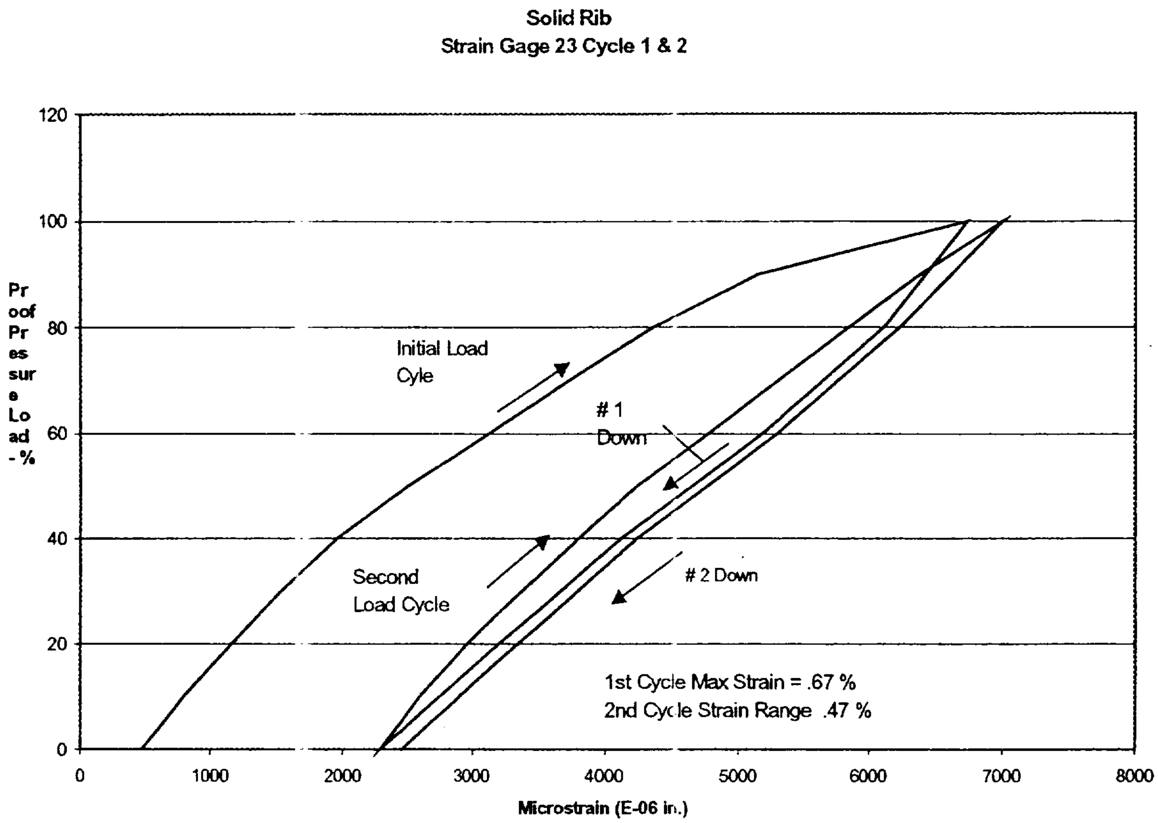

Figure 12. Solid Rib Strain Gage Data.

As shown in Figure 12, the rib surface will experience the maximum plastic deformation during the initial load cycle (total strain = 0.67 %). During the subsequent load cycle(s), the surface will see a strain range of approximately 0.47%. The difference is the result of work-hardening of the surface material and permanent deformation of the housing itself.

Design finite element analyses of the housing solid rib location predict that the proof pressure testing will create stresses that are higher than those expected during operation, 154 ksi during proof vs. 121 ksi during operation. Therefore, the maximum yielding of the rib will occur during the proof-pressure testing. Proof pressure testing of the housing is conducted using special proof test fixtures.

Hydro-static internally applied pressures generate radial loads (hoop stress) in the housing cylindrical section and axial loads (bending stress) in the diaphragm section. Pressures equal to 1.2X design operating levels are applied during each of five proof test cycles. The housing is then inspected for signs of surface cracking before being released into service.

Materials Laboratory Testing

Controlled laboratory tests were conducted to investigate the shot-peened surface stress reversal in high strain applications. Smooth strain controlled LCF specimens (shown in Figure 13) were shot peened and then inspected using X-ray diffraction to measure the surface residual stresses.

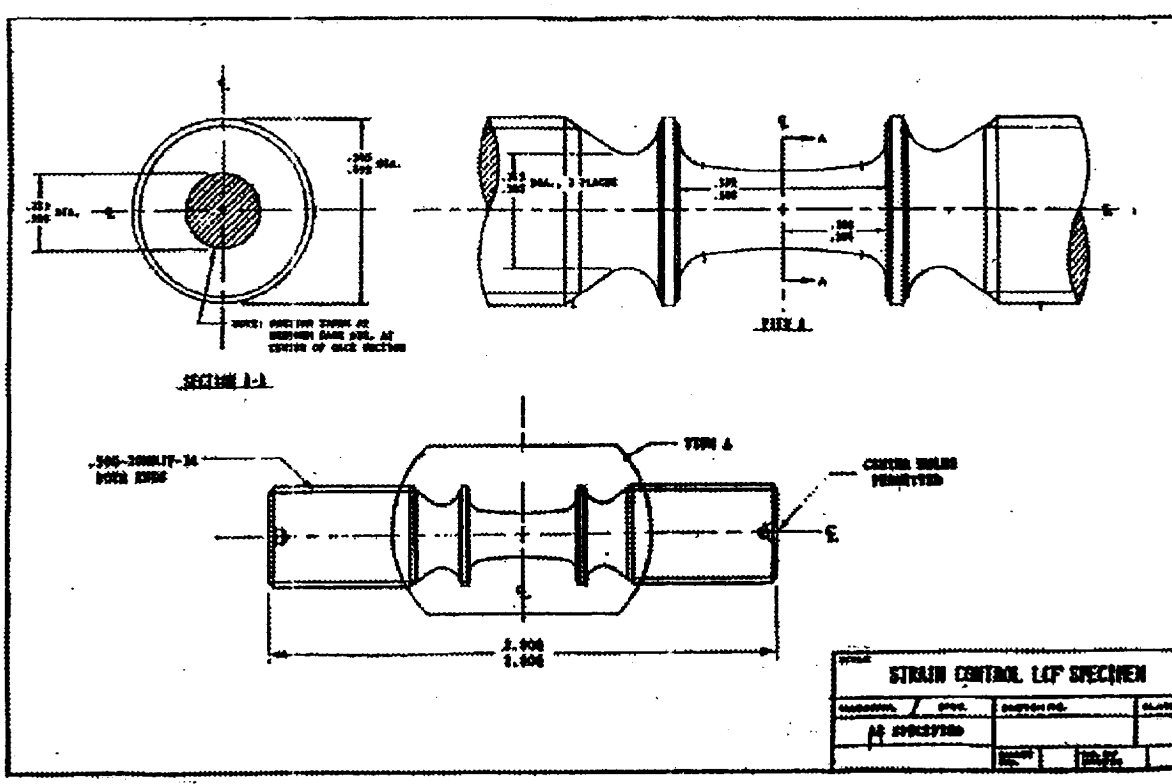

Figure 13. Residual Stress Reversal - Strain Controlled LCF Specimens

Each specimen was tensile loaded to different levels of percent strain, re-inspected to determine the residual stress level after a single load cycle, and then fatigue cycled to failure. Table II presents the results of this test series. The surface residual stress was found to have reversed in each test. The specimens strained to the higher level retained the highest tensile residual stress. Table II also gives the number of cycles to failure for each specimen. The shot peened specimens, in each case, demonstrated lower LCF life. No attempt was made to statistically validate the lower LCF life trending due to the limited sampling.

Table II - LCF Specimen Residual Stress Measurements

% Strain Tested (specimen #)	Peened	Residual Stress – Prior to test	Residual Stress – Post test (1^{st} cycle)	LCF Cycles to Failure
1.8 % (88)	No	- 45 ksi	+ 48 ksi	23
1.0 % (92)	Yes	- 77 ksi	+ 93 ksi	9
1.9 % (97)	Yes	- 81 ksi	+ 182 ksi	11
2.7 % (96)	Yes	-107 ksi	+ 175 ksi	13

The residual stress reversal for the 3 shot peened specimens shown in Table II are investigated further by analysis in the following chapter.

CHAPTER 3
ANALYTICAL MODEL

An ANSYS [6] Elastic-Plastic Finite Element Model of a tensile test specimen was constructed to further investigate the stress reversal problem and validate the laboratory residual stress measurements. Figure 14 and 15 show the 2D axi-symmetric ANSYS model used for the analytical studies. Plane82 8-node elements were used throughout. The FEM mesh density near the surface was increased to allow varying material properties to be applied as appropriate to simulate the shot peened surface. A thickness of 0.00125 inches was used for the outer 8 element rows shown in Figure 15.

The model is made up of 6705 elements with a total of 20744 nodes. Grid-points that define the geometry and sub-division surface areas are listed in the appendix. The minimum diameter section for the model is .500 inches vs. the actual tensile specimen minimum diameter of .210 inches. This 2.4X scale factor was used for modeling convenience; it will not influence any of the analytical results due to model symmetry.

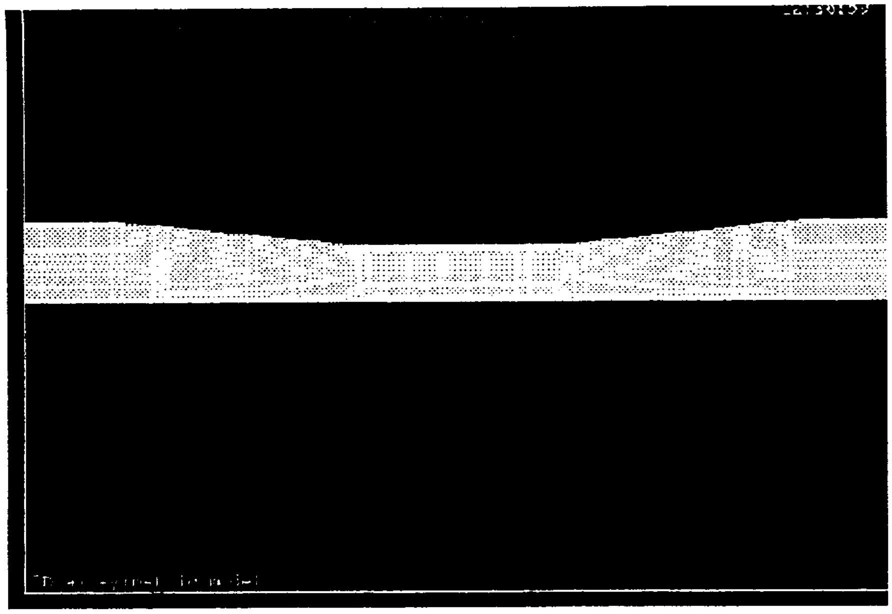

Figure 14. Axi-symmetric 2D ANSYS Tensile Specimen Model

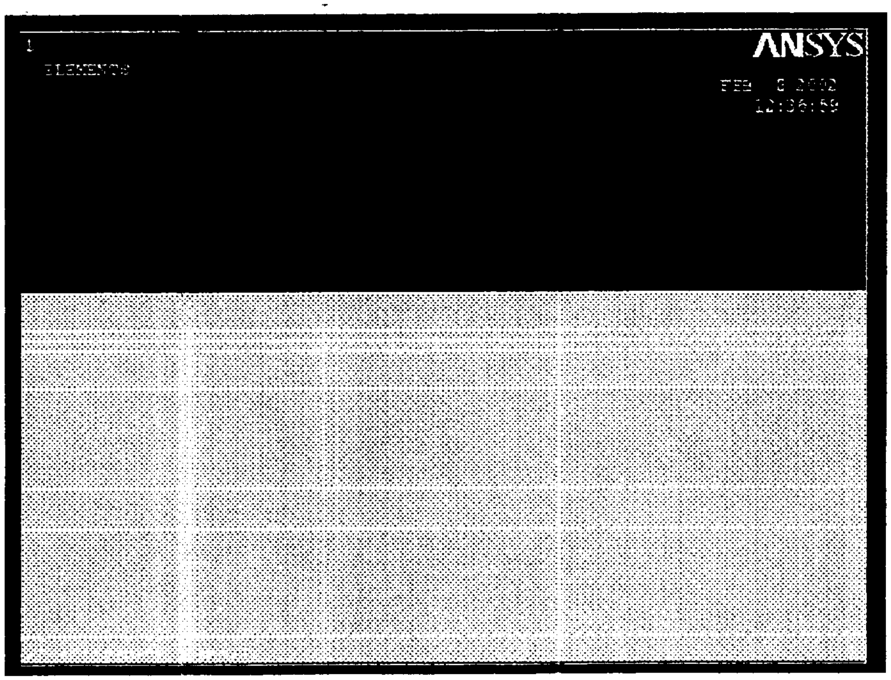

Figure 15. Axi-Symmetric Model – Surface Elements

Once the residual stress levels were applied into the surface elements, the entire model was then subjected to varying axial loads to simulate the tensile loads that were applied during the laboratory specimen tensile tests. Tensile loads adjusted to simulate ~ 1.0%, 1.9%, and 2.7% strain were modeled with uniform pressure applied to the free end of the model. Note: ANSYS uses negative pressure values to simulate tensile surface loads. Table III shows the load step sequence used for the 3 different analyses.

Table III - Analyses Load Step Sequence

Load Step	1.0% Strain Specimen	1.9 % Strain Specimen	2.7 % Strain Specimen
1	-750 degree temp. applied at surface	-750 degree temp. applied at surface	-750 degree temp. applied at surface
2	+ 80 degree temp. applied at surface	+80 degree temp. applied at surface	+ 80 degree temp. applied at surface
3	local temps. 95, 90, 85 assigned to outer surface elements	local temps. 95, 90, 85 assigned to outer surface elements .	local temps. 95, 90, 85 assigned to outer surface elements .
4	- 76530 psi (tensile)	- 80600 psi (tensile)	- 85000 psi (tensile)
5	- 83200 psi (tensile), + 163 ksi stress	- 87530 psi (tensile) + 172 ksi stress	- 91800 psi (tensile) + 180 ksi stress
6	no load	no load	no load

The material properties of the work-hardened, shot peened layer of metal was simulated in the analysis by assigning increased yield properties to the surface layers. The FEM elements at the surface (first .0025 inches) were assigned the highest proportional elastic yield stress level, 335 ksi. The yield properties were then exponentially decreased to nominal levels (155 ksi) at a depth of 0.0075 inches. This was accomplished by using an ANSYS feature that allows mechanical properties to vary as a function of temperature. This feature also permitted the material properties to be changed mid-way through the analysis. In load step 3, the outer element rows were arbitrarily set at temperatures close to, but different from, the nominal temperature of 80 degrees. Table IV shows the load step 3 temperature assignments and Figure 17 shows the yield curves used in the analyses for the various surface element rows and temperatures.

Table IV
Load Step 3 Outer Element Row Temperatures, Proportional Limits

Temperature	Element Rows	Radial Depth	Proportional Limit
T5 = 95 deg.	1 & 2	0.000 – 0.0025	335 ksi
T4 = 90 deg.	3 & 4	0.0025 – 0.005	225 ksi
T3 = 85 deg.	5 & 6	0.005 – 0.0075	170 ksi
T2 = 80 deg.	7 & 8, and remainder	0.0075 and remainder	155 ksi
T1* = - 750 deg. *Used in load step #1 only	All elements	All elements	155 ksi

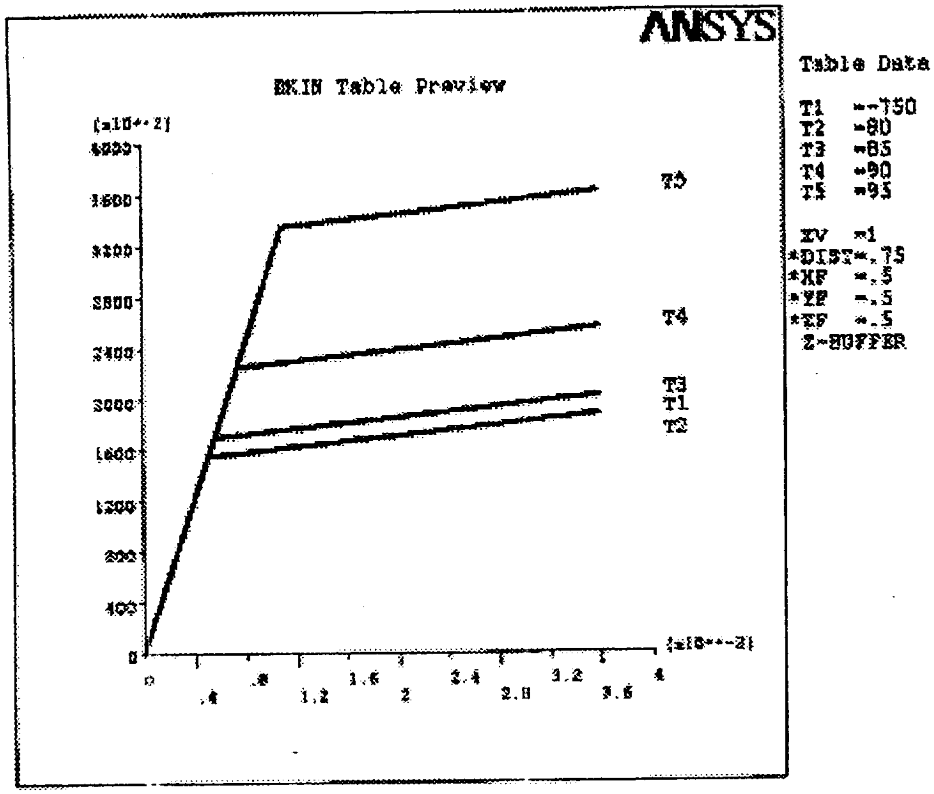

Figure 17. FEM Input Material Properties.

The surface element material properties (T3, T4, and T5 stress-strain relationships) presented in Figure 17 are estimates only. These estimated properties were used because actual data was not available to define the change in properties due to cold working in either the housing or in the laboratory tensile specimens. The 335 ksi yield point was estimated by graphically super-imposing linear-elastic stress-strain curves that would match up with the tensile specimen "measured" initial and final residual stress levels and also follow the slopes of the measured specimen (core) stress-strain data. This is illustrated in Figure 18 where the "estimated" surface and actual stress-strain data is plotted for each tensile specimen. The estimated stress-strain curves show that the relatively high residual stresses (measured at the end of the strain cycle) could only be achieved if the surface material yield point was more than 2X that of the core material. Note the consistency in the three curves, each supporting the high yield point estimate.

Empirical confirmation that high tensile surface residual stresses result from cold working of the metal to high yield levels was provided in a recently published paper by Hornbach and Prevey of Lambda Research, "The Effect of Prior Cold Working on Tensile Residual Stress Development in Nuclear Weldments"[7] In this research, Hornbach and Prevey measured the effect of work hardening and show that near surface yield proportional limits can be greater than 2X nominal levels. They also measured the distribution of the cold working into the metal. This showed an exponentially decreasing effect that dies out at about 0.006 inches sub-surface. In their investigation, the cold work was produced during tube fabrication (drawn) and tube machining (reaming) with the residual stress reversal occurring during tube welding.

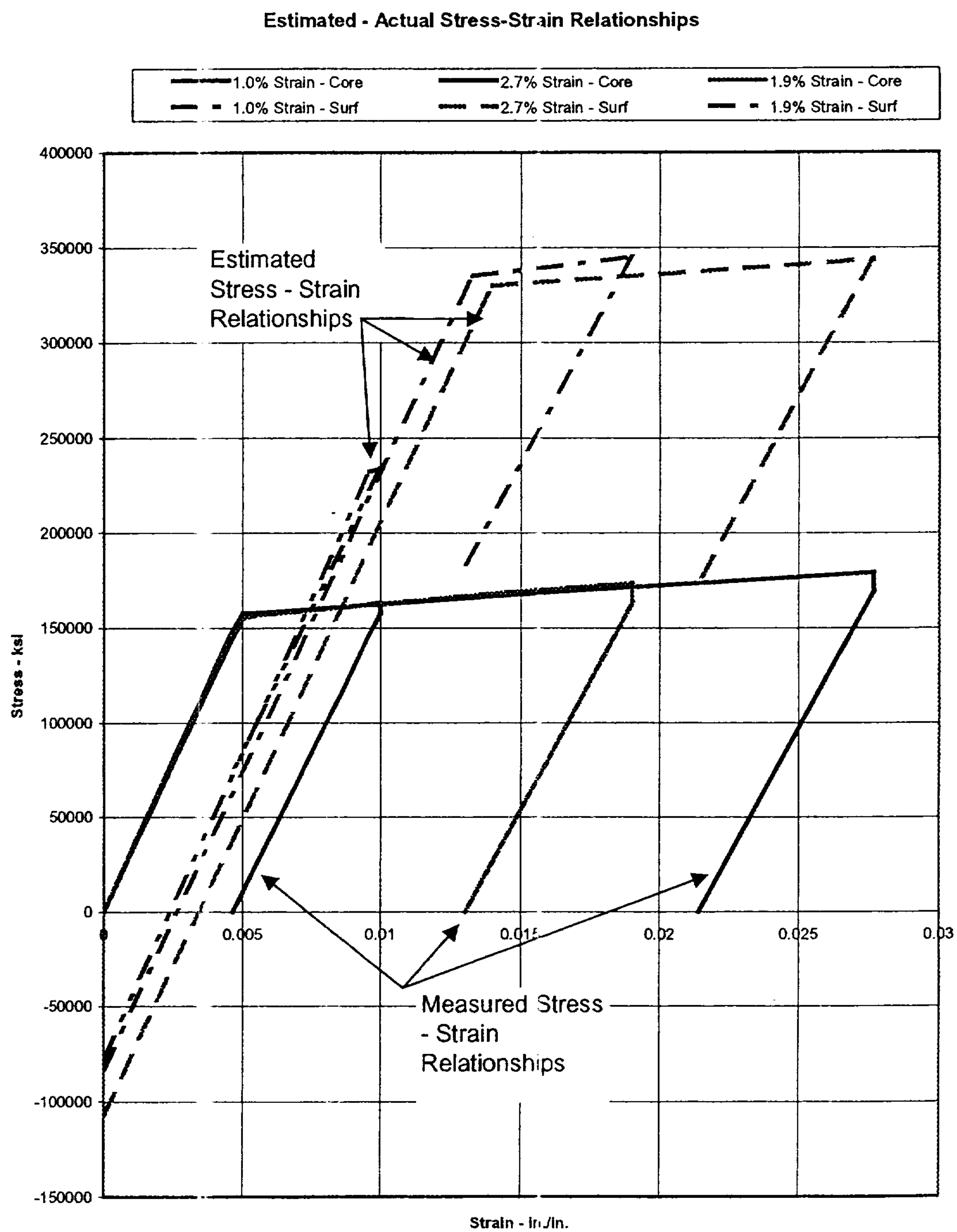

Figure 18. Estimated Surface Yield, Measured Core Yield Relationships

The FEM analysis results for the three tensile specimen load cases are shown in Figures 19 thru 21. In each case, the analysis predicts residual stress levels at the surface that are reasonably close to the specimen measured residual stress levels. The surface residual stress reversal is predicted in each case!

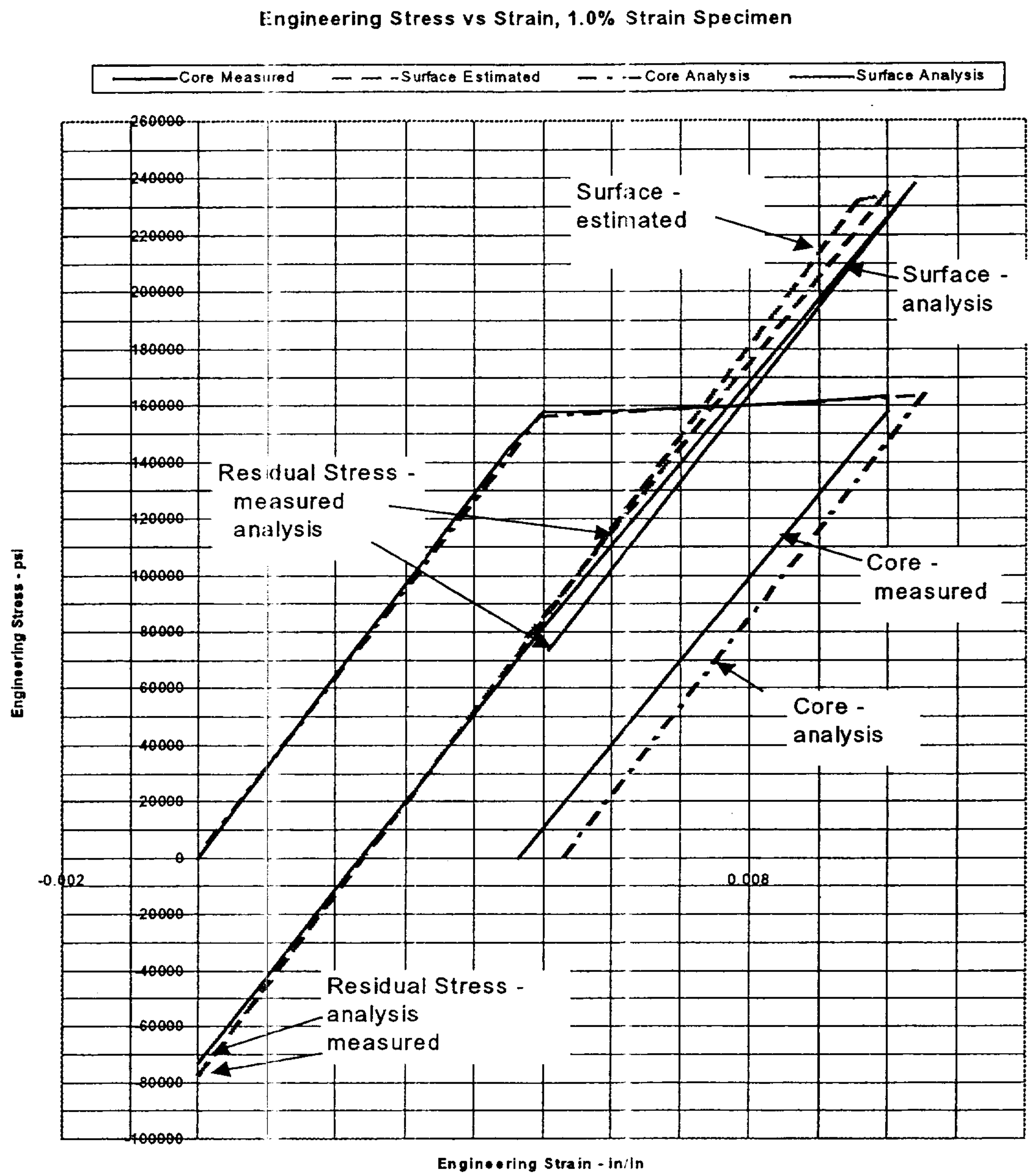

Figure 19. 1.0% Strain Tensile Specimen Analysis

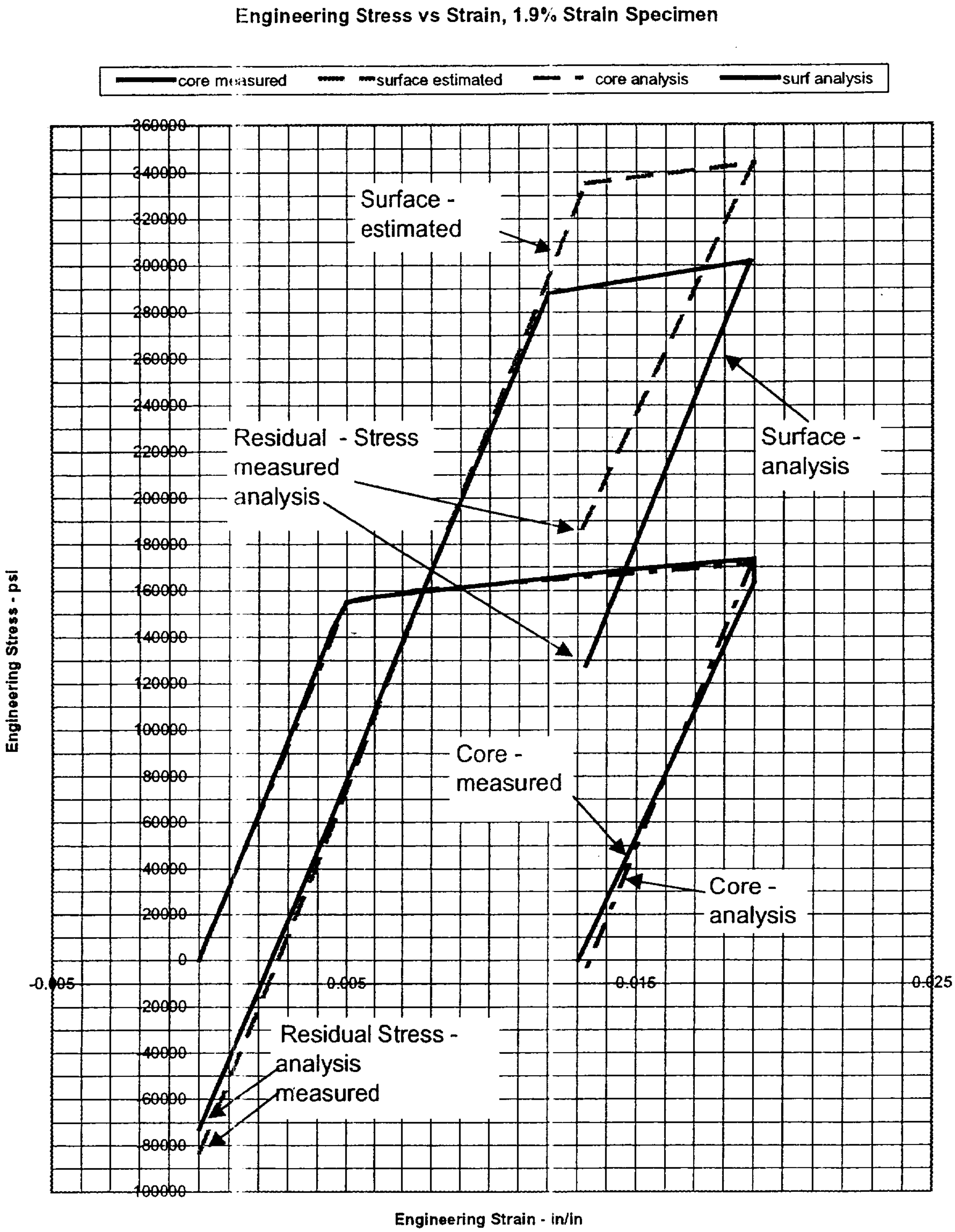

Figure 20. 1.9% Strain Tensile Specimen Analysis

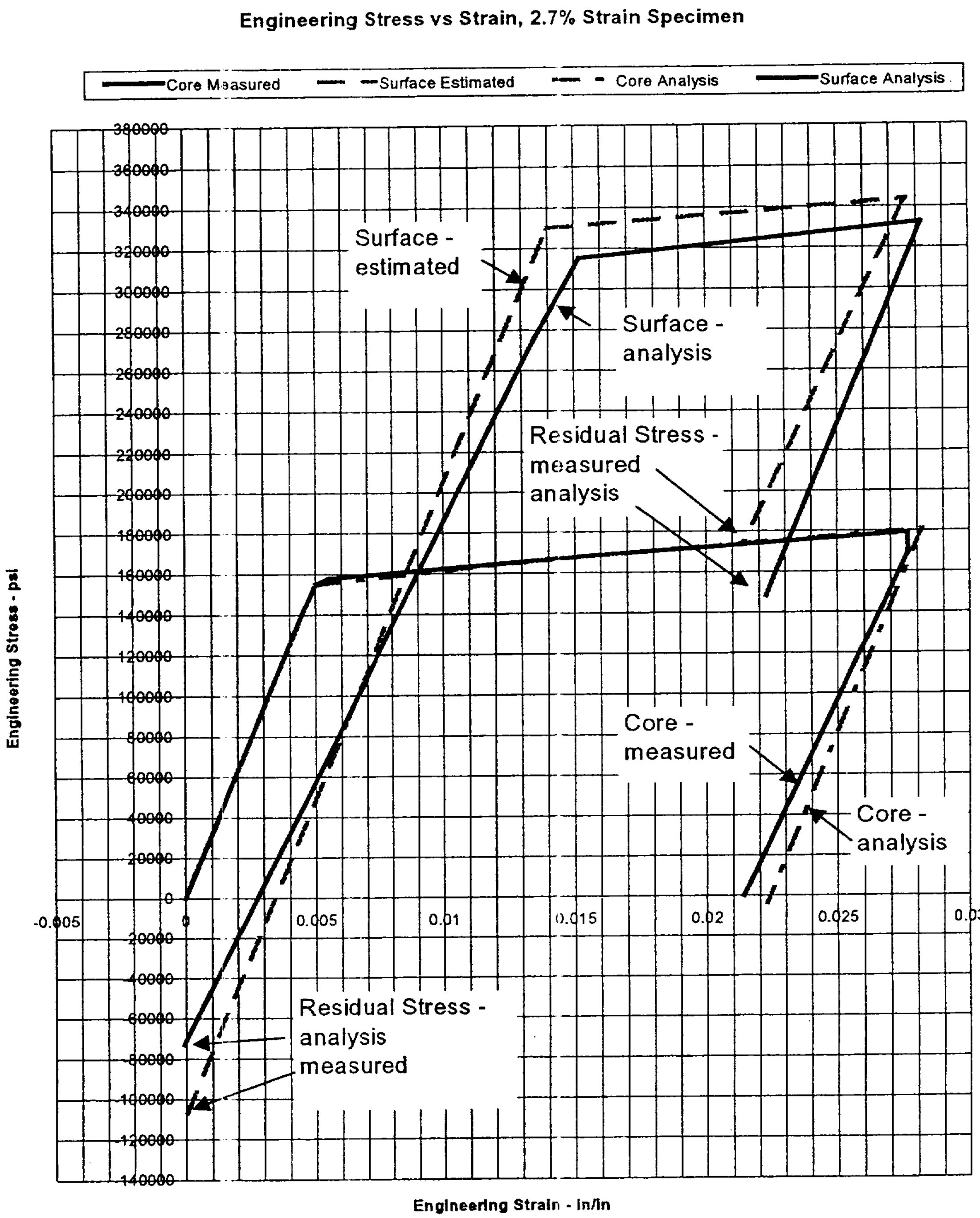

Figure 21. 2.7% Strain Tensile Specimen Analysis

Figure 22 provides a plot of the calculated Von-Mises stress (or equivalent stress - Seqv) and also the tensile (or specimen axial stress - Sy) for the outer surface elements that simulate the shot peening effects. The analyses shows relatively smooth and continuous transition to expected nominal stresses of 172 ksi (average stress applied to the 1.9% strain specimen).

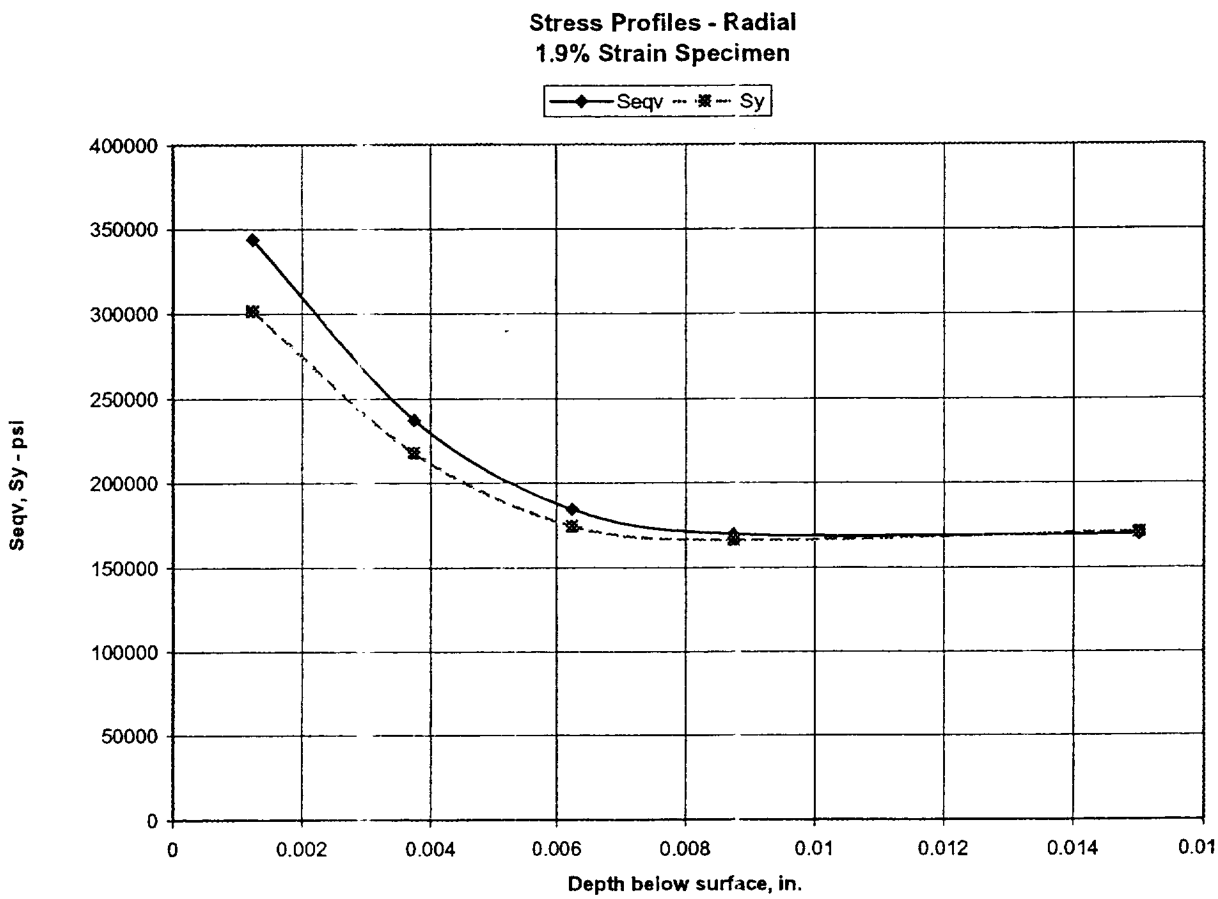

Figure 22 Analysis Radial Stress Profile Results – 1.9% Strain Specimen

Figure 23 provides a plot showing the calculated elastic and plastic strains for the outer surface elements, again for the 1.9% strain specimen. The analysis shows smooth continuous transitions between the elastic and plastic strain levels and a uniform total strain as expected.

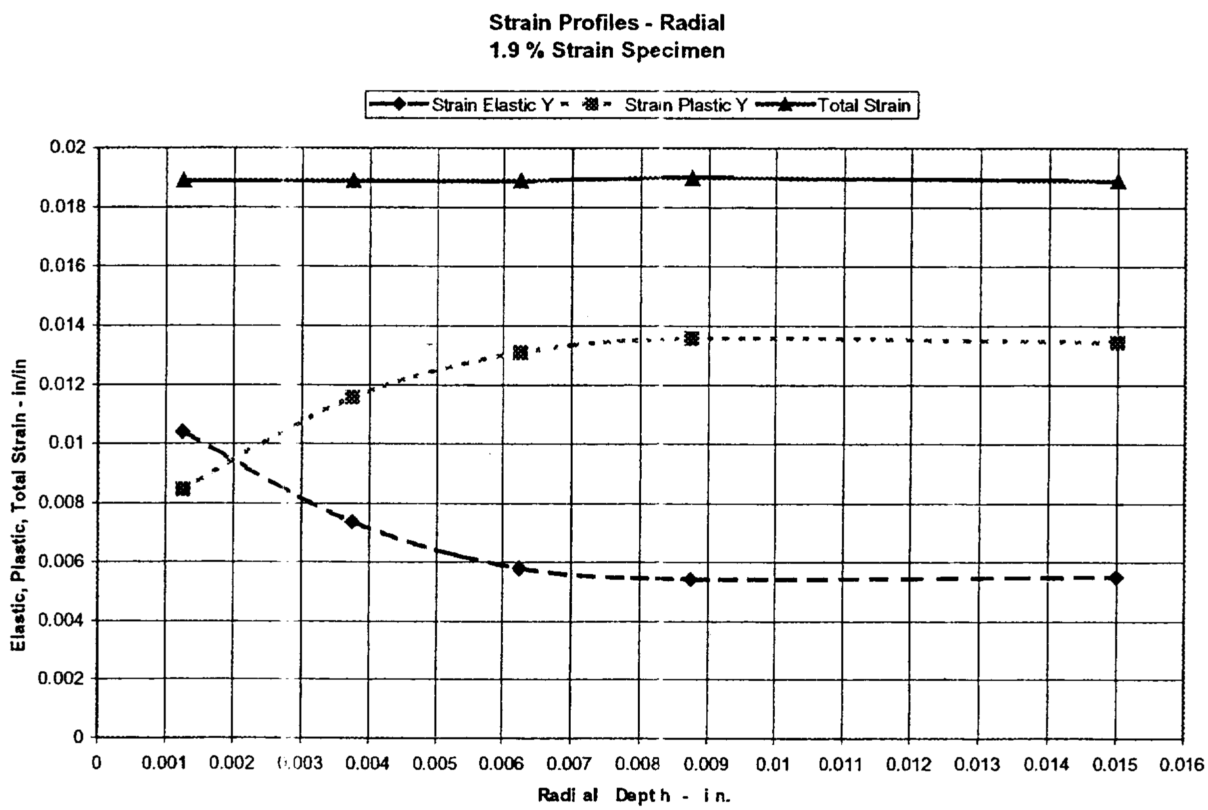

Figure 23 Analysis Strain Profile Results – 1.9% Strain Specimen

CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS

Metal surface treatments such as shot peening are applied to highly stressed hardware to improve the service life of the component. In typical shot peening applications, the surface treatment provides an improvement in the fatigue life of the metal by imparting surface compressive residual stresses. Under normal operating conditions, the compressive (negative) residual stress will serve to eliminate any tensile stresses caused during final machining. It will also effectively impart a compensating stress into the metal that will offset applied operating tensile (positive) stress. The combined effect is usually an increase in the life of the component. However, surface residual stress produced during fabrication, machining, or during surface treatments such as shot peening, can *also* cause a negative effect on the service life of a component. During the design, manufacturing and even in the proof pressure test acceptance of a component, consideration must be given to the potential that surface stress in the component may increase to unacceptable levels. The rib cracking within the pressure containment housing as described in this thesis is an illustration of this potential problem. The shot peening had a significant negative effect on the fatigue life of the part.

The analytical studies presented in this thesis support the laboratory test results and together further support the general investigation conclusion: the shot peening (because of the stress reversal) had actually reduced the LCF life of the housing. It should be noted that the housing had been shot peened prior to proof testing. Had the shot peening been applied after the proof pressure loading, the surface residual stress reversal may have been avoided. The shot peening could then possibly improve the low cycle fatigue life of the housing - provided the operational tensile stresses remain lower than those imparted during the proof cycle.

The Finite Element Modeling analytical approach presented in this thesis can be used by design and structural analysis specialists in the preliminary and final analyses of highly stressed components. By knowing the sensitivity of a particular design to surface irregularities and stress conditions, the proper recommendations for surface treatment requirements can be incorporated.

Recommendations for future work and research in this area of interest:

1. Component failure investigations should routinely evaluate surface residual stress levels to determine if the material has developed unexpected stress levels that might explain the failure mechanism.
2. New approaches and methods to improve the surface treatments of metals should continue to be pursued; especially those that reduce the likelihood of surface metal cold working.
3. Analytical modeling refinements applicable to surface elements may enhance the feasibility to incorporate surface treatment parameters into modeling techniques.
4. Additional empirical relationships that correlate the surface residual stress level with percent cold working and corresponding increase in yield strength and decrease in ductility should be developed for metals subjected to high stress conditions.

APPENDIX A

LIST ALL SELECTED KEYPOINTS. DSYS= 0

NO.	X,Y,Z LOCATION			THXY,THYZ,THZX ANGLES		
1	0.	0.	0.	0.0000	0.0000	0.0000
2	0.3500000	0.	0.	0.0000	0.0000	0.0000
3	0.3500000	0.5000000	0.	0.0000	0.0000	0.0000
4	0.3000000	1.000000	0.	0.0000	0.0000	0.0000
5	0.2500000	1.500000	0.	0.0000	0.0000	0.0000
6	0.2500000	2.500000	0.	0.0000	0.0000	0.0000
7	0.3000000	3.000000	0.	0.0000	0.0000	0.0000
8	0.3500000	3.500000	0.	0.0000	0.0000	0.0000
9	0.3500000	4.000000	0.	0.0000	0.0000	0.0000
10	0.	4.000000	0.	0.0000	0.0000	0.0000
11	0.	3.500000	0.	0.0000	0.0000	0.0000
12	0.	3.000000	0.	0.0000	0.0000	0.0000
13	0.	2.500000	0.	0.0000	0.0000	0.0000
14	0.	1.500000	0.	0.0000	0.0000	0.0000
15	0.	1.000000	0.	0.0000	0.0000	0.0000
16	0.	0.5000000	0.	0.0000	0.0000	0.0000
17	0.2500000	1.600000	0.	0.0000	0.0000	0.0000
18	0.2500000	2.400000	0.	0.0000	0.0000	0.0000
19	0.	2.400000	0.	0.0000	0.0000	0.0000
20	0.	1.600000	0.	0.0000	0.0000	0.0000

NO.	X,Y,Z LOCATION			THXY,THYZ,THZX ANGLES		
21	0.2400000	2.400000	0.	0.0000	0.0000	0.0000
22	0.2400000	1.600000	0.	0.0000	0.0000	0.0000
23	0.2200000	2.400000	0.	0.0000	0.0000	0.0000
24	0.2200000	1.600000	0.	0.0000	0.0000	0.0000
25	0.2250000	2.400000	0.	0.0000	0.0000	0.0000
26	0.2300000	2.400000	0.	0.0000	0.0000	0.0000
27	0.2350000	2.400000	0.	0.0000	0.0000	0.0000
28	0.2350000	1.600000	0.	0.0000	0.0000	0.0000
29	0.2300000	1.600000	0.	0.0000	0.0000	0.0000
30	0.2250000	1.600000	0.	0.0000	0.0000	0.0000
31	0.2475000	1.600000	0.	0.0000	0.0000	0.0000
32	0.2450000	1.600000	0.	0.0000	0.0000	0.0000
33	0.2425000	1.600000	0.	0.0000	0.0000	0.0000
34	0.2425000	2.400000	0.	0.0000	0.0000	0.0000
35	0.2450000	2.400000	0.	0.0000	0.0000	0.0000
36	0.2475000	2.400000	0.	0.0000	0.0000	0.0000

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