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AFTERMARKET PARTS: ARE THEY ALL THEY ARE "CRACKED" UP TO BE?

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Abstract: This report contains the results of a failure analysis investigation of a fractured main support bridge from an army helicopter. The part failed component fatigue testing while those of the original equipment manufacturer (OEM) passed. Even though the same technical data package was used by both manufacturers and there were no material discrepancies found, a great disparity existed in the fatigue test data. This has been a recurring problem within the Army and the intent of this paper is to provide some insight as to the technical reasons why this can occur. Emphasis will be placed on the effects of manufacturing processes on fatigue. Other failure analyses will be discussed in relationship to this topic.

Objective: To perform a metallurgical examination comparing components fabricated by "Contractor IT" to those of the OEM, with the intent of determining the disparity in fatigue life.

Conclusion: The metallurgical data collected during this investigation indicated that the difference in fatigue life between the components fabricated by IT and the OEM may be attributable to a difference in dimensions at the web where fatigue crack initiation occurred. The webs of the two OEM parts examined contained cross-sectional thicknesses that measured significantly larger than the IT components.

Recommendations:

1. Change the web reference dimension of 0.38 inch to include a tolerance range based upon a fracture mechanics model.
2. Control the shot peening process especially at the critical areas of the web, to assure complete coverage and proper compressive residual stresses.
3. The engineering drawing includes only a shot peening intensity. No direction is given with respect to type of shot, shot size or coverage.

Background: The aforementioned four helicopter main support bridges were shipped to ARL for analysis. The parts had been subjected to fatigue testing (results listed above), and had shown a difference, by an order of magnitude, in fatigue resistance between the IT components and the two OEM parts. An independent laboratory (IL) analyzed IT0011 initially, and concluded that the shot peening intensity for the IT part was most likely excessive, which produced surface microcracks, leading to premature failure. IL also

stated that the microcracks may have relieved some of the residual stress on the surface of the part. ARL performed a comprehensive investigation in order to identify the cause of decreased fatigue life within the IT parts, including dimensional verification, visual examination, chemical analysis, surface roughness, hardness, conductivity, metallography, tensile and fatigue testing, fractography, shot peening analysis, residual stress, and TEM analysis.

Dimensional Verification: The thickness of the web at the fatigue crack initiation site was measured and compared for each of the four components. As shown in Table 1, a trend was noted. The thickness measurements of the IT webs were appreciably lower. The requirement of 0.38-inch was a reference dimension only.

Table 1
Dimensional Measurement of Web
At Fatigue Crack Initiation Site

Component	Cycles To Failure	Thickness (inch)
IT0011	38,373	0.370
IT0067	36,256	0.399
01344A1	356,942	0.421
1316HMW	435,000	0.421
Requirement		0.38 (ref.)

Visual Examination: Component IT0011 was examined in the as-received condition. The part number and serial number of the failed bridge were visible. The location of fracture, as well as the material prepared for metallographic examination by IL during their analysis was also examined. Oblique lighting was used to highlight the river patterns which corresponded to a fracture origin at the edge of the cross section. Two distinct origins were observed. No gross defect was noted at the origin sites.

Chemical Analysis: A section of the IT0011 component was analyzed to verify conformance to the required chemical composition. The results compared favorably to the nominal composition of 7075 aluminum alloy as shown in Table 2.

Table 2
Chemical Composition Results (Weight Percent)

Element	UH-60 Bridge	Typical 7075 Aluminum
Copper	1.57%	1.0 - 2.0%
Silicon	0.049	0.40 max.
Iron	0.19	0.50 max.
Manganese	0.009	0.30 max.
Magnesium	2.48	2.1 - 2.9
Zinc	5.49	5.1 - 6.1
Chromium	0.22	0.18 - 0.28
Titanium	0.028	0.20 max.
Zirconium	0.021	Other elements: 0.05 max. each, Other elements: 0.15 max. total
Vanadium	0.012	
Nickel	0.006	
Aluminum	remainder	

Surface Roughness: Drawing 70400-08116 requires a surface roughness of 125 maximum all over. Conversation with representatives of the US Army Aviation and Missile Command indicated that this requirement applied to the part before it was shot peened. Since all parts were received by ARL already shot peened, it was impossible to verify conformance to this requirement. However, surface roughness measurements were taken on all four components using the stylus technique, for comparative purposes. Data were measured using a Mitutoyo Surftest Analyzer 401 stylus apparatus, and were taken on surfaces that had the paint removed with methylene chloride. A total of ten readings were taken on each sample, with the first five readings oriented perpendicular to the remaining five readings. As Table 3 shows, the average values were similar in magnitude, and no deleterious trends were noted.

Table 3
Surface Roughness (R_a) Results

IT0011		IT0067		01344AI		1316HMW	
Reading	Ra	Reading	Ra	Reading	Ra	Reading	Ra
1	260	1	180	1	240	1	220
2	240	2	220	2	210	2	200
3	190	3	200	3	230	3	200
4	220	4	220	4	200	4	140
5	180	5	220	5	160	5	210
6	180	6	220	6	190	6	180
7	240	7	190	7	200	7	200
8	180	8	230	8	200	8	170
9	190	9	200	9	180	9	220
10	200	10	200	10	220	10	170
Average	208	Average	186	Average	203	Average	191

Hardness: The hardness of the components was measured and compared. The governing specification, MIL-H-6088 requires a hardness of 78 HRB minimum, for 7075 aluminum in the T73 condition. Readings were made in the grip region of the dogbone specimens used for tensile testing. The following table summarizes the results of five readings on each component. Each component met the governing requirements, and no deleterious trends were noted.

Table 4
Hardness Measurement Results (HRB Scale)

IT0011		IT0067		01344AI		1316HMW	
Reading	Ra	Reading	Ra	Reading	Ra	Reading	Ra
1	82.9	1	81.3	1	81.3	1	81.6
2	83.6	2	81.0	2	81.3	2	82.7
3	84.2	3	80.9	3	81.9	3	82.1
4	84.4	4	81.6	4	81.6	4	82.6
5	84.7	5	81.7	5	81.9	5	82.6
Average	83.4	Average	81.3	Average	81.6	Average	82.3
Requirement	78 min.						

Conductivity: Conductivity testing was performed to determine whether the components were properly aged. The governing specification (MIL-H-6088) lists a typical conductivity range of 40.0 – 43.0 %IACS. A total of five readings were taken on similar cross sections representative of each bridge. As shown in Table 5, the results conformed to the governing requirement. No significant difference was noted between the IT and OEM parts.

Table 5
Conductivity Measurement Results
%IACS

IT0011		IT0067		01344AI		1316HMW	
Reading	%IACS	Reading	%IACS	Reading	%IACS	Reading	%IACS
1	40.63	1	42.46	1	42.14	1	41.19
2	41.72	2	42.49	2	41.00	2	41.21
3	41.52	3	42.56	3	41.03	3	41.41
4	41.95	4	42.67	4	41.24	4	41.25
5	41.43	5	42.30	5	41.01	5	41.08
Average	41.45	Average	42.50	Average	41.28	Average	41.23
Requirement	40 - 43						

Metallography: Samples were metallographically prepared representing transverse and longitudinal orientations of part IT0011. The intent was twofold; to observe the presence (if any) of gross internal defects that may have led to premature failure, and to determine whether the part had been aged properly. The samples were rough polished utilizing silicon carbide papers of increasing grit number, followed by fine polishing consisting of diamond paste and alumina. The samples were examined in the as-polished condition. No gross defects of inclusions were observed within the samples, with the exception of “foldovers” which resulted from the shot peening process. The surface of each of the samples was examined. Metal foldover was observed within each sample. The samples were subsequently etched with Keller’s reagent, and examined. The structure was examined at both low and high magnifications, and appeared consistent with the typical structure of this alloy in this condition. Further microstructural characterization was conducted on all four components and is included in the TEM Analysis section of this report.

Tensile Testing: Tensile testing was conducted on a total of four specimens from each bridge. MIL-H-6088 does not list tensile property requirements, and indicates that the properties are governed by the engineering drawing. Since no requirement was noted on Drawing 70400-08116, typical values for this alloy are listed in Table 6. These typical values were referenced from the textbook, Aluminum: Properties and Physical Metallurgy [1]. No significant differences were noted between the IT and OEM parts, as the IT specimens exhibited both the lowest and highest strength. With respect to strength, it appeared only the IT0011 specimens met the typical values of this alloy and temper.

Table 6
Tensile Testing Results

Specimen	Area (sq. in.)	0.2% Y.S. (ksi)	UTS (ksi)	%Elongation	Modulus (x10 ⁶ psi)
IT0011 #1	0.0313	65.7	74.9	14.2	10.3
#2	0.0314	64.8	74.5	15.0	10.1
#3	0.0313	65.3	75.3	13.6	12.6
#4	0.0313	65.7	74.8	14.2	10.5
Average		65.4	74.9	14.3	
IT0067 #1	0.0313	60.0	70.6	12.6	12.9
#2	0.0314	59.1	70.9	13.0	14.6
#3	0.0312	60.4	71.1	13.1	10.6
#4	0.0314	60.2	71.0	13.6	10.7
Average		59.9	70.9	13.1	
01344AI #1	0.0314	58.8	69.7	13.4	10.3
#2	0.0313	57.0	68.7	16.5	10.4
#3	0.0313	61.5	71.9	16.3	10.3
#4	0.0313	61.6	72.0	14.3	10.1
Average		59.7	70.6	15.1	
1316HMW #1	0.0313	61.6	72.9	13.7	11.4
#2	0.0314	61.3	72.3	13.5	10.9
#3	0.0313	59.6	72.3	14.8	10.4
#4	0.0315	62.2	72.9	12.9	13.7
Average		61.2	72.6	13.7	
Typical 7075-T73		63.1	73.3	13	

Fatigue Testing: Fatigue testing was conducted on a total of five to six specimens from each bridge. The specimens were sectioned from the flanges. The testing was conducted at a frequency of 25 Hz, and an R-value of 0.1. A stress level of 45 ksi was utilized. The objective of this testing was to determine whether the base material of the IT parts had a similar fatigue resistance as the OEM parts. Since all specimens were fabricated similarly, this laboratory testing would eliminate such factors as surface asperities, and dimensional irregularities, and compare the actual base material of each component. There was considerable scatter in the results (as shown in Table 7), and no concrete conclusions could be drawn. The "inner" and "outer" in Table 7 refer to the location of the flanges.

Table 7
Fatigue Testing Results

Specimen	Diameter (inch)	Frequency (Hz)	R Value	Stress (ksi)	Cycles
IT0011 Inner #1	0.1495	25	0.1	45	Setup
#2	0.1495	25	0.1	45	69,837
#3	0.1495	25	0.1	45	74,676
IT0011 Outer #1	0.1500	25	0.1	45	77825
#2	0.1500	25	0.1	45	143,180
#3	0.1490	25	0.1	45	87,342
IT0067 Inner #1	0.1500	25	0.1	45	105,847
#2	0.1500	25	0.1	45	239,024
#3	0.1500	25	0.1	45	1,500,000+
IT0067 Outer #1	0.1500	25	0.1	45	707,433
#2	0.1500	25	0.1	45	334,010
#3	0.1500	25	0.1	45	105,858
01344AI Inner #1	0.1500	25	0.1	45	Setup
#2	0.1500	25	0.1	45	89,248
#3	0.1500	25	0.1	45	127,885
01344AI Outer #1	0.1500	25	0.1	45	1,000,000+
#2	0.1495	25	0.1	45	1,000,000+
#3	0.1505	25	0.1	45	72,130
1316HMW Inner #1	0.1495	25	0.1	45	314,130
#2	0.1500	25	0.1	45	162,292
#3	0.1495	25	0.1	45	475,112
1316HMW Outer #1	0.1495	25	0.1	45	299,996
#2	0.1495	25	0.1	45	66,374
#3	0.1500	25	0.1	45	69,280

Fractography: The morphology of the fracture surface of IT0011 was mapped, and SEM micrographs were taken to document the findings. The objective was to determine whether a surface or internal anomaly caused the premature failure of the IT0011 gear during fatigue testing. SEM photomacro- and micrographs were taken of the fracture surface containing the origin. River patterns were clearly discernable, leading directly to the origin, which was located on the surface (versus a subsurface origin). No gross defects were noted at the origin. The smearing below the origin was most likely a post-fracture occurrence. These findings were consistent with those of IL The fracture morphology was transgranular at the location, which is to be expected of this alloy under fatigue conditions. Fatigue striations were noted. These striations were approximately 0.323-inch from the origin. Striations were observed as close as 0.0375-inch from the origin. A transition between transgranular morphology and the ductile region characteristic of tensile overload was observed. A ductile dimpled morphology was noted in the tensile overload region. There were no gross internal or surface defects observed during SEM analysis.

Scanning electron microscopy was also beneficial in characterizing the shot peened surface of the failed bridge. The size of the dimples is an indication of shot peening intensity, which was later compared to those in the "Shot Peening Analysis" section.

TEM Analysis: To further investigate the possibility that the material structure varied between the IT and OEM components, a representative sample of each component was analyzed using transmission electron microscopy (TEM). The second phase precipitates within the matrix and grain boundaries of each component was analyzed. TEM specimens were prepared by cutting thin slices from the sample sections, followed by grinding to a thickness of 200 μ m. Discs 3mm in diameter were subsequently punched from this material, and electropolished in a 20% nitric-methanol electrolyte at -30°C. The specimens were examined using a Philips CM-12 electron microscope fitted with a Princeton Gamma Technologies (PGT) Energy Dispersive Spectroscopy (EDS) system. Table 8 summarizes the types of secondary phases noted within the samples.

Table 8
Secondary Precipitates

Secondary Precipitate and Comments	Sample Found Within
Coarse stringers of Al ₇ Cu ₂ Fe, evident in optical and SEM	IT0011, IT0067, 01344AI, 1316HWM
Coarse Al-Si oxide particles, evident in optical and SEM	IT0011, IT0067, 01344AI, 1316HWM
Fine (E-phase) dispersoids (Al ₁₈ Mg ₃ Cr ₂), evident only in the TEM	IT0011, IT0067, 01344AI, 1316HWM
Strengthening precipitates, evident only in the TEM	IT0067, 01344AI
Ultrafine, matrix strengthening precipitates, evident only in the TEM	IT0011, 1316HWM

Of these, it was not possible to determine differences in the size, density and distribution of the Al₇Cu₂Fe and Al-Si oxide particles in the TEM due to their coarse size. However, examination of the electro-polished TEM discs in an optical microscope did not reveal any significant difference between the samples.

The grain size varied from 1 to 5 μ m, for the IT0011 and 1316HWM material, but was larger for the IT0067 and 01344AI material (2 to 10 μ m). EDS was performed to characterize the chemical composition of the dispersoid and strengthening precipitates within each sample. It was determined that the median size of these particles was 450 Angstroms for sample IT0011, 750A for sample IT0067, 800A for sample 01344AI, and 800A for 1316HWM. These measurements should be considered only estimates based upon the different shapes of the dispersoids. A possible difference in the size of dispersoids could be due to differences in solutionizing treatment temperatures. A larger dispersoid would be associated with a higher solutionizing temperature. Since the dispersoid particles remain undissolved during the solutionizing treatment, they would coarsen at higher solutionizing temperatures. Attempts to estimate the volume fraction of the dispersoids from the TEM images did not provide reproducible results, presumably due to variations in specimen thickness and image shapes.

In short, sample IT0011 had an E-phase size about 50% smaller than the other three samples, most likely a factor of the prior solutionizing temperature. Other microstructural features such as size of the strengthening precipitates, width of the

precipitate free zone and the size and distribution of the coarse (Al₇Cu₂Fe, Al-Si oxide) particles were comparable.

Shot Peening Analysis: Note 4 of Engineering Drawing 70400-08116 states, “After final machining, shotpeen all over per SS8767 to 0.008A minimum intensity. Complete shotpeen coverage not necessary in areas noted. Overspray of these areas is permissible”. A review of the shot peening invoices for each of these components, revealed that each of the parts had been shot peened by one company, but at three separate locations. Both IT0011 and IT0067 were peened at a plant that was not identified on the Purchase Order, while 01344AI was peened at a plant in West Babylon, NY. The 1316HMW part was peened at a plant in Wyandanch, NY. Table 9 summarizes the parameters used by the shot peen vendor at each of their plants.

Table 9
Shot Peening Parameters

Plant	Shot Size	Intensity	Coverage
Unidentified (IT0011, IT0067)	CS-230	0.009A	100%
West Babylon, NY (01344AI)	CS 330R*/230R*	0.008-0.012A	200%
Wyandanch, NY (1316HMW)	CS 330/230	0.008-0.012A	200%
Requirement (Dwg. 70400-08116)		0.008A minimum	

* - R=Regular shot, 45-52 HRC

As shown in Table 9, variation existed as to shot size used, as well as the coverage. The IT parts were subjected to only the 230 sieve size cast steel shot, while the remaining parts were shot with 330, and 230 (as listed in Table A of SS8767, Rev. 5, a cast shot size of 330 has a sieve opening of 0.0331-inch, while a cast shot size of 230 has a sieve opening of 0.0234-inch). Therefore, the OEM components were peened with a coarse shot, followed by peening with the finer shot. This explains the 100% coverage for the IT parts, and the 200% coverage for the OEM components. It should be noted that 200% may be beneficial for compressive depth for this material [2].

IL believed that the intensity was excessive for part IT0011, since they reported that microcracking was prevalent on the surface of the part. However, generally speaking, the diameter of a peening “dimple” should be equal in magnitude to the intensity used to peen. With this in mind, several dimples on the IT0011 were measured. The resulting average of 0.0059-inch, was well below the 0.008 minimum intensity requirement. It appeared as if the intensity for the IT part was less than nominal, rather than excessive. Surface residual stress measurements were also taken within this area and the resultant values were lower than anticipated (refer to “Residual Stress” section). The same trend was noted for the OEM parts as well.

Additionally, a piece of material taken from part 01344AI was sent to a reputable vendor to shot peen under the following conditions: CS 230 shot size, 0.008 A minimum intensity and 100% coverage. This was used as a standard for comparative purposes. The piece was milled prior to shot peening. Subsequent to peening, there was no evidence of the “foldover”. The dimples on this piece had a larger diameter than those of

the IT parts, indicative of a higher intensity . A residual stress profile was also performed on this piece, and revealed that the compressive stress was nearly double that of the bridges. These results are located in the "Residual Stress" section.

Residual Stress: A technology for Energy Corp. (TEC) Model 1610 X-Ray Residual Stress Analysis System was used to characterize shot peened induced surface and subsurface residual stresses. All data were obtained utilizing the $\sin^2\psi$ stress-measuring technique with chromium $K\alpha$ radiation diffracted from the (311) crystallographic planes at a zero-strain peak position of $139^\circ 2\theta$. Surface measurements were performed on each component; subsurface measurements were performed on components IT0067 and 1316HMW and on test section 01344AI. Layer removal and stress gradient corrections were applied to the subsurface data per SAE J784a [3]. The longitudinal stress direction was arbitrarily chosen (the transverse direction was 90° clockwise from longitudinal). The area of measurement was as close to the fatigue crack initiation site as geometry would allow. Initial surface residual stress data from component IT0011 was observed to be approximately half the value of the other components (see Table 10). However, the other IT part (IT0067) exhibited the highest readings, suggesting that surface residual stress may not have played a part in the vastly different fatigue lives.

Table 10
Results of Surface Residual Stress Measurements
Actual Components

Component	Residual Stress ksi
IT0011 - Trans	-15.1
IT0011 - Long	-16.9
IT0067 - Trans	-27.9
IT0067 - Long	-27.4
01344 - Trans	-24.3
01344 - Long	-23.2
1316HMW - Trans	-26.4
1316HMW - Long	-25.0

Subsurface measurements were performed on a representative IT component (IT0067) and a representative OEM component (1316HMW). The purpose of this testing was to compare the residual stress values at increasing depth below the surface. Again, measurements were taken in the longitudinal and transverse directions. The results (Table 11) showed that the OEM component had a compressive layer of higher magnitude than the IT component. The IT component exhibited its highest compressive stress at 0.004 – 0.0045 inches in depth, while the OEM component exhibited its highest compressive stress at 0.007 – 0.0075 inches in depth.

Table 11
Results of Subsurface Residual Stress Measurements
Actual Components

Depth (inch)	IT0067		1316HMW	
	Longitudinal Residual Stress (ksi)	Transverse Residual Stress (ksi)	Longitudinal Residual Stress (ksi)	Transverse Residual Stress (ksi)
Surface	-11.3 ± 0.6	-8.7 ± 1.0	-8.6 ± 0.9	-7.0 ± 1.1
0.001 – 0.0015	-16.5 ± 0.5	-18.0 ± 1.7	-20.6 ± 0.5	-16.9 ± 3.5
0.002 – 0.0025	-22.1 ± 1.0	-20.4 ± 2.3	-22.0 ± 1.2	-24.8 ± 5.6
0.004 – 0.0045	-26.3 ± 1.4	-23.3 ± 2.8	-28.6 ± 3.5	-25.5 ± 5.2
0.007 – 0.0075	-20.4 ± 2.0	-16.7 ± 4.1	-30.3 ± 4.1	-29.9 ± 2.7
0.012 – 0.0125	-1.4 ± 1.4	-5.3 ± 0.9	-3.0 ± 1.6	-5.1 ± 2.4
0.018	0.0 ± 1.1	-1.0 ± 2.0	-0.8 ± 2.8	-1.3 ± 2.9
0.0235 – 0.024	0.3 ± 1.0	-2.4 ± 1.8	-2.5 ± 0.5	-1.4 ± 4.7
0.0295 – 0.030	-4.1 ± 1.0	-3.4 ± 1.6	-0.1 ± 0.5	0.1 ± 1.6

Generally, the magnitude of the compressive stress should equal approximately 60% of the UTS for this alloy [2]. Appropriately, this material should have had a compressive stress approaching 44 ksi. The highest subsurface stress measured by x-ray analysis was -30.3 ksi, which was approximately 30% lower than nominal.

The residual stress of the “standard” shot peened by Metal Improvements was also determined. The readings were measured to a depth of 0.0150-inch. As shown in Table 12, the magnitude of the compressive stress throughout the standard was greater than both the IT and OEM components. The “60% of the UTS” maximum residual stress observed was comparable to the rule of thumb.

Table 12
Results of Subsurface Residual Stress Measurements
Test Section from Component 01344AI

Depth (inch)	Residual Stress (ksi)
Surface	-38.10
0.0005	-46.21
0.0015	-46.30
0.0025	-47.88
0.0050	-38.06
0.0095	-8.08
0.0150	0.97

Discussion:

Preload During Fatigue Testing: It was reported to ARL from Wayne Rainey of AMCOM that the pre-loads were "very much" higher in the IT components that were fatigue tested. This was detected in strain gages located in the area of failure upon loading of the parts into the test fixture during a static survey. The fact that the preloads were higher in the IT components served as an indicator that a dimensional discrepancy may have been present somewhere on these parts. This was verified when the thickness of each component was measured at the location of the fracture and the IT components were found to be significantly lower. The extent to which the difference in thickness affected the fatigue results should be investigated through a stress analysis of the area of concern.

Shot Peening: A concern about the integrity of the peened surface of the IT components was raised by IL. It was reported by IL that evidence of broken shot was detected along with microcracks on the surface which in turn suggested a higher than acceptable shot peening intensity. This prompted ARL to research these claims in depth. The results indicated that the intensity may have been too low as substantiated by low residual stress values of the shot peened surface of all components, IT and the OEM. The values obtained were compared to that of a shot peened "standard" provided by Metal Improvements, the vendor that shot peened both the OEM and IT components utilizing the same parameters that were used on the components. The residual stress results clearly indicate that the shot peening operation performed on the IT and OEM components resulted in surface residual stresses that were below the standard. It is important to note that the standard was fabricated from material taken from OEM component 01344AI in which the surface was milled prior to shot peening to remove any previous effects of fabrication. Microcracks and broken bits of shot were not observed by ARL on either the OEM or IT parts. What was detected was significant evidence of "foldover" on both the OEM and IT components, which may have been misinterpreted as microcracks. Foldover can be caused by directing the shot at an angle, but since it was observed on all four components, it was not believed to have contributed to the difference in fatigue results.

Another important observation made on all four parts was the non-uniformity of the shot peened surface through visual examination. The extent to which this may have affected the residual stress pattern of each component was not investigated because of the time and expense involved and due to the fact that the residual stresses were measured adjacent to the fracture zones on all four components. The fracture zone is the area of concern, and the remaining surfaces would not be involved in reducing the fatigue life, but the issue should be raised that uniformity of the shot peened surface could play a role in fatigue life.

References:

- [1] Aluminum: Properties and Physical Metallurgy, Edited by John E. Hatch, American Society for Metals, Metals Park, Ohio, 1984, p. 364.
- [2] Personal conversation with Win Welsch, 9/15/99, during meeting at ARL, APG, MD
- [3] Residual Stress Measurement by X-Ray Diffraction – SAE J784a, Society of Automotive Engineers, Warrendale, PA, 1971.

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