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X-Ray Diffraction Stress Analysis As an NDE Technique

Abstract

Plating processes are of the utmost importance to the Naval Air Rework Facilities as a means of prolonging the useful life of a part. Plating and associated processes, however, can reduce the effective fatigue life of a component. Since residual stresses are closely related to the fatigue response of a material, a series of experiments was performed to determine the optimum stress level produced by four different processing techniques. Twenty-eight 4340 steel samples were nickel plated according to standard plating operations. The samples were divided into four groups representing different processing methods: standard grinding, standard machining, abusive grinding, and abusive machining. X-ray diffraction residual stress analysis indicated that the standard and abusive grinding processes produced low surface stresses while the standard and abusive machining processes produced compressive stresses. In general, compressive surface stresses enhance fatigue properties. Fatigue testing of the samples confirmed that the compressive stresses induced by the machining operations improved fatigue life when compared to the grinding processes. X-ray diffraction stress analysis can be effectively utilized for process control and determination of remaining life in plated parts.

Introduction

Nickel-plated fatigue samples were analyzed and evaluated in an attempt to compare fatigue life to residual stress levels. Twenty-eight samples were supplied by the Naval Air Rework Facility (NARF) at Pensacola, Florida, for the residual stress analysis and fatigue testing program. The button-head, dog-bone samples had been fabricated in conformance to drawings supplied by Metcut Research Associates for low-cycle, axial fatigue testing (Figure 1). The samples were made of 4340 steel, heat treated to a hardness of 35 Rockwell C with a specified surface finish of 32 RMS. Each sample was subjected to magnetic particle inspection and then shot peened following NARF Pensacola standard preplating operations. The samples were then nickel-plated to a thickness of 0.010 inches per side and divided into four groups of seven samples each. Five mils (0.005 inches) was removed from each sample by the following methods:

Group A: Standard Grinding
Group B: Abusive Grinding (coolant cut off intermittently and greater infeed)
Group C: Standard Machining
Group D: Abusive Machining (coolant cut off and varied feed and speed)

The testing program consisted of stress analysis on the samples followed by fatigue testing. Post-fatigue test stress analysis was then performed.

Measurements

The samples were first analyzed for residual stresses. Measurements were made in the center of the gage length in the axial direction using Cr K_{β} radiation. Five Ψ tilts ranging from -43° to +43° were selected, and a Ψ−angle oscillation of $\pm 2°$ was used to reduce the effects of preferred orientation.

After stress analysis, the samples were sent to Metcut Research Associates, Inc. for fatigue testing. Room temperature, high-cycle fatigue tests were performed, using a sinusoidal waveform at a frequency of 35 Hz. Stress versus cycles-to-failure (S/N) curves were developed for each group.

The samples were then returned to Technology for Energy Corporation for post-fatigue test stress analysis. Stress measurements were repeated following the same procedure used during initial testing.

Results and Discussion

The residual stresses and the fatigue test results are tabulated in Tables I and 2. Figure 2 shows the S/N curves generated from the fatigue test data. Figures 3, 4, 5 and 6 depict the failure location for each sample.

The stress analysis data show that, in general, the standard and abusive grinding results in low stresses and the standard and abusive machining results in compressive stresses as shown in Figure 7. As a group, there was no apparent difference between the standard and abusive processing in terms of their surface residual stresses. Additionally, there was no overall difference in stress levels before and after fatigue testing. All of the abusively ground and machined samples (Groups B and D) had the same stress level within one sigma error bar before and after fatigue testing. Half of the standard grinding and machining samples (Groups A and C) had the same stress levels within one sigma error bar before and after fatigue testing. The remaining samples all agreed within two sigma error bars except for sample C5. In this one case, the pre-fatigue test stress was 53 ± 9 ksi while the post-fatigue test stress was 88 ± 4 ksi, which are the same values within a three sigma error bar. This result indicates that fatigue testing, under the controlled conditions used, did not affect the residual stress level.

Figure 8 shows the diffraction peak width at half of its maximum intensity (FWHM) averaged from the data in Table 1. The FWHM indicates the relative amount of cold working in the sample surface. As expected, the general trend showed a slightly larger FWHM (more cold working) in the samples after fatigue testing.

Fatigue testing indicated the standard and abusively machined samples had a higher fatigue resistance when compared to the standard and abusively ground samples. Since unplated samples were not tested, it is not known what effects, if any, the plating had on the fatigue properties of the 4340 base material. The surface residual stress affects the fatigue performance of a component. Case histories of such effects can be found in such publications as the ASTM

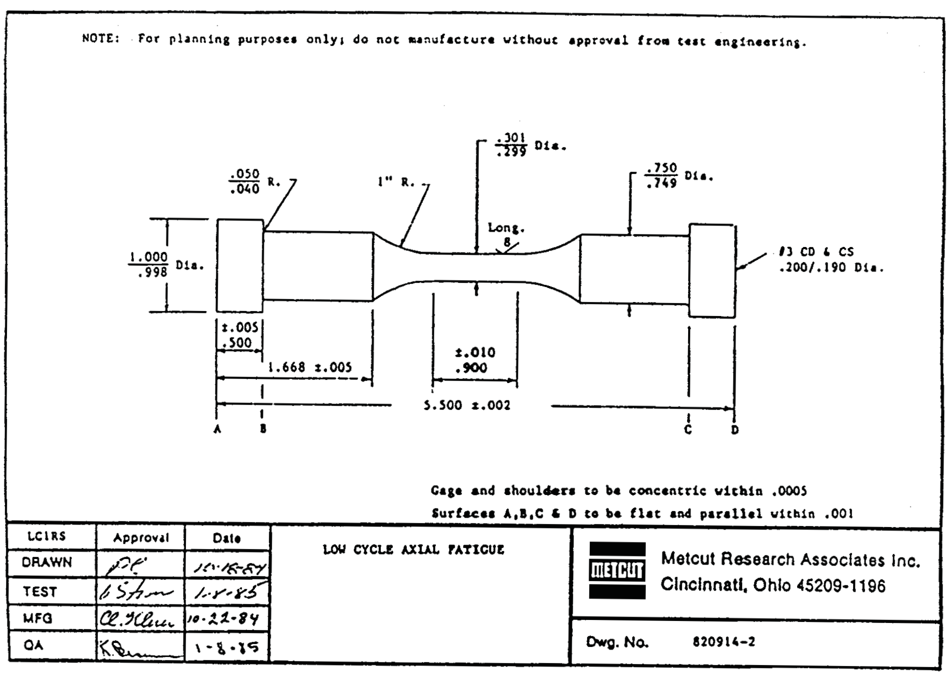

Figure 1 - Button-Head Dog-Bone Sample for Low Cycle Axial Fatigue Testing.

Table 1

Surface Residual Stresses in Nickel-Plated Fatigue Samples

Sample I.D.	Process	Pre-Fatigue Testing Stress, ksi	Pre-Fatigue Testing FWHM, °2θ	Post-Fatigue Testing Stress, ksi	Post-Fatigue Testing FWHM, °2θ
A1	Standard	− 5.3 ± 9.7	2.3	− 9.1 ± 9.2	2.5
A2	Grinding	− 8.2 ± 7.1	2.2	−12.0 ± 8.7	2.9
A3		+ 1.1 ± 4.6	2.1	+11.5 ± 3.7	2.3
A4		− 9.0 ± 4.0	2.2	+ 3.8 ± 6.3	2.1
A5		−10.3 ± 13.2	2.4	+ 5.3 ± 11.3	2.6
A6		− 5.1 ± 4.7	2.4	−23.6 ± 4.5	2.2
A7		− 5.7 ± 5.8	2.3	−33.6 ± 17.7	2.4
B1	Abusive	− 9.6 ± 7.4	2.2	− 6.7 ± 10.1	2.4
B2	Grinding	−13.2 ± 7.9	2.4	−20.4 ± 11.6	2.4
B3		−27.2 ± 11.1	2.4	+36.4 ± 10.0	2.5
B4		−36.2 ± 3.4	1.8	−31.3 ± 6.2	1.8
B5		+ 1.3 ± 4.7	2.2	−10.9 ± 13.6	2.5
B6		− 0.5 ± 6.1	2.1	− 9.5 ± 4.5	2.2
B7		− 9.1 ± 8.9	2.3	− 7.1 ± 10.7	2.6
C1	Standard	−64.5 ± 12.6	2.3	−46.8 ± 10.6	2.4
*C2	Machining	−64.7 ± 12.9	2.3	−97.8 ± 14.6	2.9
C3		−72.8 ± 10.0	1.9	−81.3 ± 13.1	2.6
C4		−77.3 ± 10.9	2.4	−49.1 ± 13.3	2.4
C5		−53.0 ± 8.7	2.2	−88.3 ± 3.6	2.7
C6		−23.4 ± 16.5	2.1	−33.9 ± 10.6	2.7
C7		−38.4 ± 10.1	2.3	−21.5 ± 10.8	2.5
D1	Abusive	−46.9 ± 7.0	2.3	−46.6 ± 10.2	2.4
D2	Machining	−74.9 ± 24.3	2.3	−61.9 ± 12.8	2.7
D3		−17.0 ± 5.2	2.3	−36.0 ± 19.9	2.4
**D4		+12.1 ± 7.5	1.8	+ 3.1 ± 9.0	2.2
D5		−31.2 ± 9.7	2.3	−35.9 ± 8.1	2.6
D6		−42.9 ± 9.3	2.2	−45.5 ± 10.2	2.6
D7		−53.3 ± 10.8	2.3	−70.2 ± 7.2	2.9

* Sample overloaded during fatigue test resulting in a void test.
**Sample in the as-plated condition.

Table 2

Axial Fatigue Data Summary
Nickel-Plated 4340 Steel
$75^{o}F$ 35 Hz. A = Infinity

Test No.	Specimen No.	Temp. (^{o}F)	Stress Max.	(ksi) Alt.	Cycles (X10^3)	Results	Test Hours
			Standard Grinding				
1	A1	75	80	80	33.3	Failure	.3
2	A2	75	70	70	67.5	Failure	.6
9	A3	75	60	60	28.7	Failure	.2
13	A4	75	50	50	38.2	Failure	.4
16	A5	75	40	40	218.4	Failure	1.8
21	A6	75	30	30	184.9	Failure	1.5
25	A7	75	15	15	10,758.1	Runout	85.4
			Abusive Grinding				
3	B1	75	80	80	13.0	Failure	.1
6	B2	75	70	70	76.2	Failure	.7
10	B3	75	60	60	36.8	Failure	.3
14	B4	75	50	50	30.8	Failure	.3
22	B6	75	45	45	213.1	Failure	1.7
23	B7	75	42	42	51.7	Failure	.4
17	B5	75	40	40	10,876.2	Runout	86.3
			Standard Machining				
4	C1	75	80	80	53.8	Failure	.6
26	C7	75	70	70	392.0	Failure	3.4
15	C4	75	70	70	2,283.3	Failure	18.1
24	C6	75	60	60	246.6	Failure	1.9
12	C3	75	60	60	916.8	Failure	7.2
19	C5	75	50	50	10,025.5	Runout	79.6
			Abusive Machining				
5	D1	75	80	80	10.9	Failure	.1
8	D2	75	70	70	46.7	Failure	.4
28	D7	75	70	70	10,338.0	Failure	80.7
18	D4	75	65	65	27.5	Failure	.4
27	D6	75	65	65	408.1	Failure	3.3
11	D3	75	60	60	6,016.2	Failure	47.7
20	D5	75	60	60	11,000.0	Runout	85.9

Note: Specimen No. C-2 ran 332,700 cycles at 70 ksi when due to a controller malfunction, the specimen was overloaded in compression. Void test.

P/A stress calculation based on gross area.

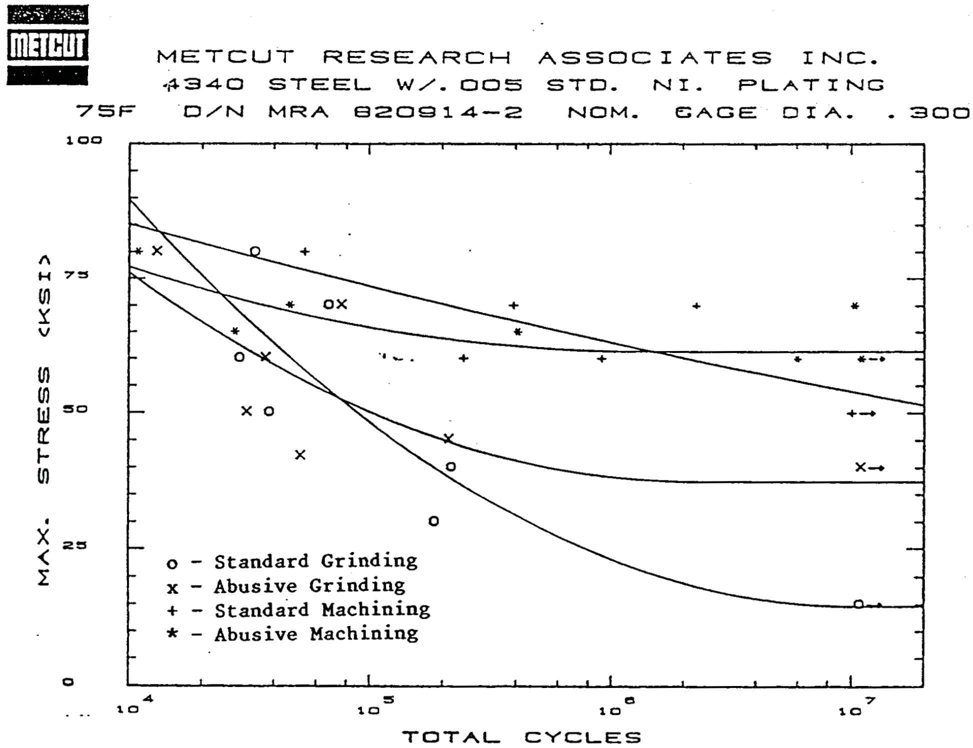

Figure 2. S/N Curves for All Samples.

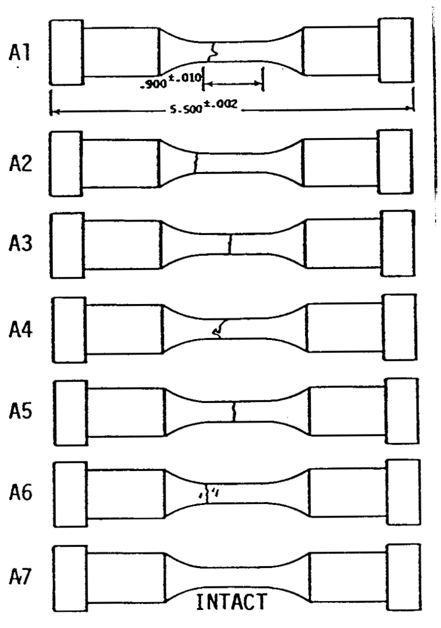

Figure 3. Failure Locations for Group A.

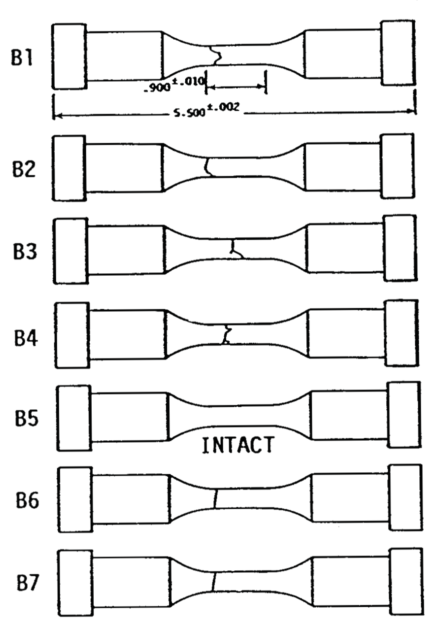

Figure 4. Failure Locations for Group B.

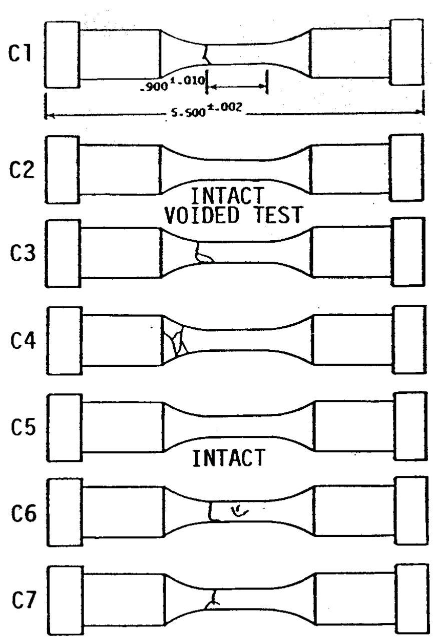

Figure 5. Failure Locations for Group C.

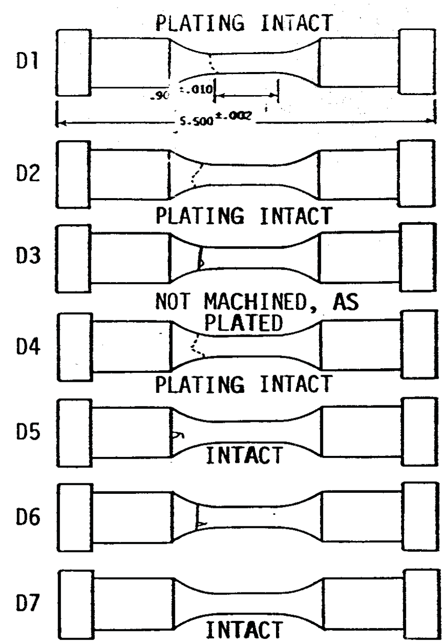

Figure 6. Failure Locations for Group D.

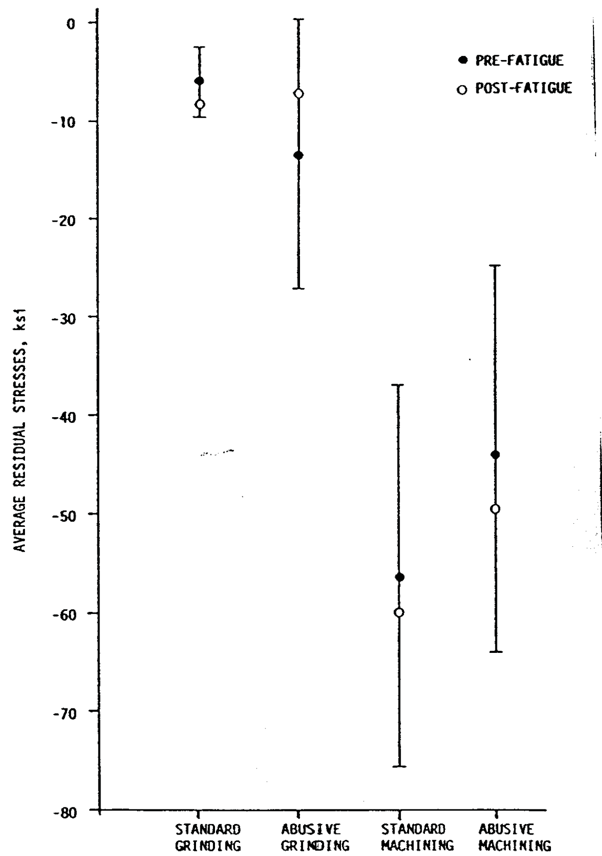

Figure 7. Average Residual Stress Versus Processing.

Special Technical Publication, STP776, "Residual Stress Effects in Fatigue."

In general, compressive stresses improve fatigue life [1]. This generality does, however, depend upon the type of cyclic load encountered. The standard and abusively machined samples that had the compressive residual stresses did show an improved fatigue life compared to the ground samples.

Conclusions

The machined samples had an improved fatigue life compared to the ground samples. This improvement was attributed to the compressive residual stresses measured in the machined samples.

There was no apparent difference in the standard versus abusive processing based on the residual stress levels. Furthermore, residual stress levels did not change significantly as a result of fatigue testing.

Reference

1. Glinka, G., "Residual Stresses in Fatigue and Fracture: Theoretical Analyses and Experiments," Advances in Surface Treatments, Volume 4 Residual Stresses, Pergamon Press, Oxford, 1987, pp. 413 ff.

Acknowledgment

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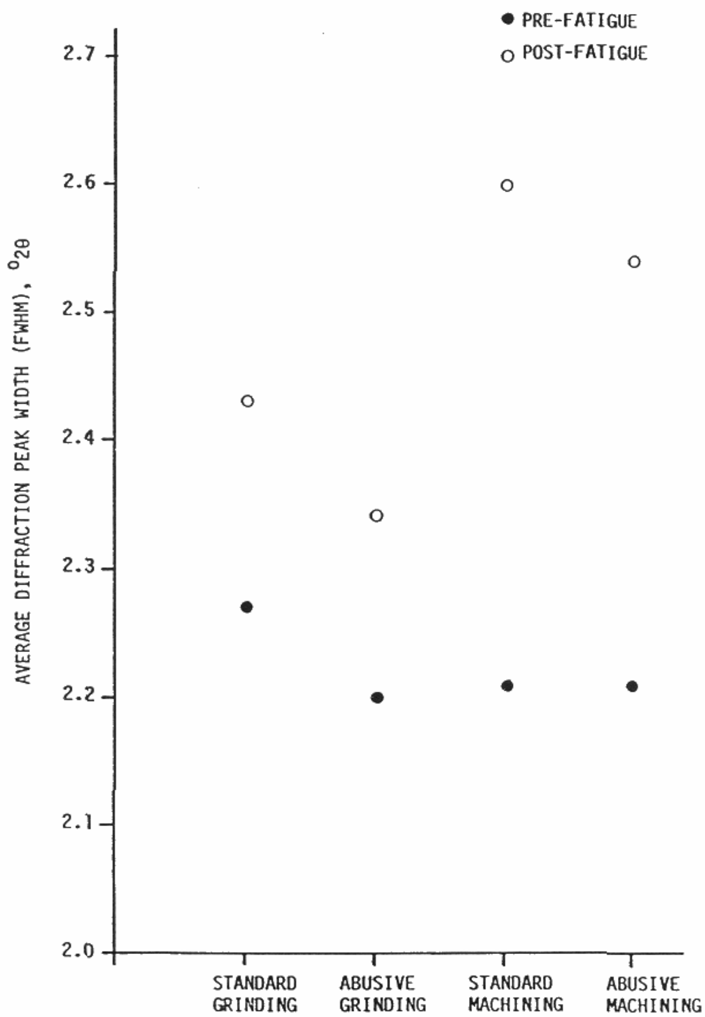

Figure 8. Peak Width Versus Process.