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IMPACT TO U.S. ARMY FATIGUE QUALIFICATION FROM SHOT PEEN PROCESS VARIATION

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Abstract: The U.S. Department of Defense defines a critical safety item (CSI) on a rotary or fixed wing aircraft as a component, which if missing or failed, will result in the loss of crew or aircraft. Many CSIs are fatigue critical and depend on shot peening to enhance fatigue life and lessen the impact from field induced nicks and gouges. U.S. Army policy has required full-scale component fatigue testing to establish retirement times for CSIs. This policy includes alternate sources of new CSIs or refurbished components, which must meet the airworthiness requirements of the original equipment manufacturer part in order to maintain fleet reliability. But full-scale component fatigue testing is, in general, very time consuming and expensive.

A summary is presented of the test plan developed by the Aviation Engineering Directorate of the U.S. Army Research, Development, and Engineering Command, carried out in conjunction with the U.S. Army Research Laboratory, to determine the effects of shot peen process variations on compressive residual stress, surface roughness, and fatigue strength of four metals commonly used in U.S. Army helicopter CSIs. A goal was to reduce fatigue test requirements where the only change was in the shot peen source and/or equipment.

In Phase I of the study, shot peen variability tests were conducted to evaluate the effects of fundamental parameters, including air pressure, impingement angle, media flow rate, and nozzle distance, on peening intensity as measured with conventional steel Almen strips. Both peened and unpeened specimens were used for fatigue strength comparison. Specimens for each selected material were also evaluated for surface roughness and compressive stress profile through the depth using X-ray diffraction. Results of Phase II are presented in this paper for Ti-6AL-4V and 4340 and 9310 Steel materials, with a summary of Phase I.

The results show that fatigue testing is not a preferred way to validate shot peen process effectiveness. The U.S. Army is moving, in general, to validation of shot peen processing through examination of surface roughness and compressive stress profile by X-ray diffraction, in conjunction with typical Almen strip use on different locations, with extra emphasis on geometrically difficult areas and fatigue critical areas.

1 INTRODUCTION

Shot peening has been used to enhance fatigue and damage tolerance of metallic components, which includes enhanced wear performance and decreased susceptibility to fretting, spalling, galling, stress corrosion cracking, and other minor handling or environmental damage on rotorcraft dynamic components [1]. Drawing specifications for peening control typically include type of shot media and size, intensity, and coverage.

For critical safety items (CSIs) where the benefits of shot peening are used to determine component retirement time, current U.S. Army aviation policy requires that shot peening is designated as a critical characteristic (CC), which requires 100% verification during manufacture or overhaul. Also, only approved sources may be utilized for manufacture or overhaul. Once a shot peening source has been approved for a particular CSI, the shot peening process must be "frozen," and any subsequent deviation requires review by the Army [2, 3]. Also, until this study, U.S. Army policy required fatigue testing of two components as part of the procedure to validate shot peen process effectiveness and qualify a source for that particular CSI. Such testing is relatively expensive both in time and money, and the Aviation Engineering Directorate (AED) of the Army Aviation and Missile Research and Development Center (AMRDEC) was tasked to determine more cost effective ways to qualify shot peen vendors.

In order to more fully understand the impact of shot peening process variability on fatigue strength, the Army Research Laboratory Weapons and Materials Research Directorate (ARL-WMRD) was tasked to execute the coupon fatigue test program developed by AMRDEC. AMRDEC then evaluated the shot peening sensitivity and impact to fatigue strength on the selected aerospace materials. These materials represent the four most common materials used on Army aviation shot peened components. The program was divided into two phases with different objectives. Phase I used standard Almen strips to assess variation in shot peening intensity expected from various shot peening parameters. Phase II assessed fatigue strength at prescribed shot peening intensities, and correlated surface roughness and x-ray diffraction residual stress analysis data to those prescribed intensities.

Based on the results of the Almen strip study of Phase I and typical component drawing requirements, specific peening intensities were applied to fatigue and residual stress test coupons in Phase II. Resulting fatigue strength, surface roughness, and compressive residual stress measurement (RSM) profile under these conditions were evaluated. Conclusions and recommendations regarding the U.S. Army current policy in qualifying shot peening vendors are discussed in section 5.

2 MATERIAL SELECTION

In Phase I, four (4) commonly shot peened aviation materials were selected for the shot peening intensity variation and fatigue testing evaluations. The materials and their characteristics are presented in Table I. All stock for each material type was from the same heat treat lot. Fatigue test coupons and residual stress profile discs were machined to the same specifications from the same machining source.

Table I. Materials for Shot Peening Intensity Variation Study

Material	Specification	Material Strength Supplier (KSI)	Material Strength ARL Tested (KSI)	Material Hardness
Aluminum 7075-T73	AMS-QQ-A 225/9	77.6 UTS 67.0 YS	80 UTS 71 YS	80-81 HRB
Titanium-6Al-4V Beta STOA Cond.	AMS-4928Q	153 UTS 145 YS	149 UTS 144 YS	34 HRC
4340 Steel 150-170 KSI	AMS 6415	162 UTS 149 YS	167 KSI 154 YS	335/341 BHN
9310 Steel 150-190 KSI	AMS 6260	189 UTS 155 YS	190 UTS 156 YS	38-40 HRC

The peening intensity study for the 7075-T73 Aluminum is not addressed in this paper because the fatigue testing is not fully accomplished. The Aluminum results will be presented at a later date.

3 SHOT PEENING INTENSITY STUDY

3.1 Technical Approach

Two shot peen vendors were used in Phase II, each vendor having slightly different equipment capability. Vendor #1 established the peening intensities that were intended for use on the fatigue and RSM specimens. For titanium, the test plan required peening at two different intensities in accordance with (IAW) AMS-S-13165 [4]. The peening intensity range of 8A to 12A required the use of S170 cast steel shot and coverage of 200%. The second peening intensity range was 5N to 11N using S70 cast steel shot, with a coverage requirement of 200%. AMRDEC required development of peening procedures that achieved nominal intensities of 10A ± 0.5A and 8N ± 0.5N (9.5N actual) for the applicable saturation curves. Upon successfully completing this requirement, Vendor #1 provided the process sheets used to achieve the nominal intensities to ARL and AMRDEC for review. The peening parameters used to achieve the nominal peening intensities were varied as specified below. Each parameter was changed independently, not in combination with any other listed or unspecified peening parameter, and the process was performed on 3 Almen strips. The intent was to approximately double the standard production tolerance(s) for a given peening parameter for each of the specified incremental variations. All 3 Almen strips for each of the 4 listed parameters were peened consecutively without further modifications to the machine, including the nozzle. The peening time used was held constant at the “2T” time as determined by the applicable saturation curve. Intensity verification strips per paragraph 4.2 of AMS-S-13165 also were peened at the “2T” value both prior to, and after making the changes detailed below for each of the four parameters. Coverage on all Almen strips was verified to be a minimum of 100% via visual inspection. Slight modifications to the plan were made when a prescribed parameter level was beyond that which could be achieved or reliably controlled by Vendor #1.

i) Impingement Angle: the peening angle was increased or decreased from the nominal angle in 10º increments (2 times a typical production tolerance) to encompass a range of impingement angles from 20º to 90º. For example, for a given impingement angle of 70º (with a production tolerance of ± 5º), 3 Almen strips would be peened at each impingement angle of 80º and 90º, as well as impingement angles from 60º to 20º. If the nominal impingement angle used was 85º to 90º, then the impingement angle was only decreased, in 10º increments to approximately 20º**.**

ii) Air Pressure: the nominal air pressure was increased and decreased in two 20% increments. For example, 60 psi nominal pressure was varied to pressures of 72 and 84 psi, as well as 48 and 36 psi.

iii) Media Flow Rate: media flow rate was increased to 120% and 140% of the nominal value, and decreased to 80% and 60% of the nominal value. Flow rate was found not to be adjustable by Vendor #1, other than by changing the air jet size, thereby giving actual differences ranging from 95% to 238% of the nominal value depending on the particular shot size.

iv) Stand Off/ Nozzle Distance: nominal nozzle distances were increased and decreased to 157% and 128%, and 71% and 42% respectively of the baseline value. Greater percentages were used for this parameter due to its limited effect on peening intensity.

Again, during the study, the parameters were varied independently, not in combination with values in adjacent columns. When a parameter was set at a level other than its nominal value the other three parameters were held at their respective nominal value. Table II presents the media shot sizes, materials, and nominal intensity requirements for the Almen strip study.

Table II. Media Shot Sizes and Intensities.

Media Shot Size	Material	Associated Intensity	Nominal Intensity Requirement
S70	Ti-6AL-4V	5 to 11N	8N ± 0.5N (9.5N act'l)
S110	4340 and 9310	8 to 12A	10A ± 0.5A
S170	Ti-6AL-4V	8 to 12A	10A ± 0.5A

3.2 Peening Intensity Study Results

A summary of findings from [5] is included here:

- Changes to air pressure and nozzle angle had the greatest effect on intensity.
- Air pressure exhibited nearly linear behavior regarding intensity until the maximum intensity for a particular size was achieved.
- Changes in nozzle/impingement angles have a pronounced effect at low angles and very little effect at angles greater 65°. At low angles, this effect is almost parabolic, implying the lower the angle, the greater the effect.
- Intensity and media flow rate rates are inversely proportional.
- Nozzle distance has a limited effect on intensity. The effect is inversely proportional.

4 FATIGUE/RSM-XRD/SURFACE ROUGHNESS STUDY

Phase II of this study includes coupon fatigue testing, X-Ray Diffraction residual stress measurement, and surface roughness evaluation of the selected materials. The peening intensities selected for each material were based on the shot peening parameter study made in Phase I.

Based upon those results and component drawing requirements for the individual materials used in this study, AMRDEC defined specific peening intensities in order to investigate the resulting fatigue strengths and relate them to profiles of Residual Stress Measurement (RSM) by X-Ray Diffraction (XRD) and Surface Roughness measurements under identical conditions. Unpeened specimens were used, as well as specimens peened to four different values. Peened specimens used two intensities, one each at the upper and lower bounds of drawing specifications, plus one higher and one lower. When a drawing specified peening intensity value exceeded that of an intensity measurement achieved during the process parameter study, the drawing specified value was used to determine the high intensities.

4.1 Test Plan

Three stress intensities, $K_t = 1$, $K_t = 1.75$, and $K_t = 2.5$, were used for each material for the fatigue strength assessment. The specimen geometries were based not only upon the stress intensity requirements (comparison to typical CSI geometry details) but also on the fatigue test frame capabilities at ARL. Details for the specimens used are illustrated in [6]. Tests were performed with sinusoidal oscillation at a frequency of 20 Hz and at an R-ratio, minimum to maximum stress, of 0.1. All tests were conducted at room temperature in air. The run-out stop point was chosen to be 2 million cycles based upon program completion calendar time requirements.

The Ti-6AL-4V Beta STOA alloy was tested at two intensity levels. The shot peening was conducted at 3N, 5N, 11N, and 14N for the lower intensity shot peening, and at 4A, 8A, 11.5A, and 12.2A for the higher intensity shot peening. Specimens were shot peened by Vendor #1 except the 12.2A which was done at Vendor #2 based upon their capabilities. A total of 240 specimens were tested.

The 4340 and 9310 steels were tested at intensities of 4A, 8A, and 12A. Specimens at 4A and 8A were shot peened by Vendor #1 and Vendor #2. Specimens at 12A were shot peened at Vendor #2 based upon their equipment capability. A total of 180 specimens were tested for each material.

RSM by XRD were performed on the disk specimens at the center and at a radial outward location (henceforth referred to as the edge) that was 0.20 inches from the center on the 0.75-inch diameter aluminum and titanium specimens and 0.35 inches from the center on the 1.0-inch diameter steel specimens. The orientation of the edge measurement location around the disk specimens was arbitrarily chosen. Measurements were made on the fatigue specimens at 0.45 inches from the notch at an arbitrarily chosen 0º orientation and at 120º and 240º from that location. Residual stresses were measured only at the surface on the fatigue specimens and at the surface and at five depths (1, 2, 5, 7, and 10 mils) from the surface on the disk specimens. The subsurface residual stress fields were characterized on the disks by alternately performing RSM and then electropolishing away layers of material.

Three disks, approximately 0.375 inches thick and equal to the diameter of the stock used, were peened along side the fatigue specimens for each peening condition. Three linear surface roughness measurements were taken across the diameter of each disk at 120º increments. Additionally, two K_t = 1 specimens from each group and two K_t = 1.75 or K_t = 2.5 specimens were selected to obtain surface roughness data. For the fatigue specimens, three linear measurements were acquired at 120º increments around the circumference in the peened area. For the K_t = 1.75 or K_t = 2.5 specimens, the data was acquired along the outside diameter (OD), not within the notch.

4.2 Fatigue Test Results

Graphical representations of fatigue test data are depicted in Figures 1-3 for each material. The fatigue data were fitted with a common S/N curve shape, $S / E_N = 1 + \beta / N^{\gamma}$, where β and γ were based on the best fit to the test curve. The test data and curve fitting for the endurance strength versus the peening intensity are also illustrated in Figures 1-3 with the endurance tabulated in Table III. The endurance values are defined at 10 million cycles.

Table III, Fatigue Endurance Strength of Ti-6AL-4V, and 4340 and 9310 Steels

	TI-6Al-4V Kt=1			1.00E+07	TI-6Al-4V Kt=1.75			TI-6Al-4V Kt=2.5		
	Intensity	Endurance	COV(%)	% Change	Endurance	COV(%)	% Change	Endurance	COV(%)	% Change
	Unpeened	124.25	0.86%		87.29	0.59%		67.23	2.33%	
Vendor #1	L1-3N	129.08	1.11%	3.88%	96.22	4.53%	10.23%	67.94	2.10%	1.06%
Vendor #1	L2-5N	130.54	0.45%	5.06%	91.87	3.03%	5.25%	69.07	1.13%	2.74%
Vendor #1	H1-11N	128.44	0.67%	3.37%	89.14	1.98%	2.12%	69.19	1.12%	2.92%
Vendor #1	H2-14N	129.90	1.15%	4.54%	88.80	3.71%	1.74%	66.52	2.23%	-1.05%
Vendor #1	L1-4A	125.98	0.78%	1.39%	84.93	2.57%	-2.70%	63.09	1.83%	-6.16%
Vendor #1	L2-8A	124.70	0.55%	0.36%	84.70	2.24%	-2.96%	63.74	3.75%	-5.19%
Vendor #1	H1-11.5A	122.58	0.81%	-1.35%	84.18	3.71%	-3.56%	64.76	2.18%	-3.68%
Vendor #2	H2-14A	121.82	0.64%	-1.96%	82.76	1.29%	-5.19%	62.03	3.20%	-7.73%
Maximum Variation				6.50%			7.31%			10.65%

	4340 Steel Kt=1			1.00E+07	4340 Steel Kt=1.75			4340 Steel Kt=2.5		
	Intensity	Endurance	COV(%)	% Change	Endurance	COV(%)	% Change	Endurance	COV(%)	% Change
	Unpeened	129.34	0.85%		87.45	0.84%		65.94	3.80%	
Vendor #1	L1-4A	137.64	2.24%	6.42%	92.25	3.55%	5.49%	69.19	0.77%	4.92%
Vendor #1	L2-8A	137.33	1.69%	6.17%	87.84	1.48%	0.45%	69.09	1.06%	4.78%
Vendor #2	L1-4A	137.74	1.23%	6.49%	88.84	2.54%	1.59%	69.20	2.17%	4.94%
Vendor #2	H1-8A	135.31	1.23%	4.62%	86.36	1.14%	-1.25%	67.06	3.08%	1.71%
Vendor #2	H2-12A	134.39	2.19%	3.90%	84.03	2.58%	-3.91%	67.72	2.16%	2.70%
Maximum Variation				2.59%			9.40%			3.23%

	9310 Steel Kt=1			1.00E+07	9310 Steel Kt=1.75			9310 Steel Kt=2.5		
	Intensity	Endurance	COV(%)	% Change	Endurance	COV(%)	% Change	Endurance	COV(%)	% Change
	Unpeened	140.07	1.40%		108.49	1.08%	(??)	64.05	1.41%	
Vendor #1	L1-4A	143.67	1.68%	2.57%	90.14	2.41%	-16.91%	72.71	3.77%	13.52%
Vendor #1	L2-8A	139.83	2.16%	-0.17%	93.10	2.37%	-14.19%	70.80	1.97%	10.54%
Vendor #2	L1-4A	144.85	0.48%	3.42%	96.30	3.24%	-11.24%	71.85	3.12%	12.19%
Vendor #2	L2-8A	141.14	0.72%	0.77%	85.86	4.47%	-20.85%	70.71	2.71%	10.40%
Vendor #2	H1-12A	138.35	3.21%	-1.23%	85.61	4.21%	-21.08%	68.34	4.02%	6.70%
Maximum Variation				4.64%			9.85%			6.82%

For the steel and titanium alloys, shot peening gave improved fatigue strength. The improvement can be seen in the lower peening intensity range, which is below the intensity specified on the drawings. However, with further increase of peening intensity, the fatigue strength shows no improvement and even decreasing values.

For 4340 steel, the maximum endurance strength variation is between +6.5% and -3.9% of the baseline unpeened strength. For 9310 steel, the endurance strength is between +13.5% and -1.2%. The maximum variation in endurance strength for various peening intensity is 9.40% for the 4340 steel and 9.85% for the 9310 steel if comparison is made with the same Kt. The fatigue data for 9310 steel at K_t=1.75 is questionable, with the unpeened strength above expectation. A metallographic analysis and geometry evaluation is planned. Results will be presented at a later date.

For titanium, the endurance strength at the N-Intensity level is between +10.2% and -1.1%. The endurance strength at A-Intensity level is between +1.4% and -7.7%. The maximum variation in endurance strength is 10.65%.

Fatigue strengths of all test samples, whether peened by Vendor #1 or Vendor #2, statistically are equivalent.

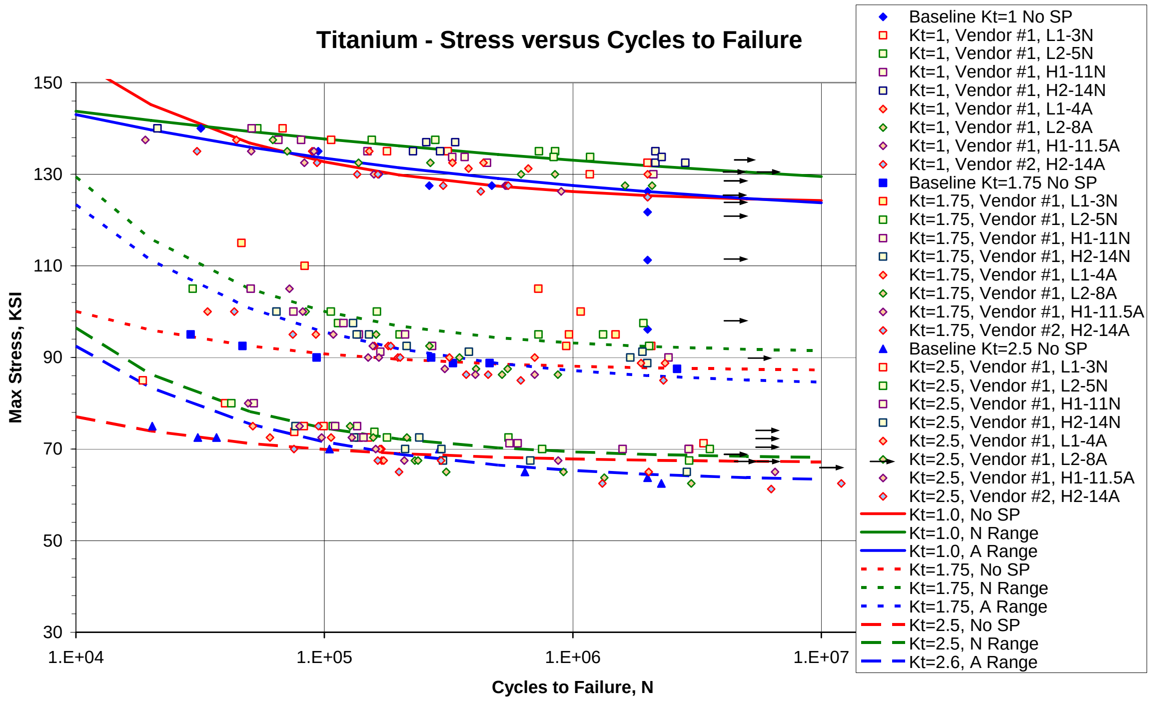

Figure 1, Fatigue Test S-N Curve for Ti-6AL-4V

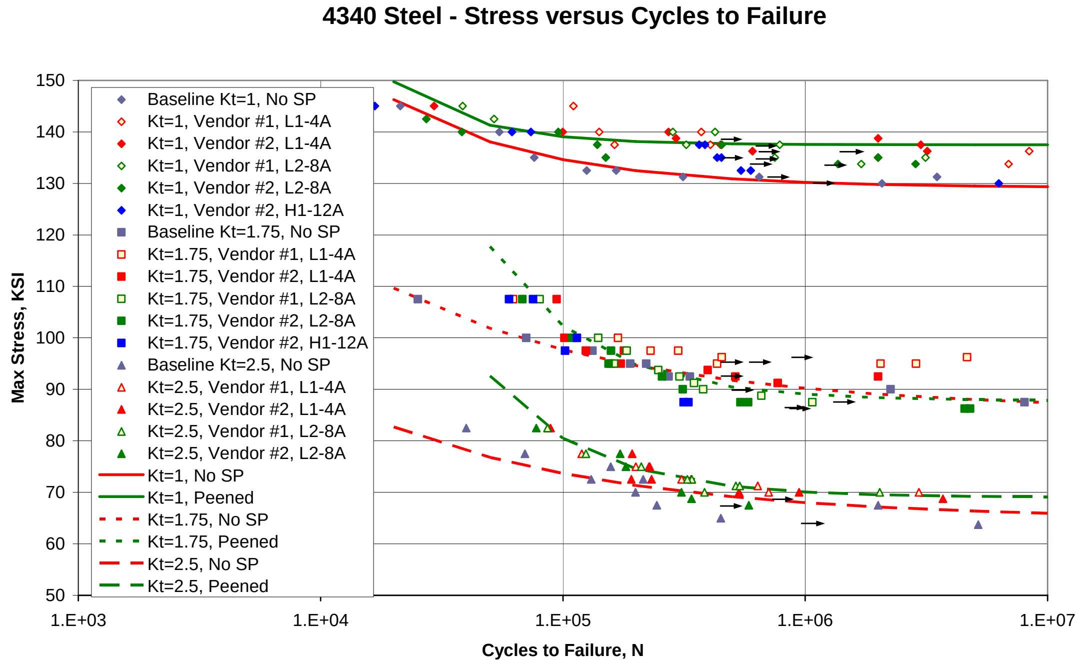

Figure 2, Fatigue Test S-N Curve for 4340 Steel

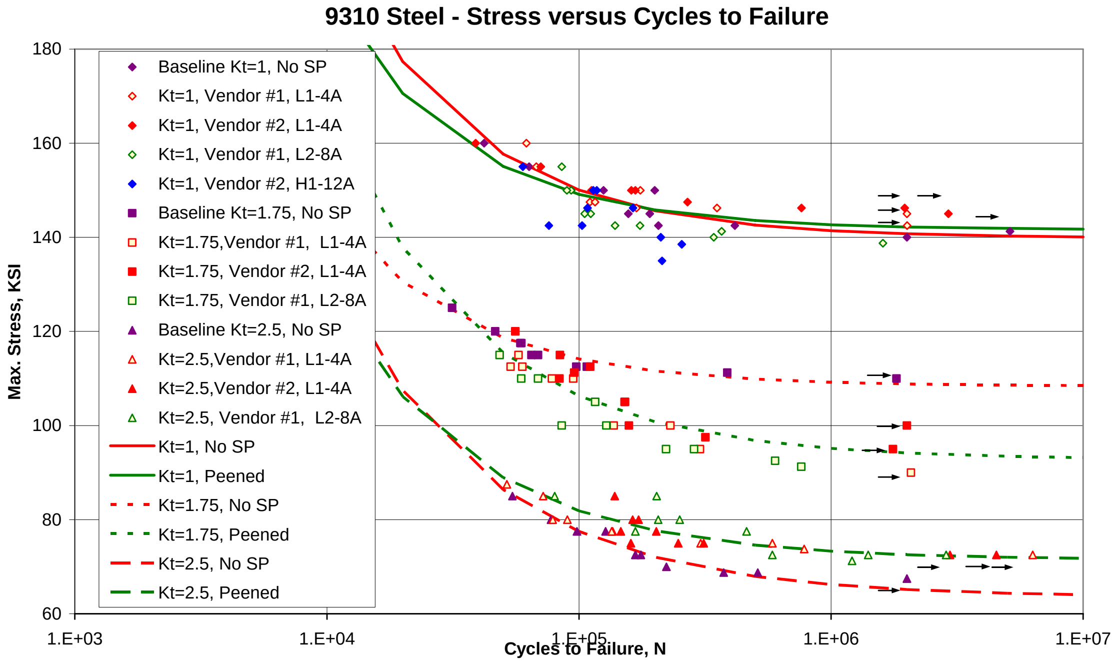

Figure 3, Fatigue Test S-N Curve for 9310 Steel

4.3 XRD/SRA and Surface Roughness Measurements

The surface roughness RMS versus the peening intensity is shown in Figure 4. The measurements were taken from the test coupons at K_t=1. For all three tested alloys, an increase in peening intensity results in increased surface roughness.

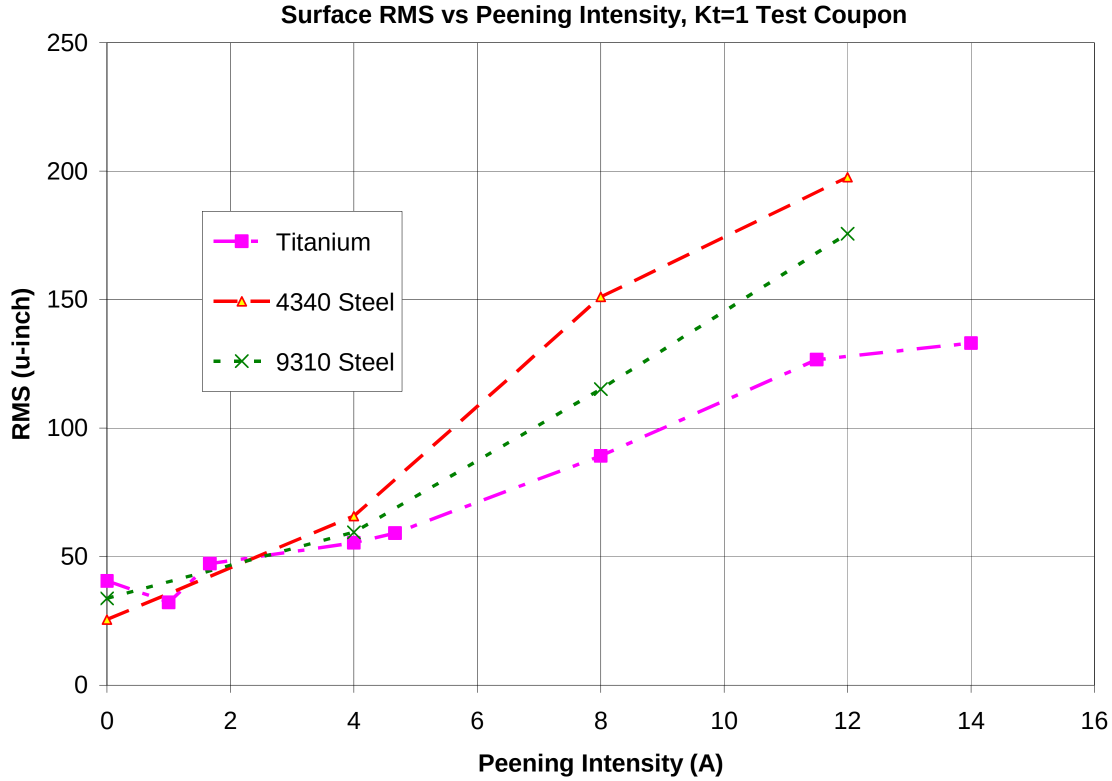

Figure 4, Surface Roughness versus Peening Intensity

The stress profiles and the variation band for the three tested alloys are illustrated in Figures 5-8. Residual stresses at six locations were evaluated. The lines plotted are the average values at the various intensities. For all tested alloys, shot peening creates a surface compressive residual stress. The peened samples reached maximum compressive residual stress at the lowest tested peening intensity, which is below the intensity specified on the drawings. When a maximum compressive residual stress is reached, a further increase in peening intensity shows little impact on the magnitude of the maximum compressive residual stress. Also, for all tested alloys, an increase in peening intensity results in increased effective depth of maximum compressive residual stress, even though the increase has very little effect on maximum compressive residual stress. The residual stress profiles from the Vendor #1- and Vendor #2-shot peened disk specimens were similar for a given intensity.

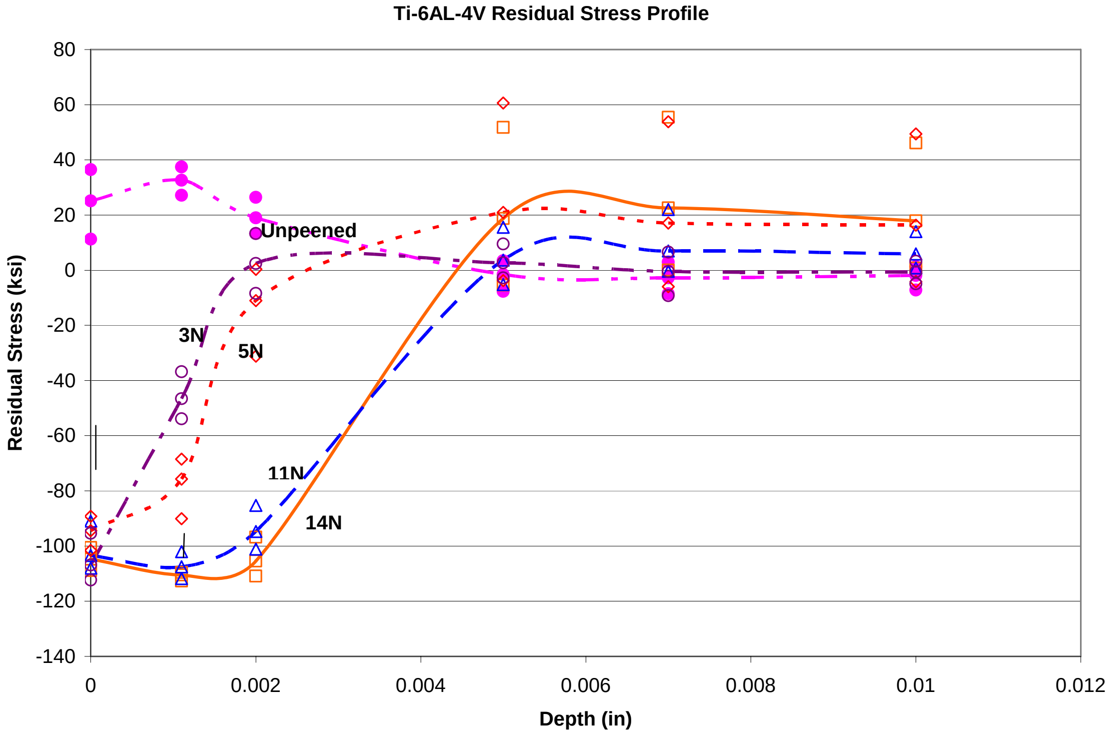

Figure 5, Residual Compressive Stress Profile for Ti-6Al-4V at N-level Intensity

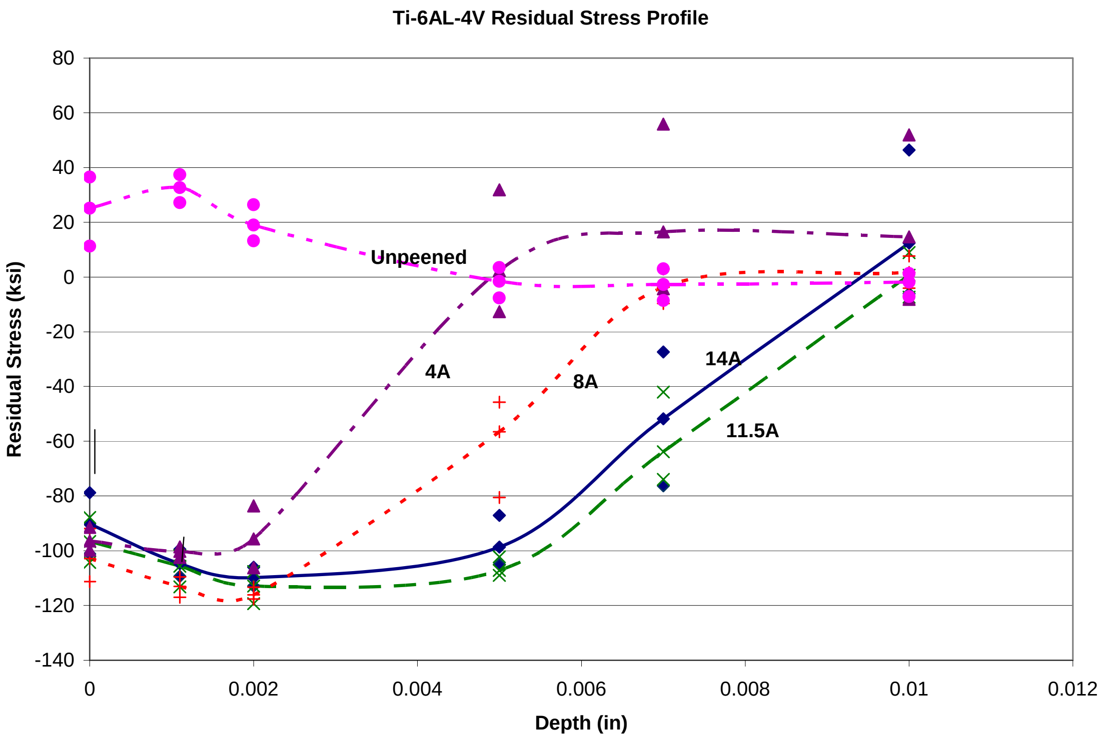

Figure 6, Residual Compressive Stress Profile for Ti-6Al-4V at A-level Intensity

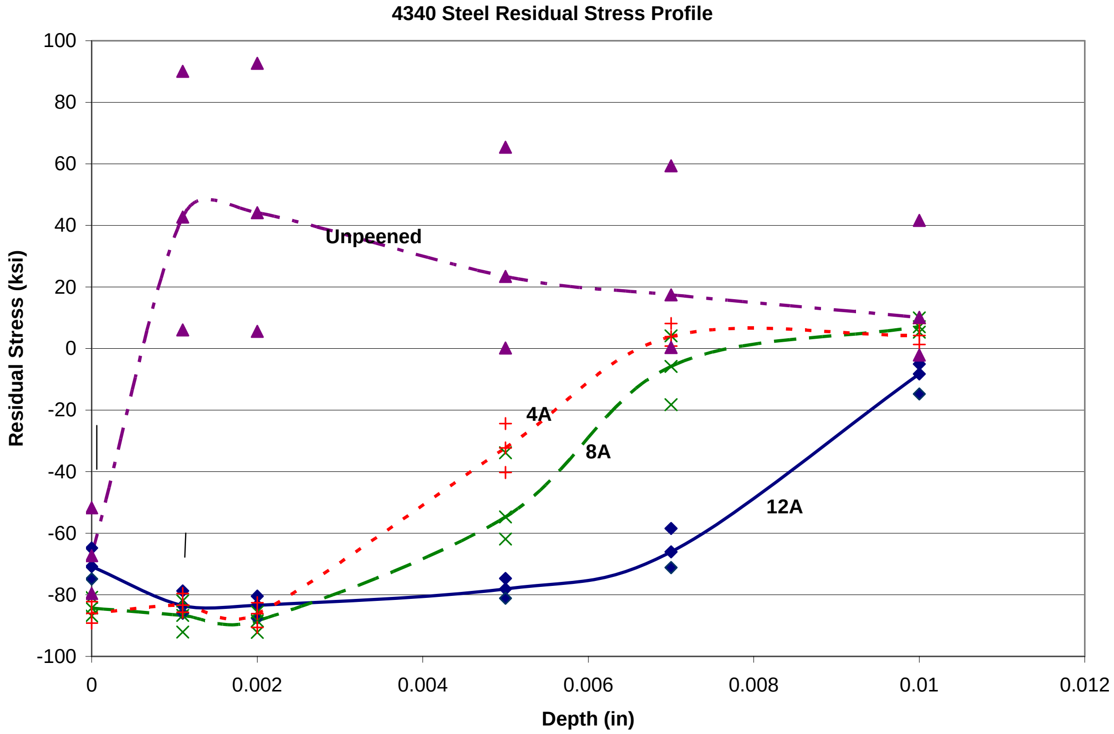

Figure 7, Residual Compressive Stress Profile for 4340 Steel

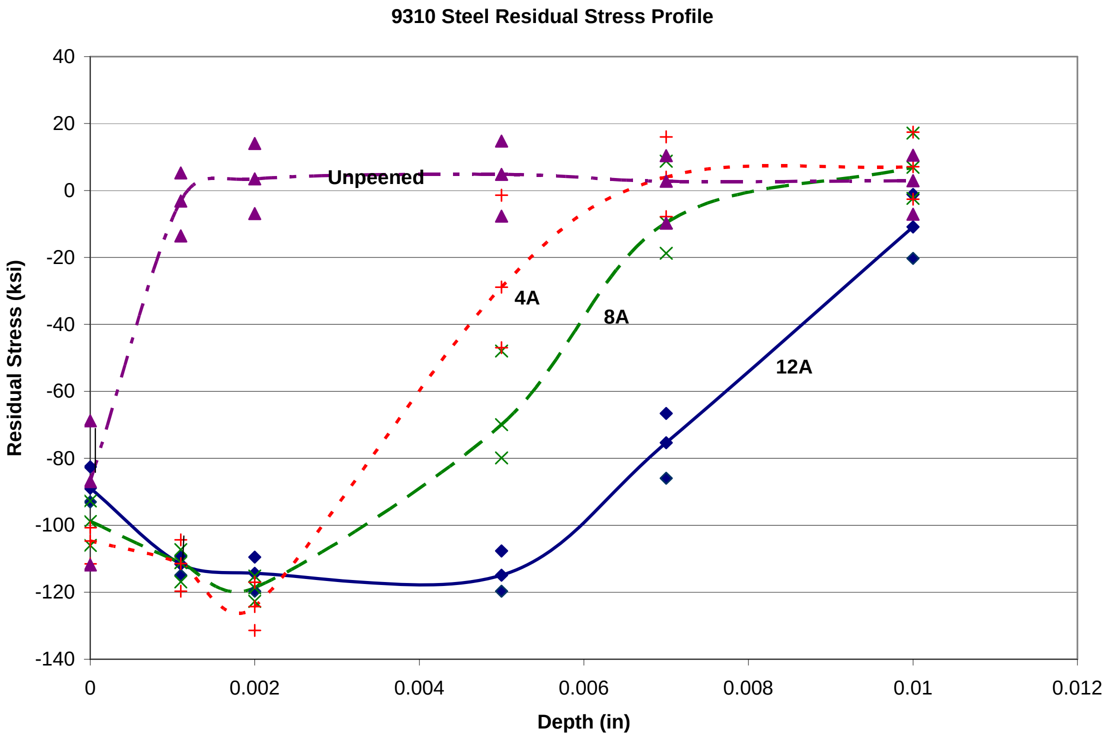

Figure 8, Residual Compressive Stress Profile for 9310 Steel

4.4 Discussion

Based on the study, three factors, maximum compressive residual stress, depth of maximum compressive stress, and surface roughness, play a significant role in determining the optimal shot peen intensity applied to a given part for improving axial fatigue strength.

Shot peening induces compressive residual stresses, generally resulting in increased fatigue strength. An increase in effective depth of maximum compressive residual stress will improve fatigue strength of a part with surface damage within the residual compressive stress zone.

For steel and titanium alloys, shot peening improved fatigue strength in the lower peening intensity range. However, further increase of peening intensity showed no improvement in fatigue strength, and slight decrease with further increase of intensity. The decrease in fatigue strength could be attributed to increased surface roughness since maximum compressive residual stress has been reached at a lower peening intensity and has little change with further increase of peening intensity. Although an increase in peening intensity results in increased effective depth of maximum compressive residual stress, the magnitude of increased fatigue strength due to increased effective depth of maximum compressive residual stress would not be expected to offset the detrimental effect of surface roughness on the fatigue strength.

5 CONCLUSIONS AND RECOMMENDATIONS

Shot peen generally improves the fatigue strength and damage tolerance of metallic components due to its induced compressive stresses. However, based on our evaluation, the shot peening process effectiveness may not be accurately verified through fatigue testing, as given in Figures 1-3 or Table III. There is not a one-to-one correlation from an endurance limit to shot peen intensity. A wide variety of shot peen intensities can produce nearly the same endurance strength.

However, the results from RSM by XRD and surface roughness show good correlation to shot peen intensity, and can be used to validate shot peen process effectiveness to good effect.

The following comments and recommendations are provided:

1. Fatigue testing of new-source or overhauled components does not appear to be a reliable approach to verify shot peen process effectiveness and the resulting compressive layer. However, it should be noted that fatigue testing of new design parts will continue to be required in order to establish baseline fatigue strength and part retirement lives.

2. Alternate methods to qualify new shot peen sources are needed. Current plans under consideration within AMRDEC include survey of a new source, evaluation of shot peen processes, monitoring of Almen strips on fatigue critical areas and geometrically difficult areas, evaluation of surface roughness, and analysis of residual compressive stress profiles on a periodic basis for comparison to first article inspections.

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