Evaluation of Vibrostrengthening for Fatigue Enhancement of Titanium Structural Components on Commercial Aircraft

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Abstract

Vibrostrengthening is a fatigue enhancement technology developed as an alternative to shot peening for the Russian aviation industry. The technology has been successfully applied to titanium, aluminum, and steel alloys. The process adapts conventional vibratory deburring process treatment parameters, by using ceramic abrasive granules followed by steel ball bearing media to achieve a surface enhancement with a predictable fatigue benefit. The benefit is obtained by a combination of surface smoothing and imposition of residual compressive stress to the surface of the component. Recent collaborative efforts between Boeing and the National Institute for Aviation Technologies (NIAT) have evaluated the vibrostrengthening process as an alternative to shot peening. A preliminary examination indicates similar fatigue performance to shot peening and applications with potential processing benefit.

1 Introduction

Shot peening is the predominant method of surface treatment for fatigue enhancement used for structural titanium components on commercial aircraft. The process is considered to be a stable and repeatable process, which is amenable to automation. For simple parts, processing time can be only a few minutes. For large complex shapes, multiple passes are required and processing time can be up to several hours per part. The process also requires careful attention to the sanding preparation of part edges, corners and curved surfaces prior to shot peen treatment to avoid edge rollover and bulging, which become potential initiation sites for fatigue cracks in service. Surface preparation for large and complex geometry structural components can take many hours per part. Such operations accomplished with hand held power tools can be a potential source of ergonomic injury risk.

Vibrostrengthening is a fatigue enhancement technology originally developed for the Russian aviation industry in the 1970’s. The technology has since been successfully applied on Russian aircraft to fatigue-rated structural details made from titanium, aluminum, and steel. The technology has not yet seen wide application outside Russia and technical research is documented mainly in NIAT internal publications. The vibrostrengthening technology is a two-step process adapted from conventional vibratory deburring and uses ceramic abrasive granules for the initial surface smoothing and edge deburring step. This is followed by a
vibropeening treatment step with steel ball bearing media to achieve a residual compressive stress surface enhancement with a predictable fatigue benefit.

Recent collaborative efforts between Boeing and NIAT evaluated vibrostrengthening as an alternative to shot peening for a family of titanium structural components for Boeing commercial aircraft. The evaluation included fatigue tests comparing the fatigue benefit of vibrostrengthening to shot peening, and supporting analyses of surface finish and surface residual compressive stress analysis.

2 Experimental Procedure

2.1 Specimen Preparation

Fatigue test specimens were machined from titanium 6Al-4V mill-annealed plates. A flat-notched \((k_t = 1.5)\) specimen configuration was used for the evaluation. Fatigue tests were performed on five specimens each, representing five treatment groups. The groups consisted of: 1) manually deburred only, 2) manually deburred and then shot peened-low intensity, 3) manually deburred and then shot peened-high intensity, 4) vibratory deburred only, and 5) vibratory deburred and then vibropeened.

The manually deburred treatment consisted of sanding the parts with portable power tools and abrasive paper to remove sharp edges and blending surfaces to remove cutter lines to achieve the recommended corner radii and surface finish preparation prior to shot peening. Shot peening was carried out on an automated machine using CS 280 hard cast steel shot. Low and high shot peen intensities of Almen 7A (0.18 mm A) and Almen 17A (0.43 mm A) respectively, with 100% coverage were selected to provide a range of baseline surface and residual stress conditions for comparison to vibratory deburring and vibropeening treatment groups. Vibratory deburring and vibropeening were each performed on a dual shaft vibratory shaking machine using a rectangular tub type container with a U-shaped cross section. Vibratory deburring was performed using 10 mm \(\times\) 10 mm triangular ceramic abrasive media, at 2.5 mm shaking amplitude for one-hour duration. Vibropeening was performed using 4 to 7 mm diameter hardened steel ball bearings at 4 mm shaking amplitude for one-hour. Both vibratory deburring and vibropeening were performed with the specimens fixed with tooling within the container.

2.2 Test Conditions and Characterization of Specimens

Fatigue tests were carried out at a single set of loading conditions (Stress amplitude = 550 MPa, Stress ratio = -0.20, cycle frequency = 20 Hz) designed for screening purposes to provide a target range of 100,000 to 1,000,000 cycles. Surface Roughness Average \((R_a)\) was measured on faces in a direction parallel with the length of the specimen. Measurements were carried out using a stylus-type surface profile analyzer with a 0.03-inch cutoff setting. Residual stress measurements were carried out using a hole drilling strain gage method in accordance with ASTM E837. The maximum principle stress values were plotted to compare the treatments.
3 Results and Discussion

3.1 Results of Fatigue Tests

Figure 1 shows the range in fatigue life performance of the five treatment groups in terms of cycles to failure for the test conditions. As expected, shot peening was shown to provide increased fatigue life over the manually deburred treatment group. A slight increase in benefit was indicated for high intensity (17A) shot peening versus low intensity (7A) shot peening. Vibratory deburring provided improved life over the manually deburred, however the wide range of response indicated that the benefit was not dependable. The vibratory deburred and then vibropeened treatment group achieved a fatigue life similar to that of the manually deburred then high-intensity shot-peened treatment group.

![Figure 1](image_url)

Figure 1. Range of fatigue life performance from screening of various fatigue-enhancing surface treatments

3.2 Surface Roughness

Figure 2 shows a range of results of surface roughness measurements carried out on the specimens of each group. The starting surface Roughness Average (Ra) of machined specimens ranged between 0.8 and 2.9 micrometers. Surface roughness measurements on specimens after deburring indicate that both vibratory and manual deburring methods effectively reduced surface roughness to below 1.0 micrometer. The surface roughness of deburred specimens was further (slightly) decreased after vibropeening. Measurements subsequently made after shot peening indicated an increase in surface roughness with highest roughness indicated for high-intensity peening.
3.3 Residual Stress Distribution

Figure 3 shows typical residual stress distributions for each of the treatment groups. The peak stresses for vibratory and manual deburring were similar and yielded the lowest peak stresses of the treatments. Low intensity (7A) shot peening and vibropeening yielded increased peak stresses of similar magnitude with the location of the peak for vibropeening treatment occurring slightly deeper than for either shot peening treatment. The maximum peak stress was indicated for high intensity (17A) shot peening.

Figure 2. Range of surface roughness measurements made on specimens from each treatment group with a surface profile analyzer

Figure 3: Distribution of principle residual stress measured by hole drilling method as a function of depth from free surface
3.4 Discussion of Processing Economics

Vibratory deburring has been employed extensively within the industry for surface finish enhancement, but generally used for small and light parts that can be processed loose within the container tumbling with the abrasive media. Large and heavy parts can potentially sustain edge damage with such a process. These parts are often deburred manually instead. Manual deburring of these parts can take several hours, depending on their size and complexity. Fixing such parts with tooling in the container during the vibratory deburring reduces the risk of edge damage and also appears to provide significant process time savings over manual deburring.

At first glance, the vibropeening process would not seem competitive with shot peening with respect to processing time, since shot peening specimens took between 36 and 48 minutes per group while vibropeening took 1 hour. For small and simple parts this may be true. For larger, complex structural components such as flap tracks and landing gear beams, shot peening can far exceed one hour per part. For such parts, the vibropeening process would provide a net savings in overall process time.

4 Conclusions

1. The vibrostrengthening two-step process (vibratory deburr and then vibropeening) provided a fatigue performance benefit for titanium 6Al-4V mill-annealed plate, slightly exceeding that for manual deburring and shot peening in the conditions tested.
2. The fatigue benefit was achieved primarily through a combination of surface finish improvement and the imposition of a residual compressive stress. These attributes have previously been shown to improve fatigue performance [1,2].
3. The basic economics of the process also suggest that vibrostrengthening be considered as an alternative to manual deburring and shot peening for potential applications on larger, complex shape parts with a need for fatigue-life performance improvement.

5 Acknowledgements

The authors are grateful to Igor K. Ananyin of the Automated Means of Production and Control, Scientific and Research Institute, PC (NIIASPK) for his technical guidance and support throughout this investigation.

6 References