OPTIMIZATION OF RESIDUAL STRESS AND FATIGUE LIFE IN LASER PEENED COMPONENTS

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ABSTRACT

Laser peening is an emerging technology for the surface treatment of metallic materials that is capable of enhancing resistance to fatigue failure. This paper describes some recent results from joint research programs conducted to generate data on residual stress and fatigue performance of laser peened materials. Specifically, we present data for residual stress imparted by laser peening and fatigue life improvement of laser peened coupons relative to as-machined coupons. These data are presented for a range of high-strength materials employed in aircraft and other demanding applications: BSTOA Ti-6Al-4V titanium alloy, 300M steel, MP35N Ni-Co-Cr-Mo alloy, and 7050-T7451 aluminum alloy. For each material, residual stress distributions were measured for treatment with different laser peening parameter sets. For particular laser peening parameter sets, stress versus life data were generated for as-machined and laser peened fatigue coupons, which quantifies fatigue life improvement attained by laser peening over a range of applied loads.

INTRODUCTION

Laser peening is a surface treatment that is used to improve material performance [1, 2]. Like other similar surface treatments, laser peening produces a layer of compressive residual stress on the surface of a part, which results in fatigue life enhancement.

In order to favorably affect performance, the residual stress produced by laser peening should be compressive near critical locations where failure is likely to occur. The residual stress produced by laser peening will superimpose with applied service stress (assuming elastic conditions) to provide a net stress reduction. Since compensating tensile residual stresses will develop as a result of laser peening treatment (to satisfy equilibrium within the body), care must be taken to ensure that these develop in non-critical locations, as they will adversely affect performance.

A systematic procedure may be adopted to develop optimal laser peening treatments for fatigue related applications. First, the laser peening processing parameters are optimized for the given material. This is readily accomplished in small flat block coupons by measuring the residual stress versus depth profile and observing microstructural alterations resulting from a range of processing parameter sets. A few of the most promising processing parameter sets are selected for further tests in the failure mode of interest. For fatigue, a small set of replicate coupons are then tested at a single stress level to determine the processing parameter set that provides the greatest fatigue life. After identifying this optimal parameter set, fatigue tests are conducted to determine stress versus life behavior for a range of cyclic stress levels. Additionally, since most applications contain unique geometric features, further testing is often performed on actual components or suitable mock-ups to optimize the laser peening coverage area for the given part.

The primary objective of this paper is to illustrate the effects of laser peening on fatigue performance for a variety of materials. The fatigue performance was quantified in similar coupons, as to minimize the influence of geometry on the results.

Additionally, representative results are shown to illustrate the effects of processing parameter variations on residual stress.

METHODS

This paper presents results for four different materials: beta solution treated and overaged (BSTOA) Ti-6Al-4V titanium alloy, 300M steel, MP35N Ni-Co-Cr-Mo alloy, and 7050-T7451 aluminum alloy. Mechanical properties are given for each material in Table 1.

Two coupon types were employed for each material, small blocks and four point bend bars. Small block coupons were used for residual stress measurement and metallurgical examination. The blocks were nominally square, 50x50 mm, with thickness matching the thickness of the four point bend bars. Prismatic, four point bend bars were used for fatigue testing in Ti-6Al-4V, 300M, and 7050-T7451 (Figure 1a). The thickness of the block and bend bar coupons was 12.7 mm for Ti-6Al-4V and 300M, and was 19.0 mm for 7050-T7451. A notched four point bend bar was used for MP35N (Figure 1b), which had an approximate stress concentration factor of $K_t = 1.3$.

Laser peening was performed at Lawrence Livermore National Laboratory in Livermore, California, using a high-average-power Nd:glass slab laser system. Before peening, coupons were cleaned with acetone and ethanol. For 300M steel, the surface was also cleaned with petroleum naptha solvent and a light abrasive pad to remove oils. An ablative layer was applied to the coupons before peening to protect the surface of the part. Adhesive backed aluminum tape was used as the ablative layer for Ti-6Al-4V, 300M, and 7050-T7451. For the MP35N coupons, a proprietary coating was used as the ablative layer. When multiple layers of peening were applied, the ablative medium was reapplied between layers. The energy of each laser spot was measured and monitored for process control. Spots having pulse energies more than 10% below the target energy were reapplied.

Several laser peening parameter sets were applied to residual stress blocks in each material. A parameter set is defined by laser pulse irradiance (GW/cm^2), laser pulse duration (ns), and the number of treatment layers (1 layer equals 100% coverage), and is denoted by a dash number giving each in succession (e.g., a coupon peened at "10-18-3" was peened with an irradiance of 10 GW/cm^2, a pulse duration of 18 ns, and 3 treatment layers). Peened blocks were tested for residual stress, and then inspected using standard metallographic techniques.

The residual stress as a function of depth from the laser peened surface of block coupons was measured using the slitting method (formerly referred to as the crack compliance method, see Prime [3]). This procedure uses measured strain release due to incremental extension of a slit into the depth of the peened surface to determine residual stress as a function of depth. For these experiments, a single metallic foil strain gage was mounted on the unpeened surface of the block, opposite the start of the slit and centered on the slit plane. Incremental slit extension was performed using wire electrical discharge machining (EDM) and strains were measured with a Wheatstone bridge strain indicator.

In Ti-6Al-4V and 300M, residual stress in shot peened material was also measured using the slitting method. In these experiments, a strain gage was mounted on the front of the block, 1.8 mm from the center of the slot, to obtain sufficient strain versus slit depth data at shallow depths of cut. This method can determine stresses reliably to a depth at least 1.0 to 1.2 times the distance from the center of the gage to the edge of the slot [3].

The present work is focused on improvement of high cycle fatigue strength, and an optimal laser peening parameter set was determined for each material. Fatigue data were then generated for a range of applied cyclic stress.

The four point bend coupons were tested on servo-hydraulic testing machines. The four point bend fixture design included an inner roller spacing of 50.8 mm and an outer roller spacing of 152.4 mm (Figure 2). Testing was performed in lab air and cyclic loading frequency ranged from 3 to 6 Hz, depending on load frame capability and coupon compliance. Approximate applied loads for a range of target cyclic stresses were determined using strength of materials calculations. Actual test loads for these target cyclic stresses were then determined for each load frame and stress level using a strain-gaged calibration coupon and dynamically measured strain versus load data at test frequency. Cyclic stress was computed from strain data assuming uniaxial stressing and elastic modulus values given in Table 1. Fatigue tests were terminated by a specified percentage change in coupon compliance. The specific compliance change varied from 10% to 30%, depending on coupon compliance and test frequency, but the value used did not have a significant impact on cycles to failure data because of large crack growth rates late in the fatigue tests.

RESULTS

Residual stress measurement results are summarized in Figure 3. For the case of Ti-6Al-4V, representative results are shown for multiple sets of laser peening processing parameters and for glass bead peening (Figure 3a). The laser peening results illustrate the extent to which the residual stress profile can be tailored by altering the processing parameters. In general, an increase in the irradiance of the laser pulse or an increase in the number of laser peening layers will increase the depth of compressive residual stress and the magnitude of the surface residual stress with diminishing returns. The processing set of 10-18-3 was selected for treatment of the fatigue specimens due to the large magnitude surface residual stress and the deep levels of compressive residual stress.

Additional residual stress measurement results are shown for the other material types. Figure 3b shows results for 300M comparing the selected set of laser peening processing parameters (10-18-3) with shot peening results. Results are also shown for MP35N (Figure 3c) and 7050 (Figure 3d). This collection of results illustrates that laser peening induces a layer of residual stress with high near-surface magnitude and large depth of compression for materials having a wide range of mechanical properties (Table 1).

Fatigue testing results are given for the four material types in Figure 4. In each case, laser peening resulted in significant performance improvements. The results for Ti-6Al-4V (Figure 4a) show that laser peening resulted in an approximate 5X life improvement at 690 MPa and a 25% increase in maximum cyclic stress at a lifetime of 400,000 cycles. Laser peening was shown to increase the maximum cyclic stress for 300M samples by greater than 50% over the range of lifetimes studied (Figure 4b). For MP35N, laser peening achieved an approximate 7X life improvement at 1170 MPa and a 70% increase in maximum cyclic stress at a lifetime of 800,000 cycles. In 7050-T7451, the life improvement due to laser peening was approximately 5X at 415 MPa. The fatigue testing results for MP35N (Figure 4c) and 7050-T7451 (Figure 4d) show that the benefits of laser peening treatment are more pronounced for lower stress levels (longer lifetimes), which has been observed elsewhere [4].

DISCUSSION

Coupon selection for the evaluation of laser peening and similar surface treatments is important, and fatigue data reported here were collected on appropriate coupons. The important features of these coupons are the surface area subjected to uniform stressing, the beveled upper surface, and the significant thickness. In the present work, the edge length of the nominally square laser spots differed among the materials, but was in the range of 3 to 5 mm. The coupons and loading fixture produced an area of constant stress that was 1290 mm^2 (25.4 by 50.8 mm), thereby incorporating 50 to 140 laser peened spots for these tests. Including a statistically significant number of laser spots provided the ability to assess process variability. Sharp-cornered coupons generally exhibit crack initiation at the corner [5] because of reduced residual stress in the corner region, thereby introducing coupon geometry as an artifact in resulting fatigue data. The beveled upper surface of these coupons removes the influence of coupon corners from the fatigue data. If sharp corners exist in an intended application, it is advisable to replace them with a radiused corner, as has been done for many years when implementing conventional shot peening. The thickness of the coupons was sufficient to restrain the deep residual stress due to laser peening, and other coupon geometries may give rise to coupon-geometry artifacts in gathered data. When evaluating laser peening, it is temping to adopt coupons typically used for material comparisons; however, such coupons may be inappropriate for the evaluation of laser peening. Axially loaded hourglass coupons can be particularly problematic because small section sizes required for high-strength materials and deep levels of compressive stress combine to cause significant tensile stresses near the coupon center that unduly influence fatigue performance. It is important to employ coupons that avoid arbitrary artifacts due to coupon geometry.

It is very interesting to normalize the fatigue data from this study by mechanical strength. Maximum cyclic stress was normalized by static yield strength (Table 1) for each material, and all data were combined into a pair of stress-life diagrams, one for as-machined data and one for laser peened data (Figure 5). The lack of correlation for as-machined coupons may be expected due to the significant range of microstructure and material type encompassed (and normalizing by static ultimate strength does not improve the situation for these data). This is consistent with the literature, which suggests that fatigue crack nucleation correlates with plastic deformation but other mechanisms tend to obliterate the correlation of stress normalized by yield strength with fatigue life in as-machined coupons over a range of materials. That being the case, the degree of correlation for the laser peened data is surprising (Figure 5b). Since laser peening induced residual stress derives from plastic deformation, a correlation of surface compressive stress with yield strength is expected. The correlation of stress normalized by yield strength with fatigue life for laser peened coupons may be due to laser peening mitigating damage mechanisms that prevent correlation for the as-machined condition. Further detailed research would be required to determine whether such correlation exists for a broader range of materials and applied loading than examined here.

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FIGURES AND TABLES

Material	S_y (MPa)	S_u (MPa)	E (GPa)	ν	Hardness
BSTOA Ti-6Al-4V	792	882	116.4	0.3	-
300M	1654	1991	199.8	0.32	54 HRC
MP35N	1585	1791	234.9	0.304	-
7050-T7451	482	544	70.3	0.33	-

Table 1 – Mechanical properties for the materials employed

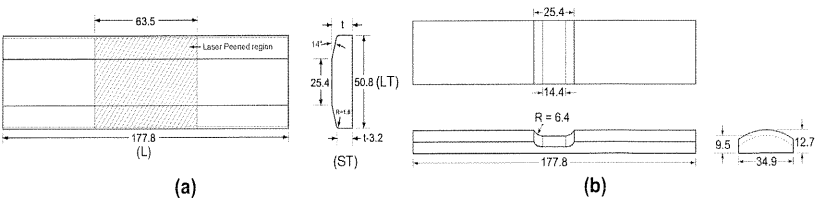

Figure 1 – Coupon geometry for: (a) smooth four point bend coupon used in 300M, 7050-T7451, and BSTOA Ti-6Al-4V testing, and (b) notched four point bend coupon used in MP35N testing. All dimensions in millimeters.

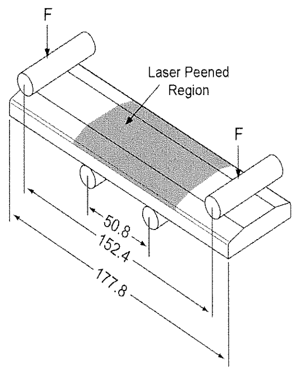

Figure 2 – Four point bend testing fixture configuration. All dimensions in millimeters.

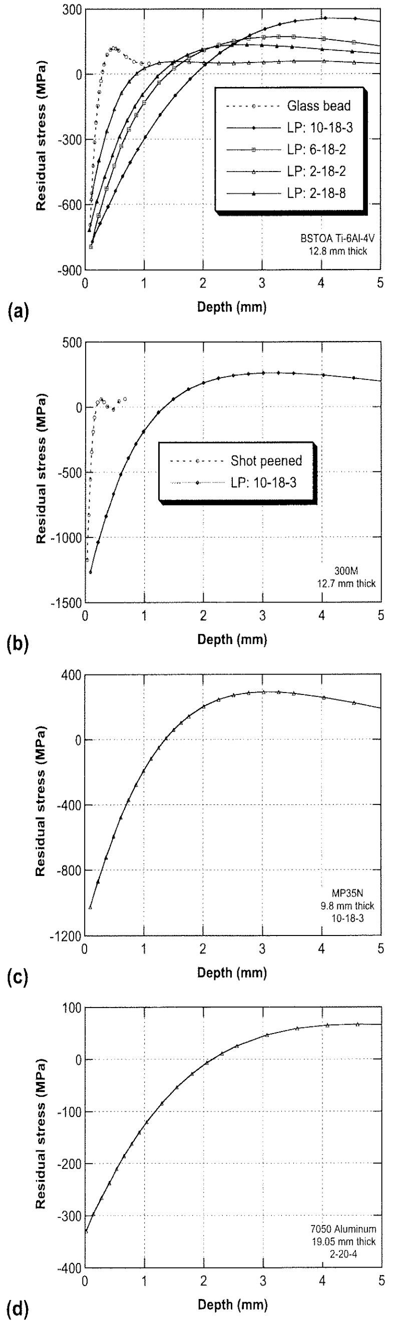

Figure 3 – Residual stress versus depth profiles for: (a) BSTOA Ti6Al4V for a range of treatments (glass bead intensity was 7-9A), (b) 300M for LP and SP (SP intensity was 6-10A), (c) MP35N, and (d) 7050T7451

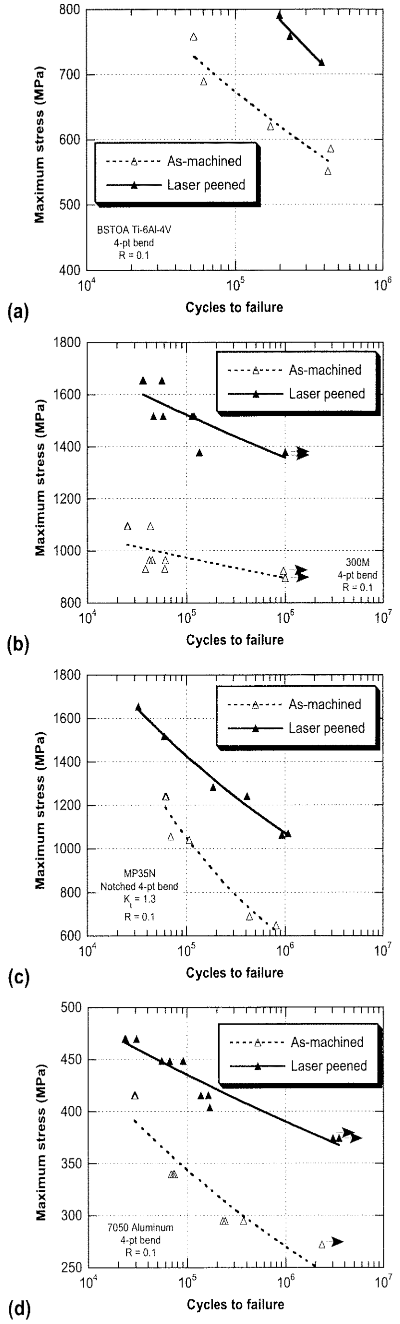

Figure 4 – Stress versus life data for: (a) BSTOA Ti-6Al-4V, (b) 300M, (c) MP35N, and (d) 7050-T7451

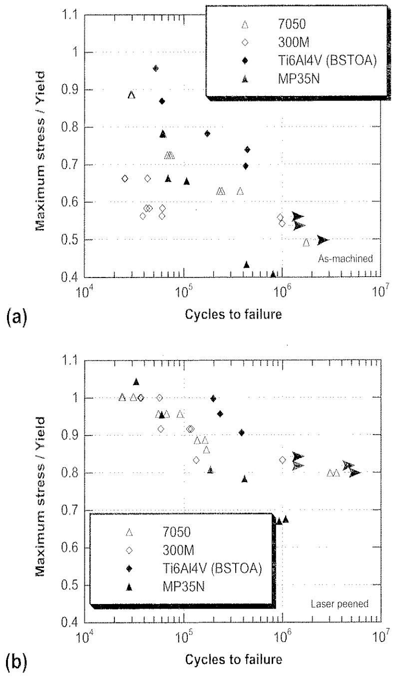

Figure 5 – Summary of all fatigue data with stress normalized by yield strength: (a) AM, and (b) LP coupons