Effect of laser shock peening on fatigue life and surface characteristics of stainless steel cortical bone screws

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Objective—To investigate the effect of laser shock peening on the fatigue life and surface characteristics of 3.5-mm-diameter cortical bone screws.

Sample Population—32 stainless steel, 3.5-mm-diameter cortical bone screws.

Procedure—Screws were randomly assigned to an untreated control group or 2 power-density treatment groups, 6 gigawatts (GW)/cm^2 and 8.5 GW/cm^2, for laser shock peening. Number of cycles to failure and findings on scanning electron microscopy-assisted morphometric evaluation, including the mode of failure, surface debris, surface damage, and thread deformation, were compared between control and treated screws.

Results—The 6 GW/cm^2 treated screws had a significant (11%) improvement in fatigue life, compared with untreated control screws. The 8.5 GW/cm^2 treated screws had a significant (20%) decrease in fatigue life, compared with control screws. A mild but significant increase in thread deformation was evident in all treated screws, compared with control screws. The 8.5 GW/cm^2 treated screws had significantly more surface irregularities (elevations and pits), compared with control or 6 GW/cm^2 treated screws.

Conclusion and Clinical Relevance—A modest positive increase in fatigue strength was produced by this design of laser shock peening on the midshaft of cortical bone screws. High laser shock peening power densities were detrimental, decreasing screw fatigue strength probably resulting from structural damage. Greater fatigue life of cortical bone screws can be generated with laser shock peening and could reduce screw breakage as a cause of implant failure; however, future studies will be necessary to address biocompatibility, alternative cleaning techniques, alterations in screw strength and pullout characteristics, and effects on susceptibility to corrosion. (*Am J Vet Res* 2004;65:972–976)

Strengthening currently available orthopedic implants without altering geometry[1,2] or changing the chemical composition of the material[3] is attractive and could provide an alternative for multiple screw types for different applications. Stainless steel cortical bone screws are subjected to a challenging environment when implanted in vivo, including cyclic loading, shear forces, and the corrosive physiologic environment. Cortical bone screws are commonly used in fracture repair, and specifically, the 3.5-mm-diameter screw is commonly used for fracture repair in horses.[4-7] Failure of cortical bone screws has been documented in vivo and is typically a result of fatigue failure.[8,9] Although different metals have been used as orthopedic implants, stainless steel (316L) is still the most commonly used material.[10-12] Surface-hardening treatments that chemically alter the metal or use of dissimilar metals may result in galvanic corrosion problems.[3] Therefore, strengthening stainless steel, particularly in complex shapes, without altering its chemical composition would be beneficial.

Peening is a process that imparts a compressive residual stress into the surface of a metal, thereby improving strength and hardness.[13,14] Residual surface stresses are defined as those stresses that are internal or within the structure of a part or assembly, even though the part or assembly is free from external forces or thermal gradients.[15,16] Residual stresses may be induced by mechanical, thermal, metallurgical, or chemical means and are difficult to measure. They may be either compressive or tensile across the surface of a metal. Because fatigue cracks initiate on the tensile surface of bent metal structures, a compressive residual stress is beneficial to the longevity of metals exposed to cyclic fatigue, stress corrosion, and fretting, whereas tensile residual stresses result in an increased susceptibility to fatigue failure.[15,16]

Laser shock peening imparts a compressive residual stress by mechanical means, similar to the process of shot peening in which a high-speed projectile is fired onto the treated component to produce a small surface indentation, the center of which will remain under a compressive residual stress. The process of shot peening results in small surface deformations on the metal. The advantage of laser shock peening is minimal surface deformation and deeper compressive residual surface stress.[4] The technique uses a laser-induced surface explosion on the metal to produce a shock wave that causes a rapid tensile surface, thereby imparting a permanent surface compressive residual stress in the treated metal.

The laser shock peening process to date has been used most prominently in the aerospace industry to

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treat gas turbine compressor blades by enhancing fatigue properties by more than 8-fold in a simulated foreign object damage model.[17] To our knowledge, the process has not been previously applied to threaded components or orthopedic implants.

The purpose of the study reported here was to investigate the application of the laser shock peening process on orthopedic bone screws and assess the effect on fatigue life. Based on previous use of laser shock peening on stainless steel 316L,[18] our hypothesis was that laser shock peening of 3.5-mm-diameter American Society for Internal Fixation stainless steel (316L) cortical bone screws at the midshaft with a power density of 6 **gigawatts (GW)**/cm^2 would enhance fatigue life and that larger power densities may further enhance fatigue life when subjected to cyclic 3-point bending. In testing this hypothesis, we compared untreated control screws with screws that had 6 and 8.5 GW/cm^2 power densities of laser energy applied and subjected them to fatigue failure and surface evaluation.

Materials and Methods

Experimental protocol—Thirty-two 3.5-mm-diameter, 40-mm-long stainless steel (316L) cortical bone screws[a] were randomly assigned to be treated by 1 of 3 different laser power densities. The eight 0 GW/cm^2 power-density screws received no form of laser treatment or preparation and were the designated untreated control group. The laser-treated screws underwent a commercial laser shock peening process.[b] The 6 GW/cm^2 power-density group consisted of 16 screws, of which 8 screws received pulse durations of 8 nanoseconds, and the other 8 screws received pulse durations of 11 to 14 nanoseconds. The 8 screws treated with 8.5 GW/cm^2 received laser pulse durations of 20 nanoseconds. These laser settings were based on previous experience, unpublished proprietary data,[b] and results of a previous study.[18]

In the commercial laser shock peening process,[b] each screw to be treated was mounted individually in a 25-mm teflon-coated cube. The cubes had a predrilled hole into which the screw was threaded to a depth of 10 mm. A proprietary opaque, black paint overlay was sprayed onto the threaded surface of the screw and dried. The Teflon cube with the inserted screw was then secured in a pneumatic vice on a robotic arm within the laser peening work cell. The area peened on each screw was centered between 18 and 24 mm from the screw tip. This area was treated by application of a high-energy pulsed, neodymium-glass laser. The laser provided 2 simultaneous beams with a beam energy of up to 50 J each and operated at a laser repetition rate of 0.125 Hz. The screw was placed under a stream of continuously running water that acted as a transparent overlay or tamping medium. The painted surface of the screw was treated in the designated area with a laser spot size of a 6.7 X 4.7-mm ellipse at 4 spots. A total of 4 laser shots were applied to each screw. Two laser shots occurred simultaneously at opposite sides of the screw (**Figure 1**); the construct was then rotated 90°, and a further 2 laser shots were applied in a plane perpendicular to the original shots. The programmable robot combined with a laser targeting device facilitated aiming and rotation of the screw during treatment. Each laser pulse travels through the water and vaporizes a thin surface layer of the black paint overlay. This vapor absorbs further incoming laser energy and forms a rapidly expanding plasma plume between the paint surface and transparent overlay, resulting in a sharp increase in pressure. This sudden increase in pressure causes a shock wave to propagate into the metal. The shock wave gives rise to strain hardening and compressive residual stresses at the surface of the part being treated. Prior to mechanical testing, the black paint was removed by use of acetone and isopropyl alcohol and the screws were then cleaned ultrasonically in acetone and alcohol.

All screws were then cyclically loaded in a servohydraulic materials testing machine[c] under 3-point bending. Each screw was placed on a brass 2-point jig, and the brass anvil of the servohydraulic materials testing machine was the third point engaging the screw over the middle of the treatment area. The same cyclic loading protocol was applied to each screw, consisting of a looped pattern of 9,900 cycles of compressive load ranging between 20 and 250 N at 35 Hz, 90 cycles ranging between 20 and 250 N at 1 Hz to dampen any inertial effects, and 10 cycles ranging between 20 and 750 N at 1 Hz in an attempt to create a discernible marker band on the cracked surface. This loading triad was repeated until the screw deformed beyond the failure displacement of 3 mm. The number of cycles to failure was recorded.

Scanning electron microscopy—All screws after fatigue testing were examined by **scanning electron microscopy (SEM)**[d]; the screws were desiccated for 24 hours prior to examination. The SEM images were obtained along the length of the screw (magnification, 25X), and close-up images (magnification, 120X) were obtained of areas in both unpeened and peened regions; the failure site was also imaged. The control screws were similarly evaluated as treated screws with the same 18- to 24-mm region from the screw tip, which was designated as the peened region of the control screws. The failure site was assessed for the mechanism of failure, including documentation of the number of cracks.

Thread damage was scored from the SEM images by examination of 7 threads in the peened area (18 to 24 mm from the tip) at a magnification of 25X. Each thread was scored on a scale of 0 to 4 (0 = normal, 1 = minimal, 2 = mild, 3 = moderate, and 4 = marked) for deformation. Thread scores were summed for each screw to calculate a thread damage index. The middle of the peened region (20 to 22 mm from the tip) and unpeened region (12 to 14 mm from the tip) on the screw were assessed for surface elevations and surface pits as an indicator of surface irregularity. Areas were chosen between threads, and control screws were examined in corresponding areas. The percentage area affected with irregularities, either pits or elevations in peened and

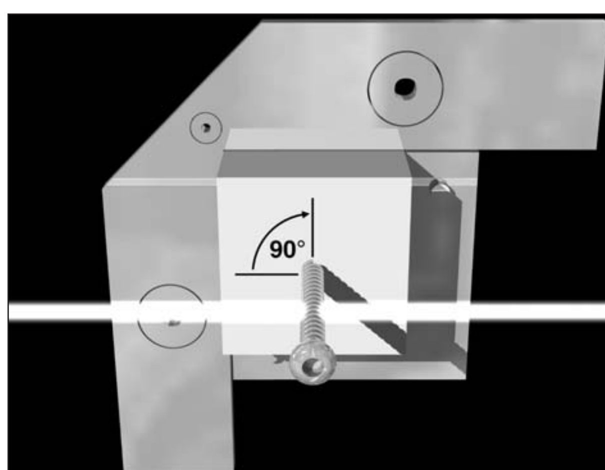

Figure 1—A drawing of a screw partially embedded in the Teflon block that is mounted in the robotic work arm. Simultaneous laser pulses are seen striking the screw on opposite sides. After these 2 laser pulses strike the screw, the construct was rotated 90° and treated again similarly by an additional 2 laser pulses.

unpeened regions, was determined for each screw by use of surface morphometry with a manual point counting technique.[19,20] A 6 X 6-cm area grid was superimposed over the SEM images (magnification, 120X) at 3 separate sites within the peened and unpeened regions on the flat surface between the threads for each screw. The area affected was expressed as a percentage of the surface in the peened and unpeened regions of each screw. Chemical analysis by use of energy-dispersive spectrometery[d] of the peened areas with surface elevations was performed and compared with the control screws.

Following failure (defined as central deformation beyond 3 mm) and initial SEM evaluations, the screws were then fractured to allow SEM examination of the fractured ends. The screws were mounted by their tip and head into an acrylic pot and desiccated for 24 hours, and the fracture surface was examined end on at magnifications of 100X and 375X. Marker bands allowed identification of the site of fatigue crack initiation. This area was examined at a magnification of 375X to evaluate any differences in the crack initiation sites for screws from different groups.

Statistical analysis—Descriptive statistics and graphs were generated for all outcome variables. A comparison of means was performed a priori[21] by use of an ANOVA on the different power density settings (0, 6, and 8.5 GW/cm^2) for the number of cycles to failure. Further paired testing was performed for pulse durations. A 2-factor ANOVA, with power density setting (factor 1) and peened versus unpeened area (factor 2) as the variables, was used to evaluate the effect of laser shock peening on surface characteristics on a percentage basis. When a significant interaction was found between factors, a Fisher protected, least squares difference post test was conducted to identify significant comparisons. Scored (thread damage index) or categoric data (number of cracks) were compared with a nonparametric Mann-Whitney *U* test. Differences were considered significant at $P < 0.05$.

Results

A significant (P = 0.025) 11% improvement in mean fatigue life was seen in the screws treated with a power density of 6 GW/cm^2 (mean, 61,650 cycles) regardless of pulse duration, compared with the mean fatigue life of the control screws (mean, 55,491 cycles). A significant (P = 0.006) 20% decrease in mean fatigue life was seen in the screws treated with an energy density of 8.5 (**Table 1**). Cracking was evident on all screws, typically on the convex surface opposite the anvil contact site; however, 2 screws treated with 6 GW/cm^2 at a pulse duration of 8 nanoseconds cracked on the concave side. A range in the number of cracks was evident between 1 and 3 cracks/screw (median, 2 cracks). No difference was found in the number of cracks and power density (**Figure 2**). Thread damage was evident in all treated screws, with mild distortion of threads in the peened area, and was significantly ($P < 0.001$) different from the control group as determined by a quantitative index (**Figure 3**).

Mean percentages of surface areas of screws affected by irregularities, either elevations or pits, in the peened and unpeened areas were determined. Surface elevations affected ≤ 1% of the surface area in the control screws but affected greater areas in the treated screws in both the peened and unpeened areas. The screws treated with 6 GW/cm^2 at a pulse duration of 8 nanoseconds had affected areas in the peened and unpeened regions of 10.6% and 4.6%, respectively. The screws treated with 6 GW/cm^2 at a pulse duration of 11 to 14 nanoseconds had affected areas in the peened and unpeened regions of 14.6% and 8.6%, respectively. The screws treated with 8.5 GW/cm^2 at a pulse duration of 20 nanoseconds had significantly (P = 0.002) more surface elevations in the peened area (36%), compared with all other areas; the unpeened area in this group also had a large surface area (28%) affected by surface elevations (**Figure 4**). Chemical analysis by energy-dispersive spectrometry revealed the presence of aluminum, which is an element not present in 316L stainless steel but is a large component of the paint overlay.[12]

Surface pitting was low in the unpeened regions of all groups, being < 2% in all screws. The peened areas in the 6 GW/cm^2 treated screws had evidence of a nonsignificant increase in surface pitting, affecting 2.9% of the peened area in the 11- to 14-nanosecond treated screws and 4.6% of the peened area in the 8-nanosecond treated screws. A significant (P = 0.03) increase in surface pitting of 6.8% existed in the peened area of the screws treated with 8.5 GW/cm^2 at a pulse duration of 20 nanoseconds, compared with all other groups and areas.

Table 1—Summary of group fatigue results.

		Values	
Power density	Pulse duration	Mean (± SD) cycles to failure	Range
0 GW/cm^2	NA	55,491 ± 8,149	40,016–64,782
6 GW/cm^2	Combined	61,650 ± 8,220	40,042–70,015
6 GW/cm^2	8 ns	60,448 ± 9,218	40,042–69,997
6 GW/cm^2	11–14 ns	62,852 ± 7,517	50,055–70,015
8.5 GW/cm^2	20 ns	43,907 ± 6,221	35,400–55,708

GW = Gigawatt. ns = Nanosecond. NA = Not applicable.

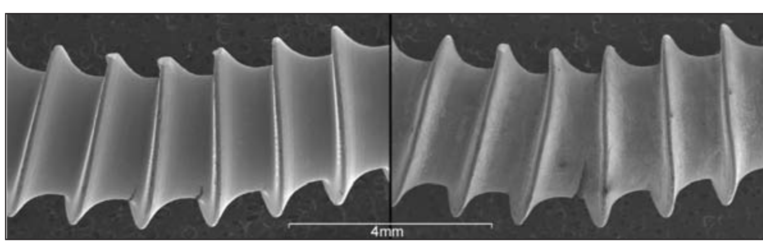

Figure 2—Photomicrograph of the failure site of an untreated control screw (left) and 6 gigawatt (GW)/cm^2 treated screw (right) after mechanical testing. Two cracks are seen on the control screw (left) and 1 on the 6 GW/cm^2 treated screw (right). Bar = 4 mm.

Figure 3—Photomicrograph used for comparison of the surface on an untreated control screw (left) with a similar peened area on an 8.5 GW/cm^2 treated screw (right). The surfaces were evaluated for elevations and pits. Bar = 800 µm.

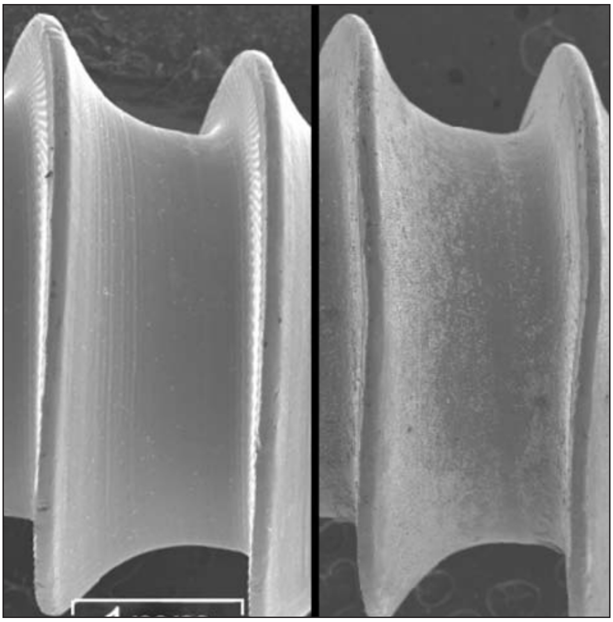

Figure 4—Photomicrograph of 2 threads for comparison of an untreated control screw (left) and 8.5 GW/cm^2 treated screw (right). Notice the irregular contour of the threads on the treated screw, which is consistent with moderate thread damage. Bar = 1 mm.

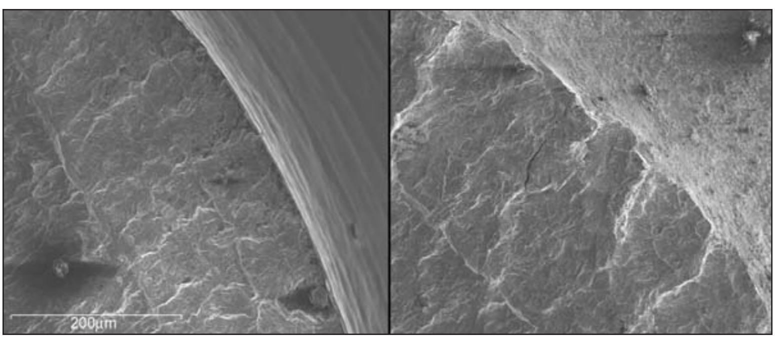

Figure 5—Photomicrograph used for comparison of the fractured ends at the point of crack initiation of an untreated control screw (left) and an 8.5 GW/cm^2 treated screw (right). Notice the irregularity of the surface on the 8.5 GW/cm^2 treated screw (right), compared with the control screw (left). Bar = 200 µm.

Examination of the fractured ends of all the screws revealed evidence of striations (fatigue bands or beach marks) for a variable distance, indicating that fatigue (slow cyclic fatigue) was the mechanism of failure.[22,23] The remainder of the surface had evidence of brittle and ductile failure in which the screws had rapid failure after fatigue testing. As demonstrated, the screws treated with 8.5 GW/cm^2 had more prominent surface damage in the peened area; this was evident subjectively at the point of crack initiation (**Figure 5**).

Discussion

The results of our study indicate that laser shock peening as a treatment process may hold potential for improving the fatigue life of cortical bone screws. In our study, a significant ($P = 0.02$) but modest improvement in fatigue life of 11% was seen in the 6 GW/cm^2 treated screws, compared with the control screws. An industry cost-to-benefit analysis would need to be performed to determine whether this increase in fatigue life would be clinically accepted. Results of a recent study[24] looking at factors influencing choice of implant in total hip and knee arthroplasties revealed that implant quality and not cost was most important to 97.1% of surgeons and that 84.8% of patients would pay additional costs for better-quality implants. Given the current 3.5-mm-diameter screw cost of $9.00,[a] an estimated doubling in cost of a peened screw would only marginally affect the total cost of fracture repair, particularly in humans.

The finding of a significant decrease in fatigue life of 20% in the 8.5 GW/cm^2 treated screws indicates that the process at higher energy amounts can weaken screws, likely as the result of damage to the screw. The small surface irregularities created by laser shock peening may have acted to increase stress, resulting in earlier crack initiation and a shorter fatigue life.

Ideally, the process of laser shock peening can be performed with the laser beam directed perpendicular to the metal surface. The laser bombardment of a designed surface, such as a thread, will place the laser beam at various angles to the metal, inducing an inherent risk of structural deformation that we identified in our study as a wavy appearance to the thread. Simultaneous opposite laser bombardment was used to minimize the risk of screw bending or indentation; however, the ability to ameliorate thread deformation is unknown. The altered surface characteristics, thread deformation, and metal fatigue characteristics associated with laser shock peening may influence screw pullout strength, which remains to be investigated. Both screw pullout strength and bending fatigue are potential sources of repair failure in vivo.

The positive results of laser shock peening applied to 3.5-mm-diameter stainless steel cortical bone screws may be further optimized in this experimental setting by application of different power density and pulse duration combinations. Application of laser shock peening to larger screws may also have provided greater increases in fatigue life, given that in smaller constructs, less residual tensile stress may be imparted as a result of the whole construct deforming rather than just the area treated. A larger screw may provide a greater volume of metal to resist deformation that may result in greater compressive residual surface stresses and a greater improvement in fatigue life. The results of application of this technology to other metallic orthopedic implants, such as titanium, can only be speculated. Because costs of laser shock peening are determined predominately by the surface area treated, some implants or specific areas of fatigue failure susceptibility may be better suited to strengthening.

The surface appeared to have remnants of the surface overlay present in the peened regions. This combined with the surface irregularities indicates the need for further investigation of the peened surface and the impact this finding would have on screw characteristics, including torsional strength, screw insertion effort, and pullout strength. Future studies would be necessary to address biocompatibility, alternative cleaning techniques, and effects on susceptibility to corrosion.

In conclusion, a modest positive increase in fatigue strength was produced by this design of laser shock peening on the midshaft of cortical bone screws. Use of larger screws, combinations of energy densities, and determination of improvements in vivo are warranted.

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[a]3.5-mm-diameter, 40-mm-long stainless steel (316L) cortical bone screws, Synthes USA, Paoli, Pa.

[b]Commercial laser shock peening process, Laserpeen, LSP Technologies, Dublin, Ohio.

[c]Servohydraulic materials testing machine, MTS Bionics 858, Company, Eden Prairie, Minn.

[d]Scanning electron microscopy, JOEL JSM-820 SEM, Company, Peabody, Mass.

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