# Effect of Shot and Laser Peening on SAE 1010 Steel Tubes with a Transverse Center Weld Subjected to Constant and Variable Amplitude Loading

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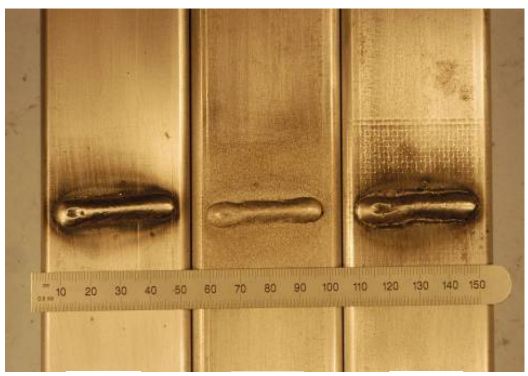
## 1 INTRODUCTION

Compressive surface residual stresses from shot peening have proven to be extremely beneficial to fatigue resistance of intermediate and high strength metals and alloys. Lower strength materials, including steel weldments, often are believed to not have this significant benefit. This is due to lower yield strengths that restrict the magnitude of induced residual stresses and the relaxation of residual stresses during cyclic loading due to local plasticity. Thus, the application of shot peening, or emerging laser peeening, has not been common in steel weldments with yield strengths less than about 400 MPa. The limited research available in the literature concerning these lower strength mild steel weldments, however, has indicated increased constant amplitude fatigue limits at $2x10^6$ cycles of between 10 to 90 %.[1-4] Most of these tests were performed with an R-ratio ($S_{min}/S_{max}$) equal of 0 or 0.1, and included longitudinal and transverse fillet welds, butt welds and bead-on-welds. Intermediate fatigue lives often showed mixed results, whereas at shorter life ($\leq 4x10^4$ cycles), no benefits from shot-peening were obtained. Laser peening produces deeper penetration of compressive residual stresses than shot peening and hence may produce better fatigue resistance than shot peening for mild steel weldments. Laser peening has been very successful in higher strength materials involving aluminum, steel and titanium alloys.[5,6] However, it is significantly more expensive than shot peening. The goals of this research were to compare the fatigue resistance of both shot and laser peened mild steel weldments under constant and variable amplitude loading as part of the Society of Automotive Engineers Fatigue Design and Evaluation (SAEFDE) committee's fatigue of weldments program.

## 2 TEST SPECIMENS AND MATERIALS

The material used in this research was low carbon SAE 1010 cold rolled (mild) steel. The test specimens were thin-walled square tubes of 50.8 mm in width and height, 305 mm in length and a wall thickness of 3.17 mm. The corners were rounded due to the tube manufacturing process. A continuous seam weld ran the length of the tubes where the cold rolled tubes were joined together. All tube specimens received a transverse center weld bead on the face adjacent to the seam weld as shown in Figure 1. This weld bead procedure was chosen to compliment other weld bead shapes being evaluated in the SAEFDE weldment program. The weld beads were fabricated manually using metal inert gas (MIG) arc welding. The weld metal was ER-705-3 with a wire diameter of 0.89 mm. The shielding gas was 75% argon and 25% $CO_2$. The weld bead started and ended about 6 mm from the tube outside edges, resulting in a weld bead about 38 mm in length. Typical weld beads for the three conditions of as-welded, shot peened, and laser peened are shown in Figure 1. The weld bead was started on the right side of each specimen and ended on the left side. The starting point was characterized by dense ripple formation and the endpoint was characterized be a dimple as shown in Figure 1. Throughout the length, the weld bead width varied from about 7 to 8 mm and the height varied from about 4 to 5.5 mm. The alteration of the surface near the weld bead due to shot or laser peening is evident on the specimens. Shot peening was done using rounded 50-55 RHC aerospace grade (AMS-2431-3) CW 14 shot that is equivalent to S110 shot. The shot peening intensity was 8A at 100% coverage in the weld bead region. The shot peening area extended 25 mm to either side of the weld bead as seen in Figure 1(b). Laser peening used 16 Joules per laser spot size of 3 $mm^2$ with a peak power density of 8 $GW/Cm^2$ with 18 ns pulse duration. Two layers of laser peening were applied over a 25 mm distance on either side of the weld bead as shown by the grid-like formation in Figure 1(c).




(a) (b) (c)

Figure 1 Test specimen weld region (a) as-welded, (b) shot peened, (c) laser peened

The chemical composition by % weight of the as-rolled tube base metal was 0.08 C, 0.44 Mn, and 0.047 S. Monotonic tensile tests of one specimen taken from two tubes in the longitudinal direction resulted in average base metal values of 0.2% yield strength, $S_y$ = 350 MPa, ultimate tensile strength, $S_u$ = 390 MPa, elongation = 42 % and reduction in area = 57%. A profile view of the weld bead showed the weld bead had partial wall thickness penetration at the starting location with increasing penetration along the weld length and complete penetration near the end of the welding operation. The heat affected zone, HAZ, extended to just beyond the weld bead width at the root radius and less than this toward the tube inner surface. Variation in weld geometry also resulted in variation of the weld toe radius. Scanning electron microscopy imaging indicated these radii ranged from approximately 0.1 to 0.4 mm depending on the location of the measurement.

The average surface macro hardness of the base metal, i.e. on the as-rolled tube, was Rockwell B = 76 with very little variation. However, the macro hardness did vary depending on which peening treatment was used. Figure 2 shows macro surface hardness values as a function of the distance from the weld bead center line. The hardness of the weld bead was higher than in the tube and ranged from Rockwell B of 88 to 94 with the higher values for the laser peened specimen. At a distance ranging from about 2 to 30 mm from the weld bead, the shot peened and the as-welded conditions were about the same varying from about Rockwell B of 76 to 80. The laser peened specimen Rockwell B hardness ranged from about 80 to 85 within the laser peened region with higher values nearer the weld bead. Thus the laser peening caused an increase in macro hardness in the weld region relative to both as-welded and shot-peened conditions.

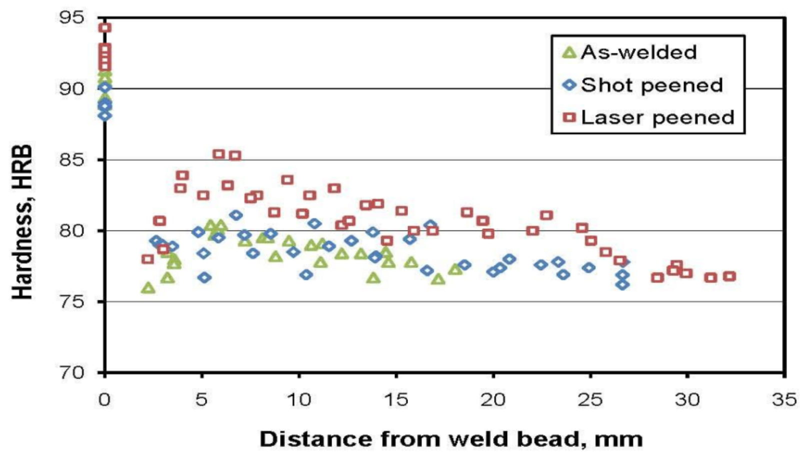



Figure 2 Surface hardness versus distance from the center of the weld

Micro hardness measurements were made on as-welded, shot peened and laser peened specimens near the weld toe root to a depth of one mm using Knoop micro hardness equipment. Measurements were taken for each condition at five different lengths along the weld bead and at five depths. They were then converted to Rockwell B hardness values for comparison to macro hardness. Figure 3 shows typical micro locations and Knoop indentations. Most readings were taken in the HAZ as shown. The knoop tests were taken on uncycled as-welded and shot peened specimens but the laser peened condition was taken on a variable amplitude specimen with about $4 \times 10^5$ cycles without failure. Micro hardness values ranged from Rockwell B 72 to 100 with the highest values at a depth of 0.2 mm (point closest to the weld root). The laser peened specimen had the higher values while both shot peening and as-welded were similar. The laser peened specimen also had higher values at the larger depths indicating the deeper penetration of compressive residual stresses.

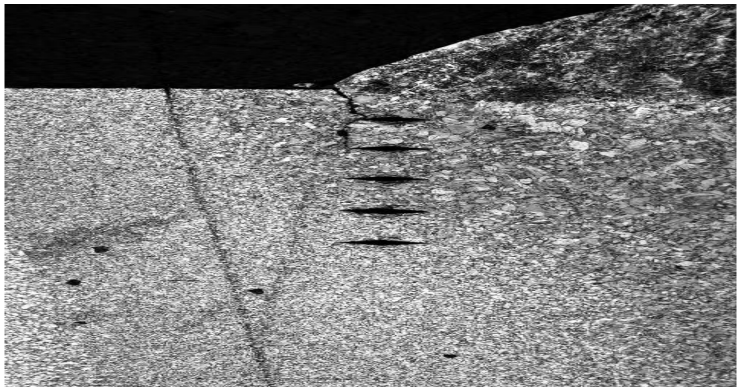


Figure 3 Typical micro hardness indentation locations and microstructure profile, laser peened

Figure 3 also indicates the location of fatigue cracks emanating from the weld bead root and the variable microstructure of the weldment. Shot or laser peening did not alter the microstructure and in Figure 3, the grain size diminishes in the HAZ as the distance from weld metal increases. The average ASTM grain size in the weld metal was 3 and in the base metal it was 8. Near the weld metal, the HAZ grain size ranged from 3 to 4 and then ranged from 4 to 8 farther toward the end of the HAZ. This is expected due to the different temperatures reached in the HAZ during welding.

Longitudinal residual stresses for all three conditions were measured at the weld bead root region using X-ray diffraction. Figure 4 shows these stresses as a function of depth below the surface of the weld bead root. The maximum measured depth was ≤ 0.76 mm (0.03 in.). This depth encompassed about 4 of the 5 micro hardness depths. It is seen that residual stresses at the surface for the three conditions are compression. This is surprising for the as-welded condition, but may be attributed to the quality of the welding technique. The maximum compressive residual stress occurred just below the surface for the as-welded and laser peened conditions and at the surface for the shot peened condition. These maximum values were greatest for the shot peened and slightly less for the laser peened. However, the laser peened had compression in all measurement depths, while the shot peened compressive depth was about 1/3 of this. The as-welded compressive depth was about 1/4 of that for shot peening. The greater depth of compressive residual stresses for the laser peened is similar to the micro hardness results. Thus, in this mild steel weldment, laser peening caused significant greater depth of compressive residual stress.

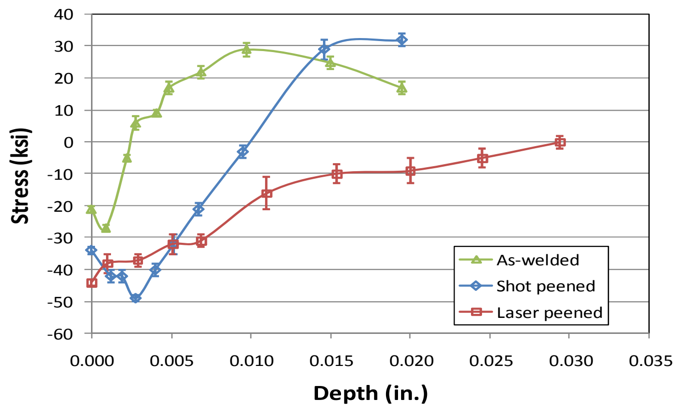



Figure 4 Weld toe residual stress measurements

## 3 FATIGUE TEST PROCEDURES AND RESULTS

Fatigue testing was conducted using a computer controlled closed loop servo-hydraulic test system in laboratory air at room temperature. 4-point bend loading was used with rollers and hardened rigid accompanying support plates between the rollers and specimens that eliminated excess roller fretting damage on the mild steel thin-walled tubes. Constant amplitude sinusoidal load control testing was done with R = 0.1 and 0.5 at frequencies between 5 and 18 Hz depending on the magnitude of the loading and the test system response. The maximum load was scaled from 32 to 80 kN. Tests were considered runnouts at $2x10^6$ cycles otherwise, failure was taken as significant cracking and loss of stiffness as indicated by a ram displacement of 5 mm or more. Three different variable amplitude load spectra were developed to supplement the constant amplitude high cycle test results. The first two were combinations of R = 0.1 and 0.5 load blocks based on 0.5% damage of the constant amplitude fatigue life data. The highest loading of 80 kN was not included due to its extremely low fatigue life and fretting induced tube buckling. The first spectrum, VA1, had 12 blocks involving both R ratios and consisted of 31 714 cycles. This spectrum was then repeated until failure. The second spectrum, VA2, was similar to the first, except it eliminated the two highest and two lowest load ranges from each R ratio and contained 17 158 cycles. Again, this spectrum was repeated until failure. Frequencies varied between 5 and 18 Hz. The third spectrum, VA3, was generated from a modified version of a grapple skidder load history from a previous SAEFDE study. Maximum loads ranged from 2 to 62 kN and the minimum loads were always positive. This spectrum contained 723 cycles obtained through rainflow counting and was repeated using 5 Hz until failure. The upper maximum of 62 kN was set to eliminate possible relaxation of residual stresses.

Conversion of the force to nominal longitudinal stress was made using finite element analysis, FEA, for linear elastic isotropic material and verified using mounted strain gages with applied loads. This calculation and experimental verification was deemed necessary, since σ = Mc/I is not very realistic with thin-walled tubular bend specimens. The edge reinforcement creates a variable stress across the outer surface with a higher stresses near the edges compared to the middle region. The difference between the FEA calculation at the outer edges and the strain gage readings were less than 3%. The FEA edge calculations were thus used to convert force to nominal bending stress.

The constant amplitude S-N fatigue test results for the three conditions with R = 0.1 are shown in Figure 5, where $S_{max}$ and $P_{max}$ are plotted against the number of cycles to failure, $N_f$. $S_{max}$ is the nominal stress calculated from FEA and $P_{max}$ is the actual maximum test force. Scatter for a given test level was very low for all three test conditions, less than a factor of two. The fatigue strength at $2x10^6$ cycles increased 52% with respect to the as-welded condition for laser peened and 30% for shot peened. These are both significant increases. The increases in fatigue strength decreased as the number of cycles to failure decreased to about $10^5$ cycles where all data converged. These test results indicate that for R = 0.1, both shot and laser peening are beneficial in the high cycle region but are ineffective in the low or intermediate cycle region.

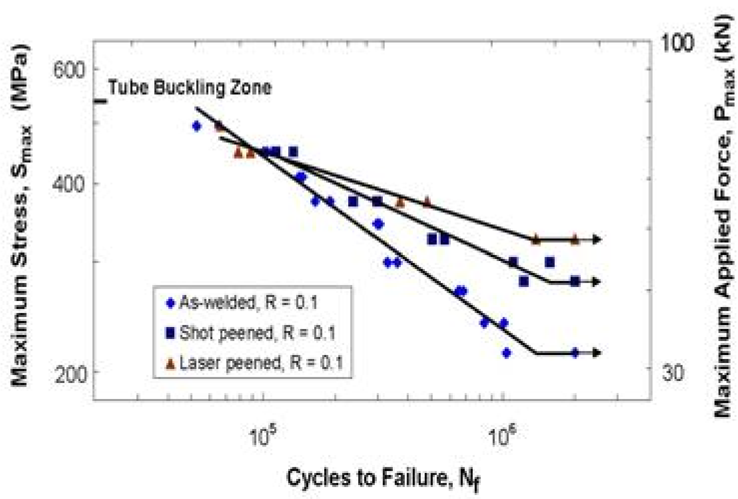



Figure 5 S-N fatigue test results for constant amplitude, R = 0.1

The constant amplitude S-N fatigue test results for the three conditions with R = 0.5 are shown in Figure 6 with both $S_{max}$ and $P_{max}$ plotted against the number of cycles to failure, $N_f$. Fewer test specimens were available for the R = 0.5 tests, and no runnout data were obtained for the as-welded condition. For comparison purposes, the as-welded data were extrapolated to $2x10^6$ cycles and thus both shot and laser peening yielded about a 20% increase in fatigue strength at $2x10^6$ cycles to failure. At the shorter lives, shot peening was still beneficial while laser peening converged with the as-welded data at about $5x10^5$ cycles. The increases in fatigue resistance for R = 0.5 were less than for R = 0.1.

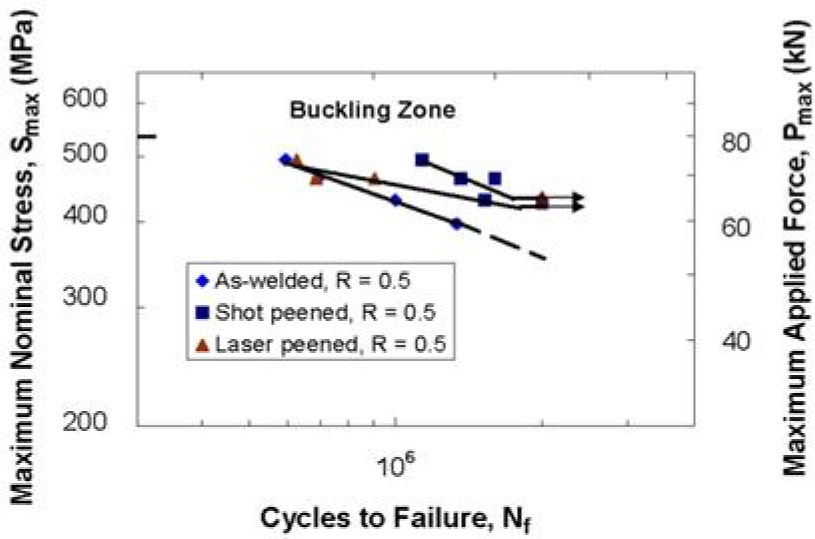



Figure 6 S-N fatigue test results for constant amplitude, R = 0.5

The variable amplitude tests with the three different spectra involved one to three specimens per test condition. Scatter for duplicate or triplicate tests ranged from 1.05 to 1.6, which is small. The mean number of blocks to failure for each spectrum and material condition are given in Table 1 along with percentage of fatigue life increase. For VA1 and VA2, shot peening provided the best result followed by laser peening. However all of these increases in blocks to failure were not significant with fatigue life increases of only 7 to 76 %. For VA3, the life differences for just one specimen per test condition were negligible, indicating shot or laser peening did not enhance fatigue resistance with this load spectrum.

Table 1 – Comparison of Average (Mean) Fatigue Results for Variable Amplitude Loading

| | | Shot peened | | Laser peened | | |
|---|---|---|---|---|---|---|
| Spectrum | Mean As-welded Life (Blocks) | Mean Life (Blocks) | Life increase compared to As-welded (%) | Mean Life (Blocks) | Life increase compared to As-welded (%) | Life increase compared to Shot-peened (%) |
| VA1 | 17.6 | 31.0 | 76 | 18.8 | 7 | -64 |
| VA2 | 24.5 | 31.9 | 30 | 28.3 | 16 | -13 |
| VA3 | 716 | 674 | -6 | 805 | 12 | 19 |

## 4 FRACTOGRAPHY

Fatigue cracks always nucleated at the weld bead root near the start of the welding process and in some cases also nucleated near the end of the weld. They grew partially or totally across the specimen weld bead root and often down the side where the welding began. Specimens did not fracture into two pieces due to the 5 mm ram displacement criterion and test system response. A typical variable amplitude macro fracture surface is shown in Figure 7 for the 12 step VA1 loading spectrum. Macro fracture surface morphology was essentially independent of peening. The variable amplitude specimens all contained ratchet marks at the crack nucleation region and elliptical beach marks as the crack grew in depth and along the weld bead direction as shown in Figure 7. Macro markings were difficult to find in the constant amplitude tests. As shown in Figure 3, cracks grew primarily in the HAZ and then into the BM in the plane of the nominal longitudinal bending stress. Scanning electron microscopy, SEM, revealed very few striations in the fatigue crack growth regions for the constant amplitude tests. However, with the three variable amplitude spectra, striations were very evident for both intermediate and high cycle fatigue specimens. Secondary cracks, perpendicular to the fracture surfaces, were present in both constant and variable amplitude tests. Final fracture regions that occurred in some specimens revealed ductile dimples. Macro and Micro fractography indicated the fatigue crack growth morphology was similar for all three conditions.

Figure 7 Typical variable amplitude fatigue fracture surface, VA3 spectrum laser peened

## 5 DISCUSSION OF RESULTS

The literature review indicated shot peening of mild steel weldments increased the constant amplitude R = 0 or 0.1 fatigue strength at $2x10^6$ cycles by10 to 90% with little increase at intermediate or low cycles to failure. However fatigue behavior under variable amplitude or other R ratios was not found. Thus, ambiguity exists as to how beneficial shot peening can be in low strength steel weldments. This research confirmed the beneficial effects of both shot and laser peening on constant amplitude R = 0.1 and 0.5 fatigue strengths at $2x10^6$ cycles, with little benefit at shorter lives. However, under three different variable amplitude spectra little influence on fatigue life was found with either shot or laser peening. This beneficial or little effect is usually attributed to whether or not the desirable residual compressive stresses are maintained or relaxed during cycling in these low yield strength weldments. The laser peened and shot peened weldments had similar near surface residual compressive stresses, but the laser peened residual stresses remained compressive to much greater depths. This greater depth was only beneficial with respect to shot-peening for the R = 0.1 tests. The macro and micro hardness values indicated surface and depth hardness was greater for the laser peened specimens. All test conditions had little scatter with cracks nucleating at the root of the starting weld area. Fatigue crack growth regions had the same morphology at both the macro and micro level for the three test conditions as did final fracture regions.

6 CONCLUSIONS

Both shot and laser peening caused increased fatigue strengths in these mild steel weldments at $2x10^6$ cycles with R = 0.1 and 0.5, but had little effect at shorter lives and with three different variable amplitude tests. The greater depth of compressive residual stresses and micro hardness from laser peening was beneficial with respect to shot peening for only R = 0.1 tests at long life. The current additional cost for laser peening of mild steel weldments would not yet be justifiable.

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