Assessment of Field Surface Treatments for Prolonging the Life of Steel Welded Joints Subjected to Fatigue Loading

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Abstract

In cases where a weld fatigue issue is discovered in the field the customer desires to have low-cost methods to increase service life. Two different surface treatment processes namely, hammer peening and rotary flap peening effects were evaluated for their ability to increase fatigue life in T-shaped fillet welds. Fatigue tests were conducted on three configurations; as-welded, welded and hammer peened, and welded and flap peened. Metallographic inspection was used to further evaluate the test samples following fatigue testing. It was found that the fatigue life improved significantly with hammer peening in comparison to rotary flap peening and have a strong potential for field applications

Keywords Hammer peening, rotary flap peening, welds, fatigue

Introduction

In heavy truck applications welds are commonly used to join structural steel components that are subjected to cyclical loads of high amplitude. Components are commonly attached to truck axles through the use of welds. Some of the flaws associated with welds includes, undercutting at the toe of the weld, the creation of an abrupt weld profile with a convex shape, excessive porosity, slag inclusions, lack of fusion, and incomplete weld root penetration invariably contribute to the reduced fatigue life in welds [1,2]. For severe applications it is desirable to have the ability to field treat welded structures to improve the fatigue service life. Two surface treatment processes are hammer peening and rotary flap peening. Hammer peening is a process in which a hardened steel rod or "hammer" is used in conjunction with a pneumatic gun to subject a material to repeated impacts. Each impact produces plastic deformation of the surface, thereby inducing a compressive stress. The surfaces requiring treatment are traversed at a rate such as to give the required coverage. As a manual process, this method of surface impingement is subject to large variation in effectiveness based on impact hammer speed of travel, force of impact, geometry and material of the hammer, angle of impact, etc. Maddox [3] found in his experiment that hammer peening improved the fatigue life of welded specimens by approximately a factor of two, and that the crack initiation site moved from the weld toe (un-peened samples) to the weld root (peened samples). Bell et al. [4] found that the crack initiation site of the un-peened samples was in the weld toe, with propagation occurring through the base plate. The peened samples experienced crack initiation at the weld root, propagating through the weld throat, then through the base material. Rotary flap peening entails the use of a thread-woven, multi-flap rotary brush on which is mounted hard shot, powered by a rotary power tool. The shot impacts the surface of the work piece causing plastic deformation, thereby inducing a compressive stress. The surfaces requiring treatment are traversed at a rate such as to give the required coverage. The process is usually applied manually to local areas of components or assemblies and is particularly useful for the peening of holes [5]. The process of using a rotary flap tool for peening is described in detail in Military Specification MIL-R-81841 (1972) and AMS 2590 [6]. This procedure was used as a guideline for preparing test samples for this research. Variables that were controlled include distance from flap core to the surface being peened, tool revolution speed, the flap assembly itself, the speed of travel, type of joint, and the number of times the tool is moved across the part surface. Since the procedure is manual in nature it is highly operator-dependent. This research was initiated to recommend a process for treating welded joints on heavy trucks that can be accomplished in the field with limited manufacturing resources. The purpose of this paper is to report the experimental results on fatigue improvement that can be obtained through the use of these peening methods.

Experimental setup and Procedure

A36 steel test specimens were designed to transmit a uniform force to a 6.35 mm (¼ in) steel base plate through a load applied to a 19.05 mm (3/4 in) thick plate welded to the center. A total of thirty T-shaped fillet weld test specimens were fabricated and typical specimen is shown in Figure 1 (top left). In *hammer peening*, a pressure regulator setting of 0.55 MPa (80 psi) was selected for hammer peening for this investigation. This pressure is readily available at most truck service shop facilities, even during peak usage hours. Ten samples were hammer peened with the following settings:

Tool tip diameter: 4.8 mm (0.1875 in), Air pressure: 0.55 MPa (80 psi), Number of passes with tool: 1, Hammer frequency: 34 Hz, Force: 20,500 N (4600 lb), Travel speed: 3.8 mm/sec (0.15 in/sec)

Rotary flap peening was conducted manually using a 3M Roto Peen kit along with a right angle die grinder with pressure regulator. Peening intensity targets were set based on Military Specification MIL-R-81841 [5] Rotary Flap Peening of Metal Parts [6,7]. According to this specification, Almen peening intensity for complete coverage for steel parts between 2.3 and 9.5 mm (0.09 and 0.375 inches) in thickness should be between 0.006A and 0.012A (arc-height inches). A rotary flap mandrel was used with a 14.3 mm x 31.8 mm (9/16 in x 1-1/4 in) flap assembly (type TC330), which is constructed with a double row of 330 tungsten carbide shot. To establish the settings for peening the test samples a rotary tachometer was used to measure the air tool rotational speed. The supply air pressure was reduced from shop supply air to provide a speed between 4200-5200 RPM. This variability in rotational speed was observed during several measurements and may be attributed to the rotary tool itself. Pressures this low are at the minimum end needed to operate the tool. The mandrel was held 6 mm (¼ in) above the peened sample. Peening settings were determined by peening several Almen test strips. The Almen test strips were found to achieve full saturation at between 2-3 minutes of peening. Almen test strip deformation was measured with a digital Almen gage. Nine of the T-shaped fillet weld samples were peened using the same settings that were established for the Almen test strips. Fatigue test specimens were peened for five minutes on each side of the welded joint to ensure saturation.

Experimental test matrix for the peening effect on fatigue is summarized in Table 1. The fatigue test samples were installed into a MTS Model 810 22-kip hydraulic load frame as seen in Figure 1. One un-peened T-sample was instrumented with a uni-axial strain gage (Vishay part number CEA-06-062UW-350). This gage was placed so that the foil sensing grid was centered approximately 1 mm away from the toe of the fillet weld. The gaged sample was installed in the hydraulic load frame as shown in Figure 1. Test samples were loaded into the tensile test machine and cycled under load control with deflection limits set to suspend testing when a crack occurs. The test controller was set to cycle the specimens using a sine wave force input. Low cycle fatigue samples were cycled from 839 MPa tension to 17 MPa tension. High cycle fatigue samples were cycled from 285 MPa tension to 17MPa tension. In order to avoid control issues it was decided that this test would not be fully reversed. The minimum load was selected for both loading levels to keep a minimum load close to zero on the load fixture at all times in order to prevent issues with non-linear control due to slop in the specimen loading fixture. Metallography study was conducted on weld specimens after sample polishing and etching with 2% or 4% Nital solution. Sub-surface quality was evaluated with microhardness measurements. Optical and scanning electron microscopy was used to evaluate the weld microstructures and also for fractured surface examination of the cracked test samples.

Results and Discussion

Typical photo macrographs of the peening process and the resulting peened surface samples by using both surface treating methods are shown in Figure 1 (right –top and bottom). Note that hammer-peened surface is very rough in comparison to the rotary flap peening.

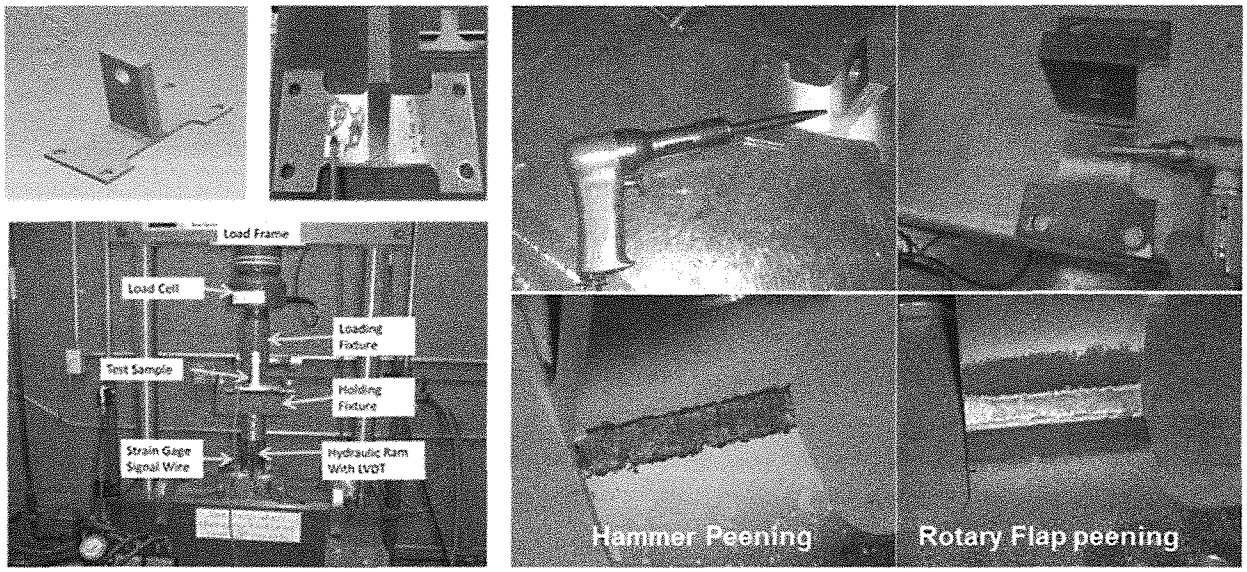

Figure 1: Test Setup (Left), and Typical peening process and peened surfaces (Right)

Variability of surface topography is shown in the optical micrographs of Figure 2, both before and after the peening operation. The images in Figure 2(b, c, d) show the weld nugget at the left, the weld toe at center, and the base leg at the right. It can be seen from these images that the un-peened sample has variation in surface integrity between the weld and the base material. The hammer-peened surface seen in Figure 2b shows the significant modification in the peened surface, including the creation of ridges and valleys in the weld surface. The flap-peened surface (Figure 2d) has the greatest uniformity of the three samples examined.

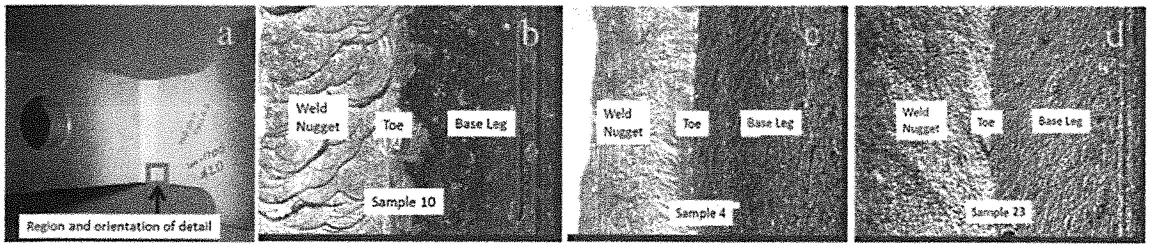

Figure 2: Detailed Surface Topography: (a). As welded sample, (c) Surface Detail – Baseline Un-Peened Sample, (b). Hammer Peened Surface, (d) Flap Peened Surface (20X)

Microhardness was measured across sectioned samples for the baseline, hammer peened, and flap peened specimens. Vickers Microhardness measurements were taken every 0.15 mm, beginning in the weld nugget away from the crack origin and traveling through the weld nugget and into the parent material. In Figure 3, sample #4 is the un-peened test case, sample# 10 is the hammer peened, and sample #22 is the rotary flap peened test samples. It can be noted that the hammer peening produced more work hardening of the weld nugget than the baseline or flap peened samples. Figure 4 is a plot of stress amplitude versus number of cycles to failure. This plot includes both low cycle (high stress amplitude) and high cycle (low stress amplitude) fatigue life. As can be observed from the data there is considerable spread observed in the experimental failure data. Hammer peening yielded very good improvement.

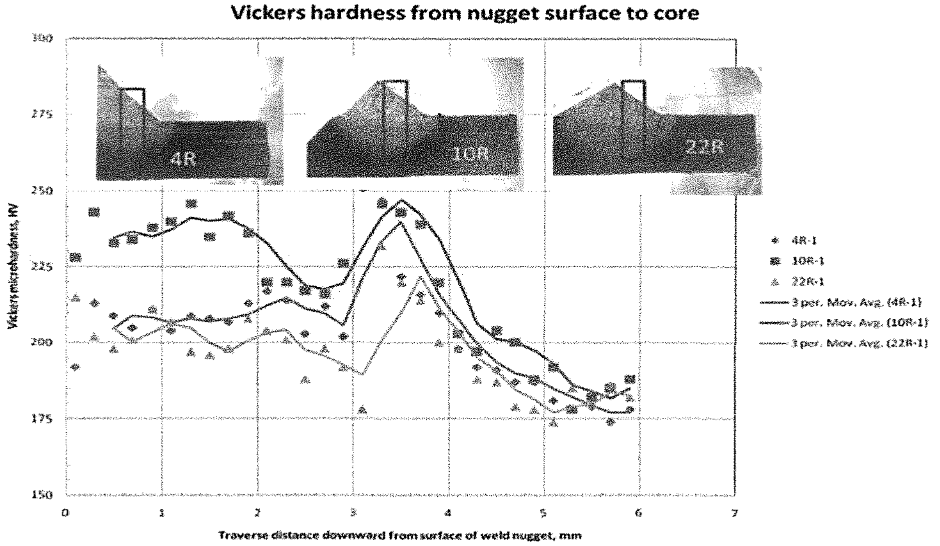

Figure 3 Microhardness vs. Distance Inward from Surface of Weld Nugget

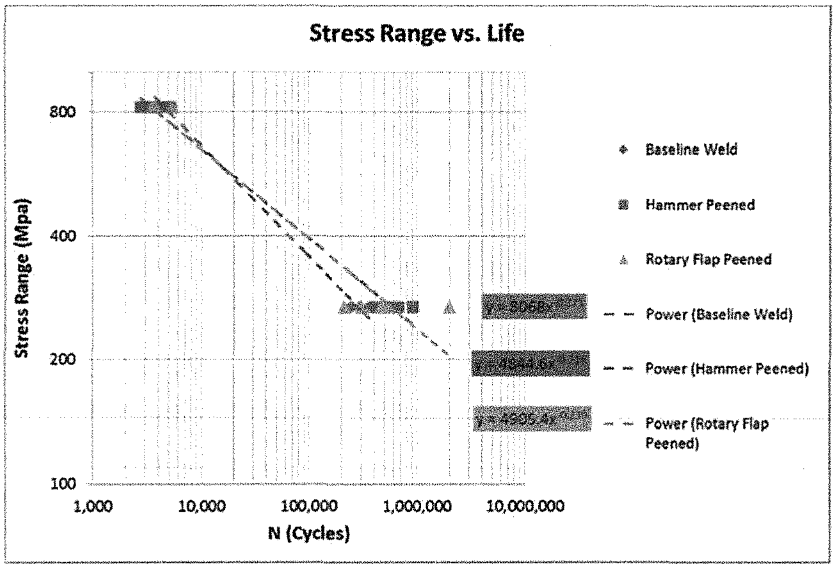

Figure 4 : Stress vs. Life Curve

The rotary flap peened samples displayed the largest variation in fatigue life. The extremes of this performance occurred in sample 23, which was suspended without failure at 2 million cycles, and sample 21, which failed at approximately 211,000 cycles for the same stress range of 268 MPa. In order to gain understanding of this variability the weld toe was examined under 20X magnification. Figures 5a and 5b shows sample 21 and the weld toe of sample 23 respectively. It is observed from these two images that the transition from the weld to the base material across the toe of the weld is very smooth for sample 23, while for sample 21 there is a groove in the part at this location. It is reasonable to conclude that the shot used in the flap peening process was too large to effectively peen this groove, resulting in a region without the beneficial surface compressive residual stresses. The smooth transition sample allowed good peen coverage, with overlapping dimples evident upon inspection, greatly prolonging the sample life. The welding and peening processes used in this project were highly manual in nature. This introduced the potential for variation in weld quality and peening coverage between samples [9]. The difference in weld toe geometry between samples 21 and 23, is an example of how this variation impacted test results. This is probably due to the undercut present in the weld toe evident in sample 21. This undercut is smaller than the diameter of the shot used in the rotary flap peening process. This prevented this region for receiving uniform peening coverage. The more gradual weld toe transition evident in sample 23 allowed for full peening coverage and greatly improved life. Inspection of the hammer peened weld specimens indicates that peening did not consistently cover the entire weld toe region. It is possible that improved results could have been achieved if peening had extended further across the weld toe into the base material. It is likely that more repeatable samples could be produced through the use of automated welding and peening processes. However, the purpose of this project was to evaluate these manual processes that can be accomplished in the field away from sophisticated manufacturing facilities. The variation seen in this test is likely typical [9], if not better than, what would be seen in the field. Hammer peening did introduce significant compressive stresses into the peened area of the test samples. This is evident from Figure 3, in which the hammer peened test sample has increased hardness near the surface of the weld as compared to the baseline or flap peened samples. The hammer peened samples also experienced different weld initiation site than the baseline or flap peened samples. Figure 5c and 5d shows crack initiation occurring in the weld nugget near the toe of the weld. All baseline or flap peened samples examined showed crack initiation only at the weld toe in the base material. This observation is consistent with results reported by Bell et al. [4] who found crack initiation in the weld root, propagating through the weld throat, then through the base material.

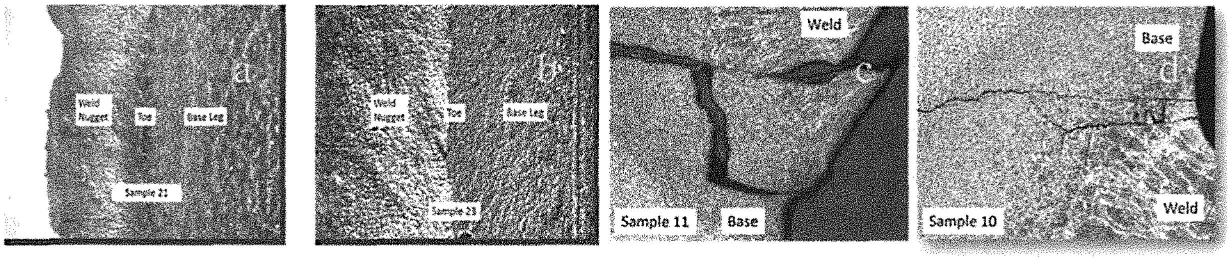

Figure 5: Weld Toe for Sample 21 (211,000 cycle failure), (a). Weld Toe for Sample 23 (Suspended without Failure at 2,000,000 cycles) (b). Hammer Peened Samples 10 and 11 Showing Crack Initiation in Weld Nugget (c, and d)

The results presented here identify significant improvement in high cycle (low stress) loading and a decrease in performance in low cycle (high stress) loading, in general agreeing with published observations for hammer peening. Due to the significant overlap in test data for the low cycle fatigue samples in cannot be said with great confidence that these three sample populations have different lives.

Summary and Conclusions

Two different surface peening processes were evaluated for their ability to increase fatigue life in fillet welds. These processes were hammer peening and rotary flap peening. T-shaped fillet weld test samples were fabricated and subjected to cyclic loading in three configurations; as-welded, welded and hammer peened, and welded and flap peened. Metallographic inspection was used to further evaluate the test samples following fatigue testing. Fatigue life estimation methods were considered based on both experimentally measured strain data and stress/strain results obtained through the use of finite element methods. The following conclusions can be drawn from this research.

1. Hammer peening was shown to increase fatigue life by 106% over the baseline un-peened samples at 50% confidence. Rotary flap peening was shown to improve high cycle fatigue life in welded samples by 52% when compared to the un-peened baseline at 50% confidence.
2. Hammer peened test specimens had greater microhardness near the surface, indicating the presence of greater compressive residual stresses than the baseline or flap peened test samples. It is believed that additional improvements can be made to the flap peening process through the addition of a toe grinding process between the welding and peening processes to smooth the toe of the weld and enable better peening coverage in the region of greatest stress concentration.
3. Additional improvements may be possible in the hammer peening process by ensuring more uniform peening coverage of the weld toe.

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