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Evaluation of Welding Residual Stress Levels Through Shot Peening and Heat Treating

Mark S. Molzen
Metal Improvement Co., Inc.

Doug Hornbach
Lambda Research, Inc.

ABSTRACT

The welding process induces residual tensile stress that is detrimental to fatigue life. Tensile stresses act to stretch or pull apart the surface of the material. With enough load cycles at a high enough tensile stress, a metal surface will initiate a crack. Significant improvements in fatigue life can be obtained by modifying the residual stress levels in the material. Two methods of performing this are through heat treating and shot peening. Both will be thoroughly analyzed in this paper through the use of x-ray diffraction. X-ray diffraction is the most accurate and best-developed method to characterize the residual stress in polycrystalline material.

INTRODUCTION

The intent of this paper is to evaluate residual stress levels as a result of welding and subsequent manufacturing processes. It is well known that when a welded component fails in fatigue the failure location is usually at the weld. Many people do not understand the role that residual stress plays in this failure.

Residual stress directly affects a components fatigue life. Detrimental residual tensile stress decreases fatigue life while beneficial residual compressive stress increases fatigue life. Both types will be thoroughly investigated through the use of x-ray diffraction in this paper.

This paper will investigate how detrimental residual stresses are created through the welding process. This paper will explain through theory and residual stress measurements how welding stresses can be modified by shot peening and heat treatment for a more beneficial condition from a fatigue standpoint.

To complete the technical study, multiple carbon steel coupons were welded and exposed to various manufacturing processes. The processes were as follows.

- Various Shot Peening Parameters
- Various Temperature Treatments
- Grinding Treatment
- Combinations of the Above Processes

RESIDUAL STRESSES

THEORY OF FATIGUE

Metal fatigue is the phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material. The type of stress of most concern is tensile stress. Tensile stress acts to stretch or pull apart the surface of the material.

Fatigue may start at a single point or several points, depending on the shape of the critical section and the type of loading. When a component is subjected to torsion and/or bending loads, tensile stress is highest at the surface of the material, which is where the overwhelming majority of cracks initiate. In addition, the component's geometry can concentrate tensile stresses at notches, holes, and cross-sectional changes.

Fatigue fractures are progressive, beginning as minute cracks that grow under the action of fluctuating tensile stress. A fatigue crack usually starts at the surface parallel to the maximum shear stress, but soon turns and advances perpendicular to the maximum tensile stress. Under the repeated action of the tensile stresses, the crack grows, weakening the section. Variations in cyclic loads cause small ridges, or "beach marks", to develop on the fracture surface. These marks indicate the position of the advancing crack root at a given time. As the section gradually weakens, the crack grows faster, and the beach marks get farther apart, larger, and more distinct. Thus, the presence of beach marks often helps to pinpoint the origin of the fracture.

In general, residual stresses are beneficial when they are opposite to the applied loading stress. The amount of residual compressive stress from shot peening is directly related to the reduction of the applied tensile stress, which can cause fatigue failure. Hence, more compressive stress results in greater improvements in fatigue properties. This is especially important since fatigue life is plotted as tensile stress on the vertical axis (on a linear scale) and life cycles on the horizontal axis (on an exponential scale). This means a linear decrease in tensile stress translates to an exponential increase in fatigue life. This is shown in the following graph commonly known as an S-N curve. Please note that the graph is not representative of any material.

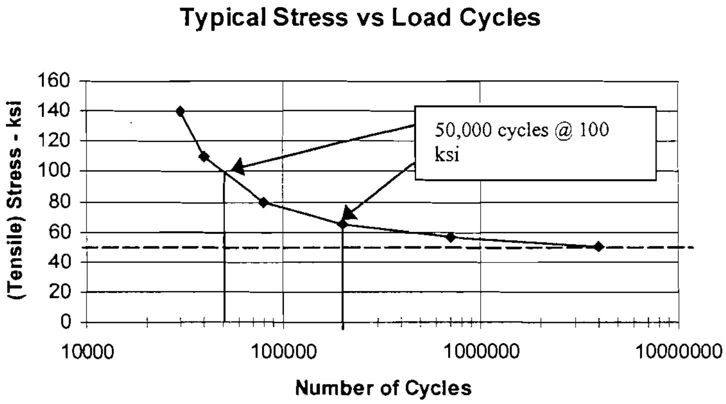

Figure 1: Typical S-N Curve

Some materials do not fail below a given stress level, no matter how many cycles they are subjected to. This stress when plotted on a S/N curve is called the endurance limit. This is noted by the dotted line in the above graph that shows at lower tensile stress levels, particularly the 50 ksi range, the life of the component approaches infinity as 10 million or more cycles can be expected. The purpose of shot peening, as stated before, is to induce compressive stresses to lower or offset the tensile stresses that cause fatigue failure.

Similarly, the stress to cause failure at any given number of cycles is called the "fatigue strength", and the number of cycles to failure at any given value of stress is called the "fatigue life." This is represented on the above S/N curve; 50,000 cycles @ 100 ksi and 200,000 cycles @ 65 ksi.

RESIDUAL STRESSES FROM THE WELDING PROCESS

Residual stresses are those that exist in a part independent of external force or restraint. Neglect of these residual tensile stresses created during welding processes can lead to stress corrosion cracking, distortion, fatigue cracking, premature failures in components, and instances of over design. When applied and residual stresses are accumulated, the net tensile stress seen by the components are much greater than the actual load applied. This is why welded components usually fail at the weld.
The American Welding Society (AWS) Handbook (Ref. 10) cautions readers to mind residual tensile stresses from welding, if the fabrication is subject to fatigue loading as described in the following statement. "Localized stresses within a structure may result entirely from external loading, or there may be a combination of applied and residual stresses. Residual stresses are not cyclic, but they may augment or detract from applied stresses depending on their respective sign. For this reason, it may be advantageous to induce compressive residual stress in critical areas of the weldment where cyclic applied stresses are expected."

The residual tensile stress from welding is created because the weld consumable is applied in its molten state. The weld is applied in its hottest, most expanded state. It then bonds to the base material, which is much cooler. The weld cools rapidly and attempts to shrink from the cooling. Since it has already bonded to the cooler, stronger base material it is unable to shrink. The net result is a weld that is essentially being "stretched" by the base material. The heat affected zone is usually most affected by the residual stress and hence where failure will usually occur. Inconsistency in the weld bonding material, chemistry, weld geometry, porosity, etc... act as a stress risers for residual and applied tensile stress to initiate fatigue failure.

RESIDUAL STRESSES FROM GRINDING

Residual tensile stresses and surface brittleness can be caused by the generation of high surface temperatures by friction during severe or conventional grinding operations. It has been found that residual tensile stresses created by grinding can approach the ultimate tensile strength of the material itself. Residual tensile stresses will dramatically affect fatigue resistance of ground parts.

In abusive and conventional grinding, tensile stress is created from generation of excessive, localized heat. The localized area attempts to expand. It cannot because it is surrounded by cooler, stronger metal. This metal yields in compression due to the resistance to its expansion. Upon cooling the yielded material attempts to contract. The surrounding material resists this contraction thus creating a residual tensile stress.

Because heat is the major cause of residual stresses in grinding, the importance of coolant for controlling these stresses is evident. Coolant is easily applied using automatic grinders, but it is rarely used with manual or hand grinders. If we had used an automatic grinder with coolant, with a gentle grind, this would in effect cold work the material and induced a slight amount of beneficial compressive stress at the surface. The residual stress distribution data for a gentle grind is not presented in this paper.

MODIFICATION OF RESIDUAL STRESS FROM THE SHOT PEENING PROCESS

Shot peening is a cold working process used to increase the fatigue properties of metal components. During the peening process, the surface of the component is bombarded with small spherical media called shot. Each piece of shot striking the material acts as a tiny peening hammer, imparting to the surface a small indentation or dimple. In order for the dimple to be created, the surface fibers of the material must be yielded in tension. Below the surface, the fibers try to restore the surface to its original shape, thereby producing below the dimple, a hemisphere of cold-worked material highly stressed in compression.

Overlapping dimples develop a uniform layer of residual compressive stress in the metal. It is well known that cracks will not develop in a compressively stressed zone. Since nearly all fatigue failures originate at the surface of a part, compressive stresses induced by shot peening provide considerable increase in part life. When controlled properly, all surface area, which is susceptible to fatigue crack initiation, is encapsulated in a uniform layer of high magnitude compressive stress.

Located throughout the paper are residual stress profiles (graphs) which were generated by the use of x-ray diffraction. These are plots of residual stress (tensile and/or compressive) versus depth from the surface. The three important variables (when shot peening is applied) are the surface compressive stress, maximum compressive stress, and depth of compression. This surface compressive stress is the stress at a depth of 0.000" or the very outermost surface layer. The next important variable is the maximum compressive stress which occurs.usually at .001" - .002" below the surface. The maximum compressive residual stress produced at or under the surface of a part by shot peening is at least as great as half the tensile strength of the material being peened. The final variable is the depth of the compressive layer, which is where the compressive residual stresses convert to tensile residual stresses. The subsurface tensile stress is a result of the previous welding operation and re-static balancing of the near surface compressive layer.

MODIFICATION OF RESIDUAL STRESS THROUGH ELEVATED TEMPERATURES

Complex parts that have been welded, cast, or machined often develop internal stresses that could cause distortion of their shape or affect their fatigue strength. To relieve these stresses, parts made from carbon steel are heated to between 1000 °F and 1200 °F (538 °C and 649 °C) and held at that temperature for a period of time determined by their cross sectional thickness. Parts are then cooled slowly to minimize the development of new residual stresses.

Metal is weaker when it is at higher temperatures. This is why residual stress (compressive or tensile) is relieved at higher temperatures. The strength of the metal is reduced and stresses are able to relieve themselves. Higher temperatures and longer exposure times are able to relieve more residual stress. The stress relieving process is benefical for welding stress as it reduces them, but detrimental for shot peening as beneficial compressive stress is removed.

MEASUREMENT OF RESIDUAL STRESS USING X-RAY DIFFRACTION

X-ray diffraction (XRD) is the most accurate and best developed method for quantifying residual stress due various mechanical/thermal treatments such as bending, coiling, shot peening, welding, machining, various finishing operations, etc... and offers several advantages over other methods, such as mechanical, ultrasonic or magnetic techniques. XRD is a linear elastic method in which the residual stress in a material is calculated from the strain in the crystal lattice. The theoretical basis and explanations are discussed elsewhere.(1) XRD can be employed to quantify the residual stress as a function of depth to thousandths of an inch below the surface, with high resolution due to the shallow penetration of the x-ray beam. XRD techniques are well established, having been standardized and developed by both the SAE(2) and the ASTM.(3,4)

XRD methods have been used for many years in the aerospace, automotive and nuclear industries to quantify residual stresses and are employed in quality control applications to verify and confirm specific levels of compressive stress on shot peened components. As engineers rely more on residual stresses to increase the performance of components, it is necessary to understand and control residual stress levels.

In order to determine the residual stresses as a function of depth for this test study, XRD residual stress measurements were obtained in the longitudinal direction, parallel to the weld deposition for the welded samples. Measurements were made from the surface to a nominal depth of 15×10^{-3} in., in nominal increments of 1×10^{-3} in., for the ground samples. Measurements were made from the surface to a nominal depth of 30×10^{-3} in., in nominal depth increments of 2×10^{-3} in., for the shot peened and welded samples. These depths were chosen to best define the residual stress distribution due to grinding, shot peening, and welding. The residual stress measurements were made at mid-length on the processed side of each sample

X-ray diffraction residual stress measurements were made by the two-angle $\sin^2\psi$ method per SAE J784a.(2) Multi-angle measurements were obtained at 35×10^{-3} in. below the surface on the As-Welded sample to verify a linear dependence of lattice spacing vs. $\sin^2\psi$. The results show a linear response of lattice spacing vs. $\sin^2\psi$, indicating a condition of plane stress at the surface, appropriate for XRD methods. Measurements were made employing the diffraction of chromium K-alpha radiation from the (211) crystallographic planes of the BCC structure of the 1018 steel. The diffraction peak angular position at each psi tilt was determined from the position of the K-alpha 1 diffraction peak separated from the superimposed K-alpha doublet assuming a Pearson VII function diffraction peak profile in the high back-reflection region.(5) The diffracted intensity, peak breadth, and position of the K-alpha 1 diffraction peak were determined by fitting the Pearson VII function peak profile by least squares regression after correction for the Lorentz polarization and absorption effects and for a linearly sloping background intensity.

A 0.1 x 0.3 in. irradiated area (long axis in the longitudinal direction) was used on the sample surface for all of the residual stress measurements. The radiation was detected employing a scintillation detector set for 90% acceptance of the chromium K-alpha radiation.

The value of the x-ray elastic constant, E/(1 + ν), required to calculate the macroscopic residual stress from the strain measured normal to the (211) planes of 1018 steel was previously determined empirically(6) by employing a simple rectangular beam manufactured from 1018 steel loaded in four-point bending on the diffractometer to known stress levels and measuring the resulting change in the spacing of the (211) planes in accordance with ASTM E1426-94.(4)

Material was removed for subsurface measurement by electropolishing a nominal 0.7 x 1.0 in. pocket at mid-length of each sample in a phosphoric-sulfuric acid base electrolyte solution. The electropolishing minimizes the possible alteration of the residual stress distribution as a result of material removal. All macroscopic residual stress data obtained as a function of depth were corrected for the effects of penetration of the radiation employed for residual stress measurement into the subsurface stress gradient.(7) Stress relaxation due to layer removal was corrected by employing the method of Moore & Evans,(8) assuming the specimen behaved as a flat plate in the area which was electropolished. The higher the stress and the greater the depth of removal, the larger the relaxation will generally be.

Systematic error due to instrument alignment was monitored employing a powdered iron zero stress reference sample. The measured residual stress in the powdered iron sample was found to be within ± 1.3 ksi of zero stress.

The microscopic residual stress was determined during the macrostress measurement by measuring the full width at half maximum intensity (FWHM) of the (211) diffraction peak in the psi = 10 deg. orientation. The (211) diffraction peak width is a sensitive function of the chemistry, hardness, and the degree to which the material has been cold worked. In martensitic steels, it is commonly observed that plastic deformation produced by processes, such as shot peening or grinding, will cause work softening and a reduction in the peak width. In work hardening materials, the diffraction peak width increases significantly as a result of an increase in the average microstrain and the reduced crystallite size produced by cold working. Empirical relationships between cold work or hardness and peak broadening for several nickel base, titanium and steel alloys have been determined. No calibration curves were obtained to define such dependence for the 1018 steel peak breadth investigated in the present analysis.

RESULTS OF MANUFACTURING PROCESSES

This study used 1018 carbon steel coupons of dimensions 1 in. x 1 in. x 3 in. long. The hardness was Brinell Hardness Number (BHN) 150 – 180 (R_b 80 – 90).

WELDED CONDITIONS

A certified welding technician from Metal Improvement Co. using an AWS E7018-3/32 weld rod performed the welding. The welding was performed at 90 amps.

Graph 1 shown in Figure 2 demonstrates the residual tensile stress generated from this welding procedure. The stress is ~ 7.0 ksi in tension at the surface. As explained in the theory section of this paper, this tensile stress is detrimental and will accelerate fatigue failure. For example, a component that would normally experience a 40 ksi tensile stress will actually experience a net 47 ksi stress.

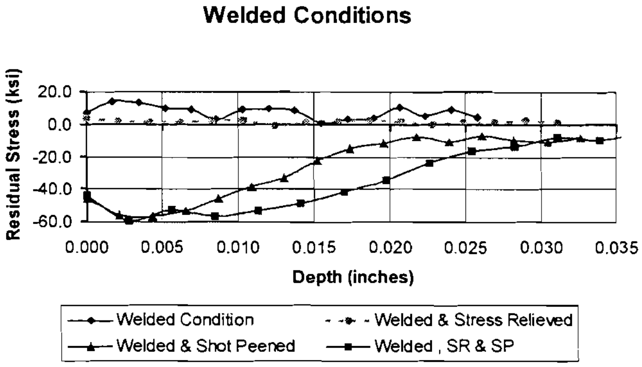

Figure 2: Graph 1 – Welded Conditions

WELDED AND STRESS RELIEVED

Graph 1 demonstrates that the 7.0 ksi tensile stress is reduced to ~ 3 ksi through stress relieving. The stress relief temperature was 1150 °F for one hour. One can see that 100% of the tensile stress is not removed by stress relieving. However, any reduction of tensile stresses is beneficial from a fatigue standpoint. If the tensile stress had a greater magnitude, it would have experienced a greater decrease through stress relieving than the 4 ksi above. This will be demonstrated later in this paper. Stress relieving will never reduce the residual stress below zero.

WELDED AND SHOT PEENED

Graph 1 demonstrates the large stress reversal induced by shot peening. The 7.0 ksi tensile stress has been converted to ~ 60 ksi of compressive stress at the surface. This represents a stress reversal of ~ 67 ksi. Since less tensile/more compressive stress is better, one can see noticeable benefits from shot peening welds. A component that would normally experience a 40 ksi tensile load (at the surface) will experience a net ~ 20 ksi compressive stress. This will dramatically improve fatigue performance in a repetitively loaded environment.

The shot peening parameters used in this study were hardened cast steel shot (0.046" ∅) and the intensity or the kinetic energy used was at a 6 - 7C. The depth of compressive layer is ~ 0.023" deep as shown in Graph 1. This means that should a fatigue crack ever develop, its growth will be resisted by the compressive layer until it achieves a depth of ~ 0.023". Compressive surface stress provides this two-fold benefit. Crack initiation is significantly delayed and crack growth is significantly retarded.

Photograph 1 shown in Figure 3 (courtesy of Mr. A J. Brar; Seagate Technology, Minneapolis, MN) is a 30x magnification of the shot peened surface. One can see the uniform overlapping dimples from the peening process. In the welding process, it is important to minimize any overlaps, folds, or undercuts that would be geometrically too small for the peening media to cover with dimples.

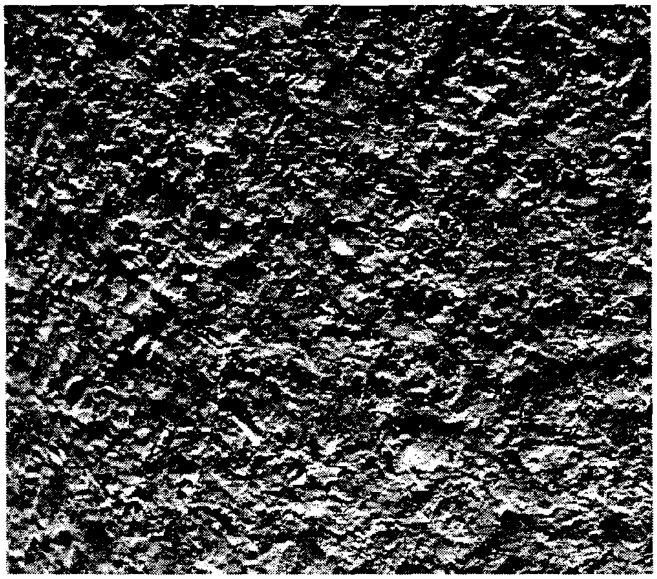

Figure 3: Photograph 1

WELDED, STRESS RELIEVED AND SHOT PEENED

Stress relieving and shot peening are both used to lower tensile stress conditions. Graph 1 shows that the maximum compressive stress is ~ 60 ksi which is similar to the welded and shot peened condition. One notes that the depth of compression is ~ 0.032" deep.

The reason for the additional compressive depth is that the coupon was shot peened after stress relieving. The thermal exposure softened the material causing a decrease in the yield strength of the metal. The shot peening therefore deformed a deeper layer of material as a result of the decrease in material strength.

One can see that this is an optimal condition from a fatigue standpoint. One should note that this process is the most expensive from a manufacturing perspective, as more operations are required.

SHOT PEENED VERSUS DUAL PEENED

A dual shot peen operation is used to improve fatigue properties beyond that of a single peened surface. This is accomplished by shot peening the same surface a second time at a reduced energy level (intensity). Photograph 2 shown in Figure 4 is a 30x magnification of the dual peened surface. One can see that the surface finish is less aggressive than the single peened surface finish. This is because the smaller media is able to obliterate the high points from the first peening operation.

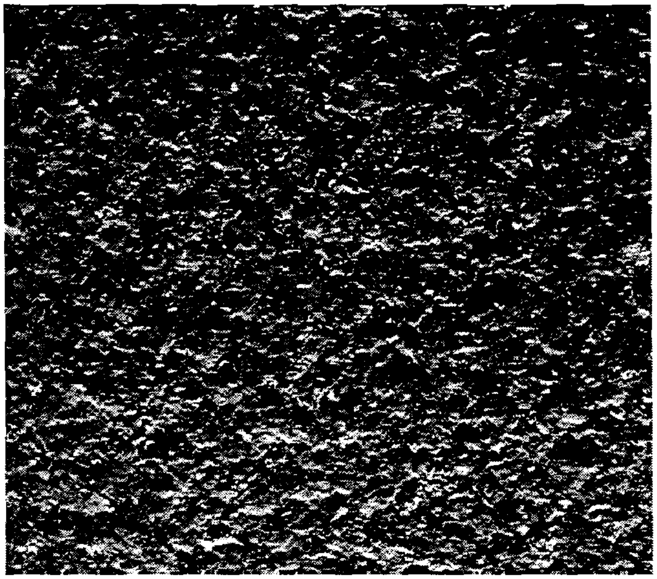

Figure 4: Photograph 2

Fatigue testing has shown that dual intensity peening will produce an even greater improvement in fatigue resistance than single peening. The purpose of dual peening is to increase the compressive stress at the surface fibers (depth=0.000") with a secondary peening operation. By further compressing the top surface fibers, initiation of a fatigue crack becomes more difficult. The dual peen was performed with a 0.023" ∅ shot at a 10 - 12 A kinetic energy/intensity. Since this is a lower intensity, there will be no change to the depth of the compressive layer. It would take a greater intensity, which has more kinetic energy to drive in a deeper depth of compression.

The reason that dual peening increases the surface compressive stress is that the magnitude is a function of disruption or dimpling of the surface. A properly shot peened surface has a uniform dimpled appearance. The surface consists of high points and lower plateaus. These are the result of the surface material being displaced as the peening media impacts it. A more aggressive peening operation (higher intensity) will result in larger dimples. The high points are less compressed than the lower plateaus.

The smaller media is able to further compact the high points left from the first peening operation. The dual peening leaves another uniformly dimpled surface, but the high points are smaller than the first peening operation. This results in a finer surface finish and more compressed top surface layer.

Graph 2 shown in Figure 5 demonstrates the surface improvement. The (single) peen operation from before resulted in an ~ 45 ksi surface stress. The dual peen operation further compressed the surface to ~ 55 ksi. An improvement of 10 ksi at the outer surface should significantly improve fatigue performance from a single peen operation. This is because on the S/N curve the tensile stress is 10 ksi closer to the endurance limit.

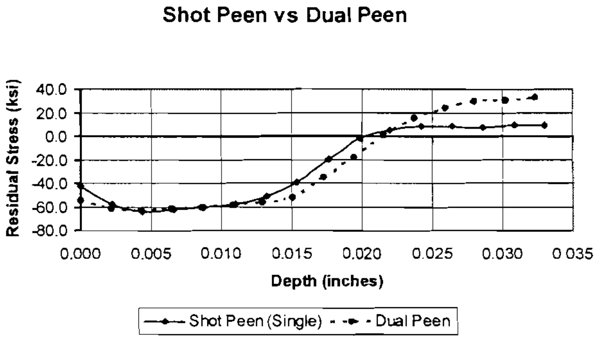

Figure 5: Graph 2 – Shot Peen vs Dual Peen

RESIDUAL STRESSES FROM GRINDING

The abusive and conventional grinding was done using a hand-held grinder with a Norton aggressive bond, type 27 grinding wheel. In this process, material is removed by hard, sharp particles plowing material out in furrows. Tensile stresses were created from generation of excessive, localized heat. Abusive grinding is generally indicated by a "red hot spot" on the metal during grinding.

Graph 3 shown in Figure 6 is the residual stress distribution created by abusive and conventional grinding. This study evaluated ground coupons that were both previously welded and not welded. It is quite evident that abusive and conventional grinding generated high magnitudes of residual tensile stress at or near the surface of the material. The detrimental tensile stress is as great (and opposite) as the shot peening compressive stress, ~ 55 ksi. This tensile stress will, of course, dramatically decrease fatigue resistance.

SHOT PEENING WITH VARIOUS 30 MINUTE BAKE TEMPERATURES

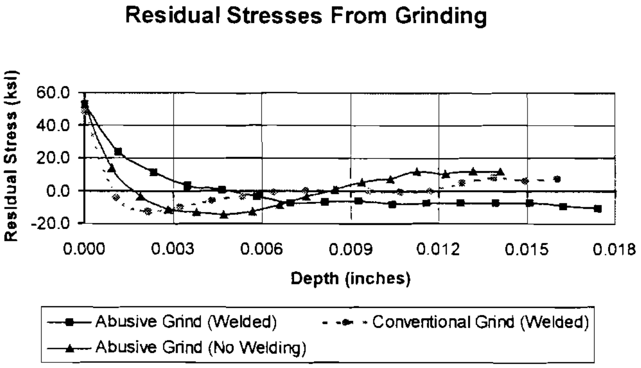

Figure 6: Graph 3 – Residual Stresses From Grinding

This is an interesting study on how heat relieves residual stresses (tensile or compressive) at various bake temperatures. As stated previously, higher temperatures and/or longer baked times will relieve more stress. The study took similar shot peened coupons (0.046" ∅ @ 6 - 7C) and brought three to LCL Services, St. Paul, MN. who baked them at 500 °F,
700 °F and 900 °F for 30 minutes.

Graph 4 shown in Figure 7 demonstrates what various temperature treatments will do to relieve residual compressive stresses. The outer surface stress is primarily affected at the 500 °F and 700 °F bakes. The 900 °F bake relieved significantly more compressive stress than the 500 °F and 700 °F bakes. It is interesting to note that ~ 50% of the compressive stress remains after the 900 °F bake. This is 150 °F lower that the temperature the coupons were stress relieved at.

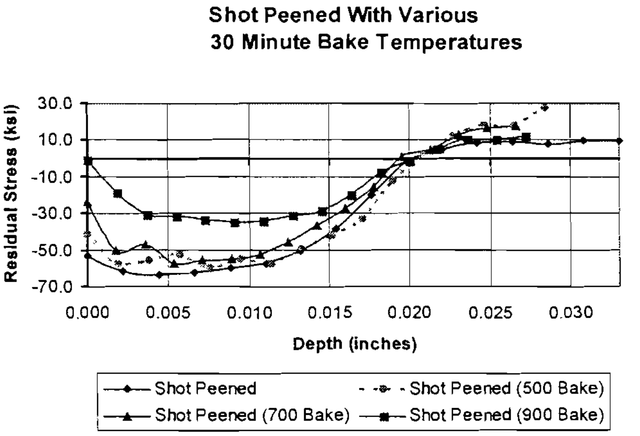

Figure 7: Graph 4 – Shot Peened With Various 30 Minute Bake Temperatures

CONCLUSION

When weldments are used in a fatigue environment, the designer needs to consider both stresses from applied loads and residual stresses from the manufacturing. This paper has demonstrated that welding and grinding processes create residual tensile stresses. These stresses can be reduced through heat treating and shot peening processes to improve fatigue properties.

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- All Heat Treatments
  LCL Services
  Roseville, MN (651) 639-1129

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