SHOT PEENING SUCKER RODS TO PROLONG FATIGUE LIFE

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ABSTRACT

Shot peening has been utilized for many years in a variety of industries as a surface conditioning process for metals. When properly performed, shot peening imparts beneficial residual compression stresses to the surface and subsurface of a metal which enhances the fatigue resistance and corrosion tolerance properties. Shot peening is primarily used on components that operate in cyclic loading environments. Since sucker rods are subjected to alternating loads, shot peening should prove to be a viable method of retarding the effects of cyclic fatigue, thereby extending the service life of the rod. This paper will encompass: the shot peening method, effects, control, and benefits, shot peening vs. shot cleaning, residual stress measurement test results, high cycle rotational bending fatigue test results, testing of peened vs. non-peened new sucker rods, testing of shot peened vs. shot cleaned used rods, and testing of single peened vs. dual peened new rods to compare different peening processes and formulae.

INTRODUCTION

Shot peening is the discipline of controlled surface impingement alteration of metallic objects to enhance fatigue life by conditioning a surface and inducing beneficial residual compressive stresses. Peening evolved from a rudimentary art prompted by an inadvertent discovery of the advantageous consequences of hammering the surface of a metal. Centuries ago, metal implements, particularly military paraphernalia, were formed into the desired shape by hammering. Shields, swords, spear tips, axes, helmets, body armor, etc. were all subjected to hammering as a process of manufacture. At some point in time metal workers came to the realization that such hammering, if done in a particular manner, could enhance the fatigue strength and thereby extend the fatigue life of these materials. It was a long period of time before this knowledge became widely known because it was passed down through generations from master to apprentice in a secretive manner in order to preserve their livelihood and position in the marketplace. Eventually the cloak of secrecy was breached and hammer peening became a universal practice.

The mechanics of peening is relatively simple. Each hammer blow causes plastic deformation of the metal, stretching it radially and creating a depression. The underlying layers of the material react to this deformation resulting in residual compression stresses at the surface and subsurface of the metal. This compression layer is beneficial primarily because it retards crack initiation and crack growth. Cracking is the most prevalent mechanism of failure in metal components utilized in cyclic loading applications. A crack forms, usually at the site of a stress concentrator on the surface, and perpetuated by the cyclic loading advances to a critical dimension resulting in failure of the part. Cracks do not progress as aggressively in compression; therefore the residual compression from peening significantly slows the crack initiation and growth time, thereby prolonging the life of the metal component.

Modern day shot peening involves bombarding the surface of a metal with a barrage of high velocity particles. Each particle acts as a miniature peening hammer inducing the residual compression stress effects. Shot peening has been used successfully for decades in various industries and applications such as automotive, aerospace, railroad, medical, and military. Gears, torsion bars, axles, springs, aircraft landing gear, jet engine turbine blades, crankshafts, aircraft and marine propellers; all benefit from shot peening. These are all made of metal and all are utilized in cyclic loading applications. Sucker rods share these two common aspects and therefore should benefit from shot peening as well. This paper will explore that premise.

PEENING METHOD

All sucker rod specimens tested were shot peened at the TRC Services of Texas, Inc. facility in Midland, Texas using a Wheelabrator single-wheel downblast skew roll peening machine (Figure 1) designed specifically for sucker rods. The machine consists of a manganese blast cabinet with entry and exit vestibules, entry and exit skew roll conveyors, a motor driven blast wheel, a screw conveyor to transfer spent media, a bucket elevator for conveying feed shot, a multi-stage media separator/classifier to sort shot by size and shape, multiple culled shot collection receptacles, a shot replenisher, and a dust collection system. Sucker rods are conveyed through the cabinet at a controlled linear speed and rotation. The multi-vane blast wheel (Figure 2) propels shot particles onto the rod at high velocity at a rate of millions of particles per second. Spent shot is transferred to the classifier system where undesirable shapes and sizes are purged from the machine and acceptable particles are fed back into the blast wheel along with new particles from the replenisher.

Peening is performed using various media types including ceramic beads, glass beads, cut wire shot, and steel shot. Peening media used for this project was cast steel spherical shot pellets. These pellets are available in various sizes and hardness. Typical pellet size is quite small, standard sizes ranging from .007" to .130" in diameter and hardness ranges from 45 to 62 HRC. The critical properties of the shot media used for the tests described in this paper were consistently monitored and controlled by the classifier systems on the machine and by quality assurance testing in adherence to a stringent operating procedure.

As a result of years of research and experimentation, TRC has developed a discrete specialized "recipe" for shot peening and does not publicly divulge this formula. Notwithstanding, all sucker rod specimens tested were peened using identical operating parameters. Blast media properties, blast stream intensity, coverage rate, exposure time, shot flow rate, and all other pertinent factors were maintained in congruence as much as possible for all test specimens.

PEENING EFFECTS

The collision impact of each shot particle affects the surface and subsurface of the material being peened. An indentation (Figure 3) is created, inducing a region of compression (Figure 4) in the adjacent area. This compression zone (Figure 5) is approximately three times the diameter of the dent. Consequently, compression zones from multiple particle strikes in close proximity will overlap. Since peening involves a colossal number of particle strikes, the overlapping compression zone effect grows very rapidly into a uniform layer of residual stress at and below the surface of the metal. So, a material that is verified to have what is considered full peening coverage (98%) on the outer surface actually has well beyond 98% coverage of residual compression stress zones at the surface and subsurface.

PROCESS CONTROL

There are a number of variables that affect shot peening effectiveness and repeatability such as peening intensity, surface coverage, shot velocity, shot flow rate, impingement angle, blast stream exposure time, and shot properties. These variables have to be quantified and regulated in order to achieve the preferred peening benefits. This is accomplished by implementing control measures such as adherence to specifications and written procedures, blast stream intensity measurement, coverage verification, peening media inspection, equipment adjustment and maintenance, and operator training.

Blast stream intensity is measured using the Almen method. This method was developed and introduced in the 1940's by J. O. Almen, an engineer at General Motors. This is at present the industry-wide accepted method for measuring blast stream intensity. This method involves the use of a small steel test coupon or "strip" (Figure 6) and a precision test gage. The strip is made of SAE 1070 cold rolled spring steel with a hardness of 44-50 Rockwell C. The strip is 3 inches long, .750 inches wide and is available in 3 different thicknesses to cover a range of anticipated blast stream intensities. The strip is attached to a fixture and one side exposed to the blast stream. This causes the strip to stretch and bow to a particular curvature predicated by the energy level of the blast stream. The precision test gage (Figure 7) is used to measure the extent of the arc of deflection in the strip. The degree of this curvature, known as arc height, is an index correlated to blast stream intensity. Peening intensity is determined by plotting a saturation curve using multiple exposure times until doubling the Almen strip exposure time results in 10% or less increase in arc height.

Complete coverage is crucial in shot peening so that the entire peened area is engulfed in residual stress. Coverage is simply the measure of surface area that has been sufficiently impinged by particle strikes. Peening coverage is typically verified visually under 10 power magnification. Blast stream exposure time will affect coverage and is controlled by conveyor speeds, work present sensors, and work handling mechanisms.

Shot velocity, flow rate, and impingement angle are controlled by wheel speed, distance to the workpiece, motor size, wheel characteristics, feed gates and impeller system control cage settings.

Shot integrity is a vitally important to the peening process. In order to achieve the optimum surface and subsurface conditioning and compressive stress levels, the shot must be maintained very near to "as new" size, shape, and weight. Since spent shot is recycled through the machine, repeated impacts eventually cause the shot particles to begin to disintegrate by flaking and fracturing. This results in smaller, misshapen, and sharp edged particles and fragments which do not have the required mass to impart proper compressive stresses and may damage the work piece due to their jagged edges. The classifier and separator systems must cull out unqualified shapes and sizes so that only the desirable shot re-enters the work mix. This must be verified by regular sampling and inspection of in-use media as well as inspection of new media added to the machine. Shot is inspected for shape by taking representative samples of new and in-use media and scrutinizing under a 20x top-lighted microscope (Figure 8). A percentage or count of undesirable particles per specified sample size is calculated and compared to a tolerance. Shot size is verified by agitated screening of samples of new and in-use media using a series of certified sieve screens (Figure 9) and comparing weight (Figure 10) or volume of shot passing through and retained on screens to specified tolerances.

PEENING BENEFITS

If all process parameters are properly controlled, the beneficial consequences of shot peening will be effectuated. Depending on the component and application, these benefits may include: improved fatigue properties, stress corrosion cracking resistance, relief of residual tensile stresses, reduced susceptibility to hydrogen embrittlement, crack arrest, and resistance to hydrogen assisted corrosion.

SHOT PEENING vs. SHOT CLEANING

Shot *peening* is a rigidly controlled process for specific surface conditioning. By comparison, shot *cleaning* imposes minimal process control and is simply a particle impact method used primarily for the removal of surface contaminants. Shot cleaning and shot peening both utilize a hail of high speed particles to perform a task, but few if any of the aforementioned shot peening process control features are necessitated or applied in shot cleaning. Therefore, it stands to reason that a shot cleaned sucker rod will most likely not have the beneficial residual compression layer and may contain surface damage from broken particle strikes. For this reason, a shot cleaned sucker rod will most likely not deliver the same in-service fatigue performance as a shot peened sucker rod.

SPECIMENS AND TEST METHODS

Substantial funds were accrued for this test project and an extensive series of tests were carried out over a three year period for the purpose of comparing TRC shot peened sucker rod specimens to "as received" condition sucker rod specimens. The expression "as received" as it pertains to this paper is defined as: new sucker rods in their unaltered state and condition as purchased or otherwise procured from a manufacturer or authorized distributor; and Class 1 inspected used sucker rods in their unaltered state and condition as purchased or otherwise procured from a third party inspection company. A select number of the "as received" new rod specimens were purportedly shot peened by respective manufacturers prior to the testing, the remainder of which were not peened.

All sucker rods in the tests were prepared by immersion in a chemical solvent bath to remove all surface coatings and inhibitors. The rods were then shot peened enveloping one-half of the total length. The remaining half was left in as-found condition. This provided individual rods that were shot peened along one half of the longitudinal axis, and in "as received" condition on the opposite half (Figure 11), so that each specimen group could be segmented from the same rod. This assured that within test groups each specimen was of the same material, with shot peening being the only variable.

Four principal phases of testing were conducted: new rod residual stress measurement, used rod residual stress measurement, new rod fatigue testing, and used rod fatigue testing. The test methods employed were: blind drilled hole strain gaging, and high cycle rotational bending fatigue.

RESIDUAL STRESS MEASUREMENT

The first phase of testing was undertaken to determine if there were actually any residual compression stresses present in sucker rods shot peened at the TRC facility and if so, to what degree. Sucker rods used for this test were one inch diameter, API Special Alloy D, four-foot pony rods with matching heat codes. Two new pony rods and two Class 1 used pony rods were used for this test. The pony rods were prepared and proportionally shot peened in the manner described in the previous section. All rods remained intact since segmenting was not necessary for this particular test method.

After experimenting with residual stress measurement techniques, among them Barkhausen noise analysis and X-ray diffraction, it was determined that blind drilled hole strain gaging was the most ideally suited method of choice for small diameter round bars such as sucker rods. This method involves the use of a specially configured strain gage known as a rosette containing several grids, each oriented radially in a different axis on a two-dimensional plane. The rosette is affixed to the surface of the rod and the grids are wired and connected to a multi-channel static strain indicator. A precision targeting device (Figure 12) is aligned over the exact geometric center of the rosette and an ultra high speed air turbine drill is used to drill a flat-bottomed hole at the center of the rosette. The hole creates a stress-free cylindrical air space in the metal. The existing stress field in the surrounding metal acts upon the newly created free surface and adjusts for equilibrium. The cylindrical hole will expand or contract in a direction predicated by the residual stresses in the material, and the strain gages in the rosette measure this movement. The relaxed strains correspond to initial residual stresses in the rod. The magnitude and orientation of the residual stresses is calculated from the measured strains. The descending penetration of the drill allows incremental subsurface stress measurements to be made at various depths below surface as the drill advances.

Stress Engineering Services, Inc. in Houston, Texas was commissioned to perform the testing. Drilled holes were .040" in diameter and .040" maximum depth. It was anticipated that the effective compressive stress in the shot peened rod portions would extend to approximately .015" to .020" below the surface, with the maximum stress at approximately .010" below surface. The drilled hole gaging method was validated to provide a maximum sensitivity up to a depth of .030" which was deemed adequate to capture the expected stress effects of interest.

Measurements were performed every .003" of hole depth. Over a hundred measurements were executed. The shot peened portions of the rod samples showed a significant increase in residual compressive stress levels compared to the "as received" portions (Table I). The magnitude of compressive stress was an average of 32.5% greater on the shot peened new rods and an average of 60.4% greater on the shot peened used rods. At the .012" below surface level, shot peened used rods showed an average increase in compressive stress of 82.5% over non-peened portions. The statistical differential in compressive stress levels between shot peened and non-peened used rod samples was greater than that of new rod samples. This was to be expected since used rods may have residual tensile stresses from cold working caused by the repeated load reversals of the pumping cycle. Shot peening overcomes these tensile stresses and supplants them with compressive stresses. This would account for the greater difference in stress levels between shot peened and non-peened used rod samples. Compressive stress levels in the shot peened portions, both new and used, peaked at the .009" below surface depth and remained substantial through the .015" depth before gradually tapering off, with all stresses remaining compressive throughout the entire depth range.

FATIGUE TESTING

The next phase of testing was undertaken to compare performance of shot peened rod specimens to "as received" rod specimens in physical tests. High cycle rotational bending fatigue was the method selected for these tests. Over 150 million total cycles of testing was completed assessing over 100 sucker rod specimens.

A fatigue testing machine was designed and fabricated for TRC by A D & E Engineering in Odessa, Texas. It is a cantilever type rotational bending apparatus (Figure 13) consisting of a load frame, an electric drive motor intermeshed via a spider gear shaft to a threaded collet sleeve sheathed within two pillow-block bearings, a collet nut and interchangeable collet grip, a dual roller bearing yoke with gas shock stabilizers, a threaded member with side load adjustment collar and vertical/horizontal travel assembly, a digital load sensing device, and an electronics package consisting of a digital timer, digital cycle counter, digital rpm control, and shut-off brake control. The vertical/horizontal travel assembly provides variable side load and variable distance from fixed point, enabling adjustable moment of inertia capability. Cycle frequency can also be adjusted via the rpm controller.

When a sucker rod specimen is inserted into the machine, a controlled bend can be applied at a controlled leverage point. This results in tensile stresses on the convex side of the bend and corresponding compression stresses on the concave side of the bend. These stresses are at a maximum on the surface of the rod and cascade to zero stress at the center of the rod cross-section. The high speed rotation of the drive motor results in a rapidly repeating tension/compression cycle at any given point on the rod circumference at any given position in the rotation. This cyclic loading eventually results in fatigue failure of the specimen. All specimens were tested to failure and cycle counts were recorded.

New Rods

The first stage of fatigue testing was performed on new rod specimens. A total of eighty new rod specimens were tested. Specimens were taken from new 3/4” diameter API Carbon D and API Alloy D sucker rods. Rods from five different manufacturers were tested. Half the length of each rod was shot peened and the other half preserved in the “as received” state. Rods were then segmented into 39” lengths resulting in eight test groups with ten specimens per group. Each test group contained five shot peened specimens and five “as received” specimens. Rods within each test group were same manufacturer, same grade, and matching heat codes. Each test group consisted of six specimens taken from one rod: three shot peened and three “as received”; and four specimens taken from a second rod with matching heat code: two shot peened and two “as received”. Each specimen was permanently marked and given a unique specimen number. Four of the test groups contained specimens from rods that were purportedly shot peened by the manufacturers prior to receipt at the TRC test facility.

All fatigue machine parameters, side load, distance from fixed point, rotation speed, etc. were identical for all specimens. Specimens were tested at a calculated stress of 50% of tensile strength and cycled at 23½ revolutions per second until failure.

Overall, shot peened specimens outperformed “as received” specimens by a margin of 1.7 to 1 with total cycles to failure for shot peened specimens being 86.9 million versus 51.4 million for “as received” specimens (Table II). Average cycles to failure for shot peened specimens was 2,173,201 cycles. Average cycles to failure for “as received” specimens was 1,285,326 cycles. This equates to an average fatigue life increase of 69% for shot peened specimens.

The Alloy D specimens responded better to peening, with shot peened Alloy D specimens yielding a 74% increase in cycle life versus a 61% increase for shot peened Carbon D specimens. Alloy D specimens (both shot peened and “as received”) also outperformed Carbon D specimens by approximately 3 to 1 in total cycle life.

“Dual peened” specimens, those which were shot peened by manufacturers and subsequently shot peened again by TRC, outperformed single peened specimens by a 2.24 to 1 margin, yielding 124% greater average cycles to failure. In the “as received” groups, manufacturer shot peened specimens outperformed manufacturer non-peened specimens yielding 119% greater average cycles to failure. Non-peened specimens had a 66% increase in cycle life after TRC peening. Pre-peened (manufacturer peened) specimens had a 70% increase in cycle life after TRC peening. Dual peening increases coverage by a factor proportional to the respective blast stream exposure times of the two peening operations. This extended coverage results in more overlapping compressive stress zones and, dependent on process parameters, can increase total residual compressive stress magnitude by a slight degree. This effect eventually becomes minimal as a virtual saturation point is approached where further plastic deformation becomes negligible. The 70% increase in cycle life of dual peened specimens indicates that TRC peening may indeed have increased the compressive stress magnitude beyond the existent stress levels from manufacturer peening.

Used Rods

The next stage of rotational bending fatigue testing was performed on used sucker rods. The purpose of this testing was to compare shot peened rods to shot cleaned rods, and to determine if used rods with undesirable residual stresses from load reversals would benefit from shot peening. Test rods were 3/4” diameter, API Special Alloy D, Class 1 inspected, used sucker rods, all from the same manufacturer with matching heat codes. Rods were prepared and proportionally shot peened in the same manner as the rods from the previous fatigue tests. Six specimens were taken from each rod: three shot cleaned and three shot peened. A total of 24 specimens were tested. Specimens were tested at a calculated stress of 60% of tensile strength and cycled to failure. Initial loads used were the same as the new rod tests, but after the first control specimen exceeded 7 million cycles without failure, the loads were increased to the 60% value in order to accelerate the testing. This resulted in lower cycles-to-failure counts than those in the new rod tests.

The shot peened specimens yielded a 72% greater cycle life than shot cleaned specimens. Total cycles for shot peened specimens was 9,687,145 compared to 5,628,910 cycles for shot cleaned specimens. Average cycles to failure was 807,262 for shot peened specimens versus 469,076 for shot cleaned specimens (Table III).

CONCLUSIONS

The test results demonstrate that shot peening, if properly administered and applied, can provide beneficial effects for oilfield sucker rods. The shot peened test specimens showed substantial residual compressive stress levels and had significantly greater cycle life than non-peened specimens.

The peening process must be meticulously monitored and controlled to be effective. Most probably, the key factors in the superior performance of the shot peened specimens were controlled blast stream intensity and controlled shot media properties. The test results substantiate that the specialized shot peening formula and technique used in the testing is a viable method of prolonging fatigue life of new and used sucker rods.

Shot cleaning and shot peening are two distinctly different methods with differing objectives. Shot cleaning is not equivalent to shot peening and did not deliver test results congruent to shot peened rods. Typically, sucker rod shot cleaning operations do not require blast stream measurement and control nor shot media measurement and control. This can lead to unpredictable surface and subsurface effects and consequently, inconsistent or nonexistent fatigue resistance.

Manufacturer shot peened specimens had greater average cycle life than non-peened specimens. This is further confirmation that shot peening sucker rods can increase fatigue life, and that manufacturer peening can be beneficial. Dual peened specimens (manufacturer peened plus TRC peened) performed even better in the tests and, in addition, manufacturer peened specimens yielded greater cycle life after TRC peening. This is evidence that manufacturer shot peening coupled with secondary TRC shot peening can improve sucker rod fatigue life. This also indicates that the specialized shot peening formula used in this testing is somehow different than manufacturers' process parameters in such a way as to achieve increased cycle life, and may be more optimally suited to sucker rods. This could be related to a number of variables such as blast stream intensity, shot size, exposure time, quality control, etc.

Used sucker rods may benefit the most from the merits of shot peening since the process relieves detrimental service-induced residual stresses and converts the stress profile back to a compressive state. The compression layer also minimizes the notch effect of surface discontinuities associated with crack initiation.

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Table I – Residual Stress Measurement Summary

Measurement Depth	% Increase in Compressive Residual Stress due to Peening	
	12-mil	40-mil
New Rods	27.3%	37.7%
Used Rods	82.5%	38.3%

Table II – Rotational Bending Fatigue-New Rods

Total Cycles All Specimens

As Received	Shot Peened	Life increase
51.4 million	86.9 million	69%

average cycles to failure - carbon D vs. alloy D

steel type	As Received	Shot Peened	Life increase
carbon	767,183	1,234,250	61%
alloy	2,148,898	3,738,120	74%
ratio	2.8 to 1 (180%)	3 to 1 (200%)	

average cycles to failure - mfg peened vs. non

mfg peened?	As Received	Shot Peened	Life increase
no	806,425	1,342,452	66%
yes	1,764,227	3,003,951	70%
ratio	2.19 to 1 (119%)	2.24 to 1 (124%)	

Table III – Rotational Bending Fatigue-Used Rods

Average Cycles to Failure

Rod	As Received	Shot Peened	Life Increase
Rod "A"	698,189	760,557	9%
Rod "B"	337,799	665,873	97%
Rod "C"	252,686	360,747	43%
Rod "D"	587,630	1,441,872	145%
Overall	**469,076**	**807,262**	**72%**

Total Cycles

As Received	Shot Peened
5,628,910	9,687,145

Figure 1 – sucker rod shot peening machine

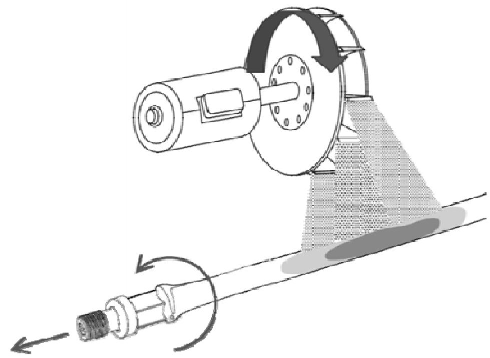

Figure 2 – centrifugal force blast wheel

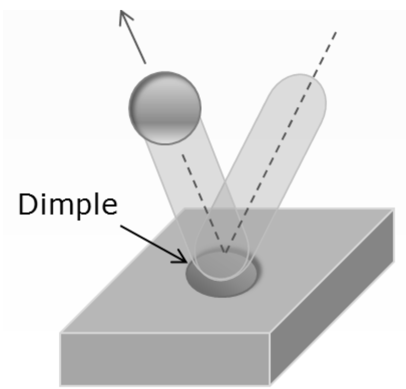

Figure 3 – particle impact creates dent

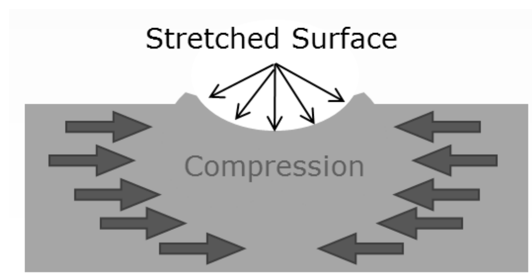

Figure 4 – compressive stress in area adjacent to dent

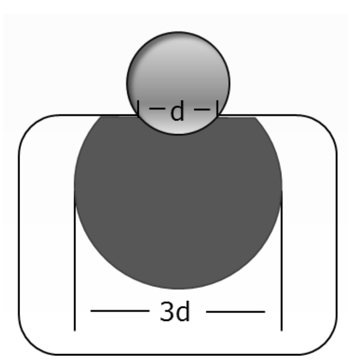

Figure 5 – stress region is 3 times dent diameter

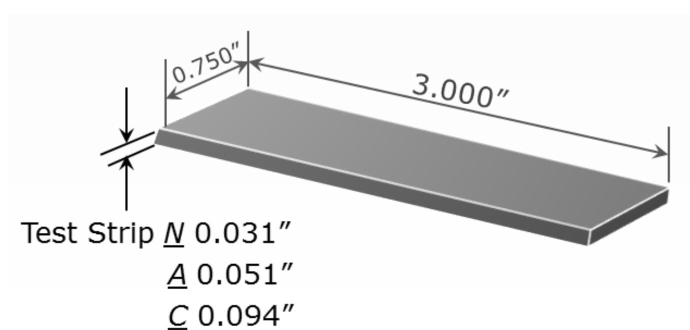

Figure 6 – Almen strip

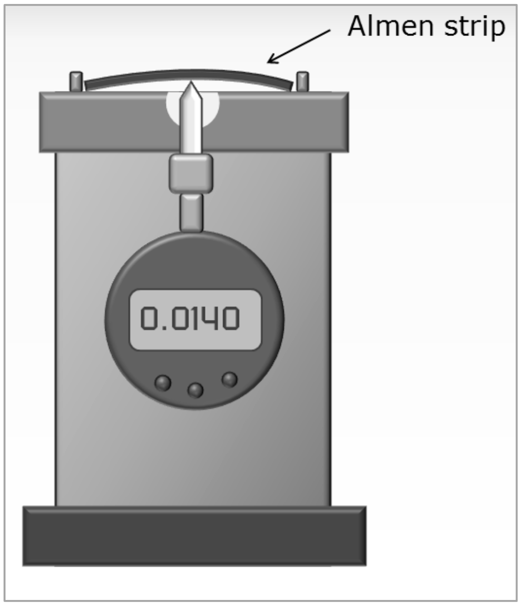

Figure 7 – Almen gage

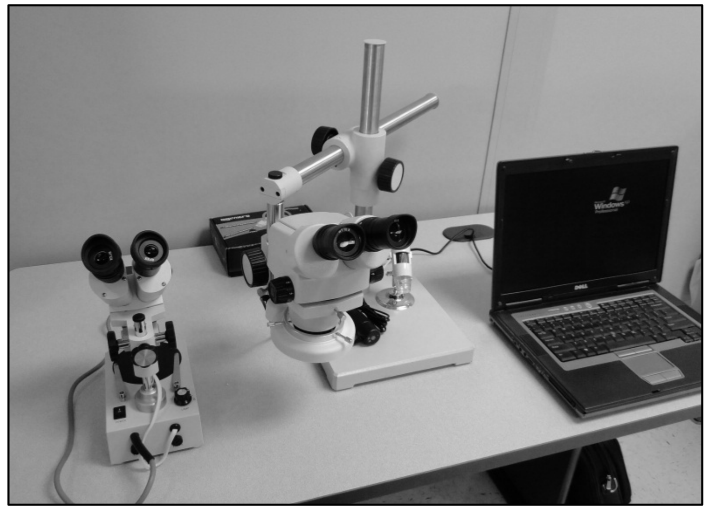

Figure 8 – optical and digital scopes for particle shape analysis

Figure 9 – sieve screening for particle size analysis

Figure 10 – digital scale for weighing screened samples

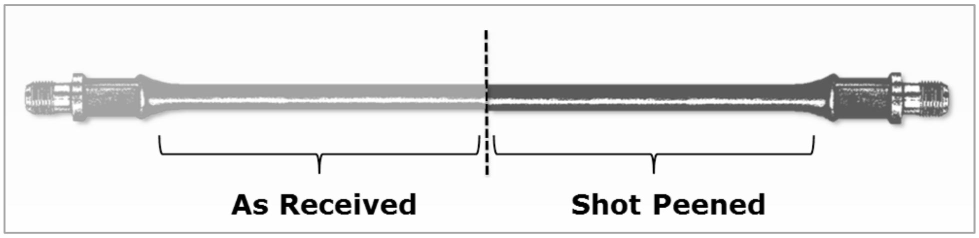

Figure 11 – test specimen diagram


Figure 12 – blind drilled hole strain gage apparatus affixed to 1” sucker rod

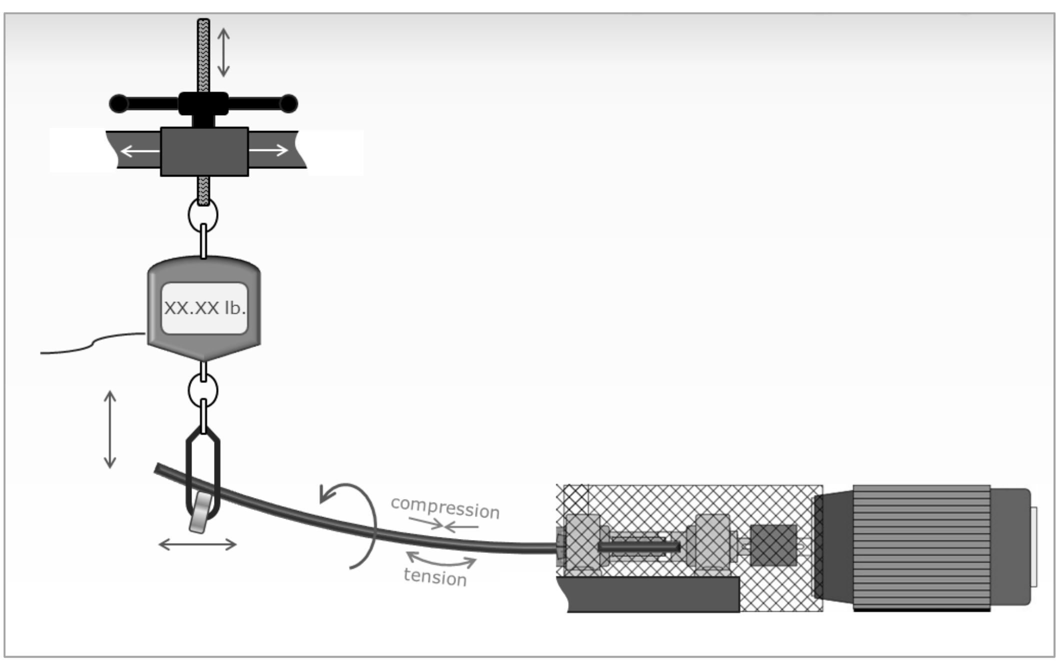

Figure 13 – rotational bending fatigue machine diagram