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Shot Peening Overview

by

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Last Revised
January 18, 2001

With special thanks to Metal Improvement Co for their technical contributions
http://www.metalimprovement.com

Shot Peening Overview

1. INTRODUCTION

1.1 Shot Peening Described

Shot peening is a cold working process in which the surface of a part 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 an even layer of metal in residual compressive stress. It is well known that cracks will not initiate or propagate in a compressively stressed zone. Since nearly all fatigue and stress corrosion failures originate at the surface of a part, compressive stresses induced by shot peening provide considerable increases in part life. 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 yield strength of the material being peened. Many materials will also increase in surface hardness due to the cold-working effect of shot peening.

Benefits obtained by shot peening are the result of the effect of the compressive stress and the cold working induced. Compressive stresses are beneficial in increasing resistance to fatigue failures, corrosion fatigue, stress by corrosion cracking, hydrogen assisted cracking, fretting, galling and erosion caused by cavitation. Benefits obtained due to cold working include work hardening, intergranular corrosion resistance, surface texturing, closing of porosity and testing the bond of coatings. Both compressive stresses and cold-worked effects are used in the application of shot peening in forming metal parts.

1.2 Residual Stresses

Residual stresses are those stresses remaining in a part after all manufacturing operations are completed, and with no external load applied. These residual stresses can be either tensile or compressive. For example, a welded joint will contain high magnitude residual tensile stresses in the heat-affected zone (HAZ) adjacent to the weld. Conversely, the surface of induction hardened components may contain residual compressive stresses.

In most applications for shot peening, the benefit obtained is the direct result of the residual compressive stress produced.

A typical profile of residual compressive stress as it changes with depth is shown in Fig. 1. It has four important characteristics:

1) **SS** - Surface Stress, the stress measured at the surface.

2) **Cs_{max}** - Maximum Compressive Stress, the maximum value of the compressive stress induced, which normally is highest just below the surface.

3) **d** - Depth, the depth of the compressive stress is the point at which the compressive stress crosses over the neutral axis and become tensile.

4) **Ts_{max}** - Maximum Tensile Stress, the maximum value of the tensile stress induced. The offsetting tensile stress in the core of the material balances the surface layer of compressive stress so that the part remains in equilibrium. TS_{max} must not be allowed to become large enough to create early internal failures.

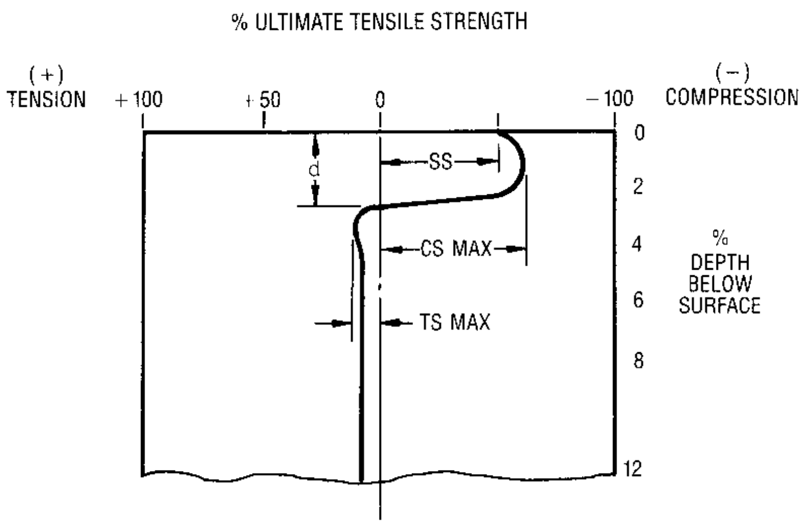


Fig. 1 Example of Residual Stress Profile Created by Shot Peening

1.2.1 Magnitude

The maximum value of the residual compressive stress (Cs_{max}) is often called the magnitude of the residual stress induced. Variations in the shot peening process have little effect upon the magnitude of the compressive stress induced as long as the shot used is at least as hard as or harder than the material being peened. The magnitude of the compressive stress is primarily a function of the material itself and has a value of at least one-half of the yield strength of that material.

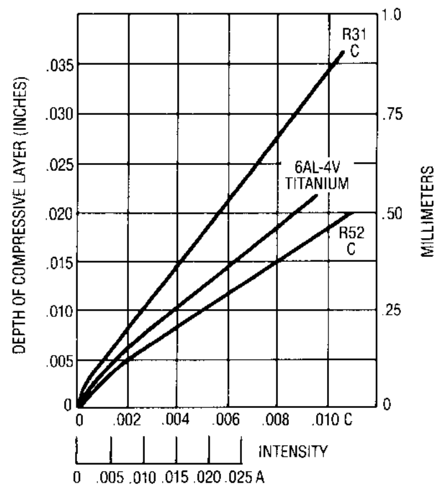


Fig. 2 Residual Stress Produced by Shot Peening vs. Tensile Strength of Steel

The depth of the compressive layer is influenced by variations in peening parameters. Figure 3 shows the relationship between depth of compressive layer and shot peening intensity for three materials: Steel hardness R_c31, Steel hardness R_c52, and Titanium 6Al-4V. Depths for steels with other hardness can be interpolated from the chart.

1.3 Load Stress Profiles

1.3.1 Smooth Specimen

Figure 3 illustrates the distribution of stress in a smooth beam with no external load applied which has been shot peened on both the upper and the lower surfaces. Since the beam is in equilibrium with no external forces, the area under the stress distribution curve in the regions of compressive stress must be equal to the corresponding area under the curve in the region of tensile stress. Further, the sum of the moments of these areas must be equal to zero.

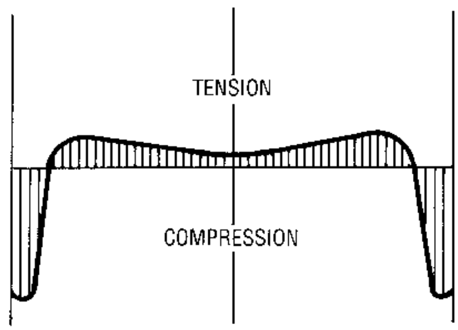


Fig. 3 Typical Residual Stress Distribution After Peening

Figure 4 shows the same beam after shot peening as in the above figure, but with an external bending moment being applied. The resultant stress at any depth will be equal to the algebraic sum of the residual stress and the stress due to the applied load at that depth. The resultant curve of the stress distribution is the solid line and the bending load is shown as a dashed line.

Note that even after loading, the stress at the peened surface is greatly reduced by the compressive stress of shot peening. This condition will help prevent initiation and, more importantly, the propagation of surface cracks.

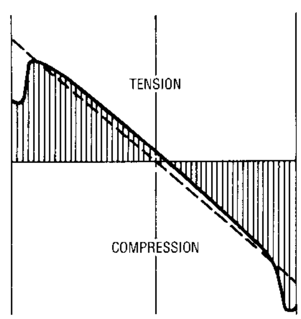


Fig. 4 Superposition of Applied and Residual Stress

1.3.2 Notched Specimen

Figure 5 illustrates the distribution of stress in a beam with a notch at the surface and under bending load (Kt=2.0). The notch dramatically concentrates and increases the effective stress experienced by the beam at the surface (Kt=2.0 effectively doubles the surface stress).

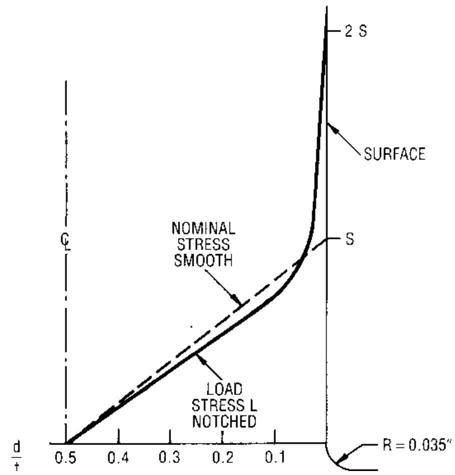


Fig. 5 Distribution of Bending Stress in a Notched Beam

Figure 6 shows the load/stress profile of the same beam but shot peened prior to the application of the bending load. Shot peening reduces the stress experienced at the surface of the beam by over fifty percent - essentially negating the detrimental stress concentration effect of the notch.

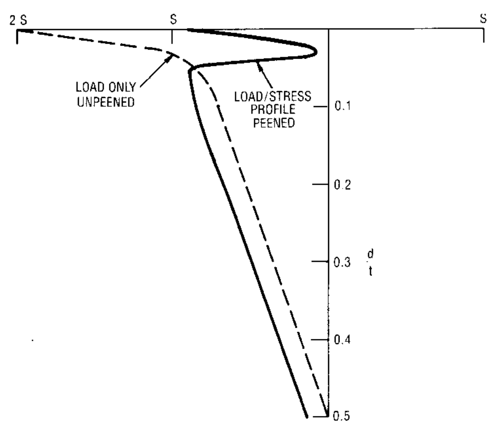


Fig. 6 Load/Stress Distribution of Shot Peened Notched Beam under Bending Load

2. MANUFACTURING PROCESSES - EFFECT ON FATIGUE LIFE

2.1 Beneficial Manufacturing Processes

Surface hardening which typically leaves the surface of the part with a residual compressive stress is a beneficial manufacturing process. Honing, polishing and burnishing are surface enhancement processes which remove many of the defects and stress risers which can occur during other manufacturing operations. Surface rolling will leave the surfaced in residual compressive stress but is limited to regular geometries while shot peening, properly controlled, produces the best results.

2.2 Detrimental Manufacturing Processes

Manufacturing processes are known to have significant effects on fatigue properties of parts. The effects are either detrimental to fatigue properties or beneficial. Detrimental processes can include through-hardening, grinding, abusive machining, plating and welding. These processes tend to induce residual tensile stresses into the part, thereby lowering fatigue characteristics. Nontraditional machining, (ECM, EDM) also results in fatigue debits. In EDM (Electro-Discharge Machining) a recast layer is produced which can be brittle and notch sensitive and under residual tensile stress. Fatigue failures can originate in the recast layer and propagate into the base metal. In ECM (Electro-chemical machining), the chemical used can attack the grain boundaries leaving them in a weak, notch sensitive condition.

2.2.1 Grinding

Residual tensile stresses and surface brittleness can be caused by the generation of high surface temperatures during severe 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 stress will dramatically reduce the fatigue or stress corrosion resistance of ground parts. Shot peening after grinding can overcome the detrimental effect of tensile stresses induced by severe grinding, as shown in Figure 7.

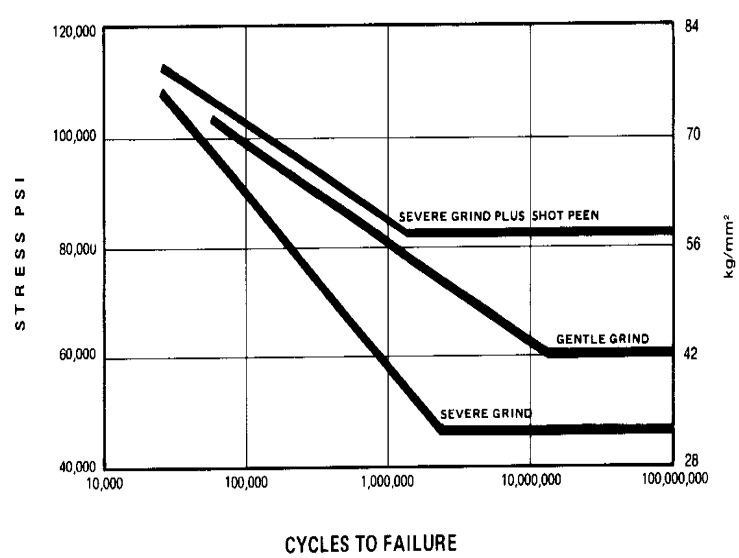


Fig. 7 Reversed Bending Fatigue of Flat Bars of Rockwell Hardness C45

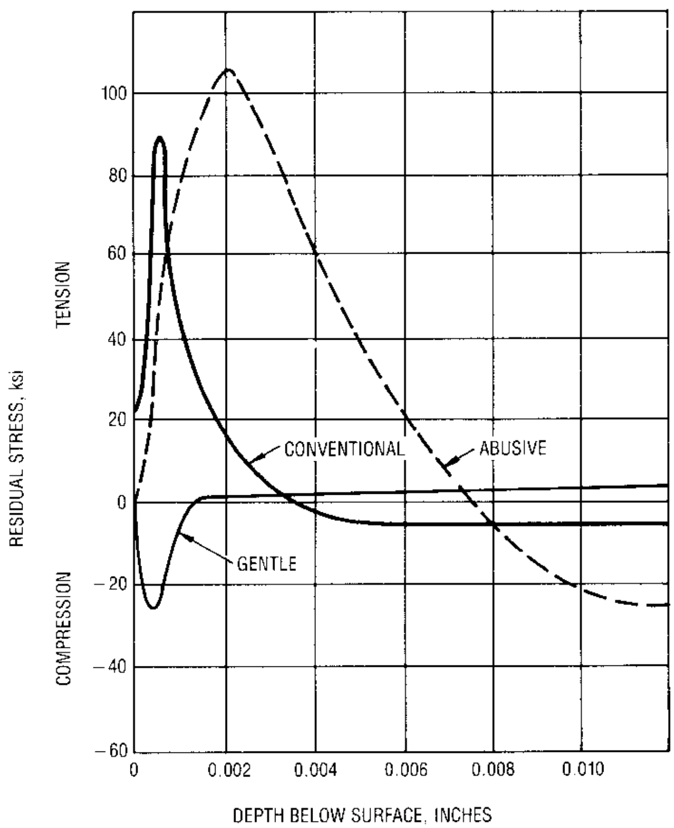


Fig. 8 Residual Stress in 4340 Steel (Hrc50) After Surface Grinding

Figure 8 shows the stress distribution created by different grinding techniques - conventional, abusive and gentle. It is quite evident that conventional grinding and abusive grinding can generate high magnitudes of residual tensile stress at or near the surface of the parts. This tensile stress will, of course, dramatically affect fatigue resistance.

2.2.2 Electro Discharge Machining (EDM)

Although the spark erosion process is essentially "force-free;" this should not be construed to mean that the eroded components are stress free. Not all the molten metal produced during the discharge is expelled into the working gap. That which remains resolidifies to form a hard and brittle skin on the work surface. Accompanying thermal stresses, plastic deformation and shrinkage induce residual tensile stresses in the work piece which, under certain conditions, have been found to approach the ultimate tensile strength of the material near the surface.

Shot peening can be very beneficial in restoring the fatigue strength of parts that have been electro discharge machined (see Fig 9). In this figure, the effect of shot peening on electro-chemical machined, electro-discharge machined and electro-polished (ELP) surfaces are shown.

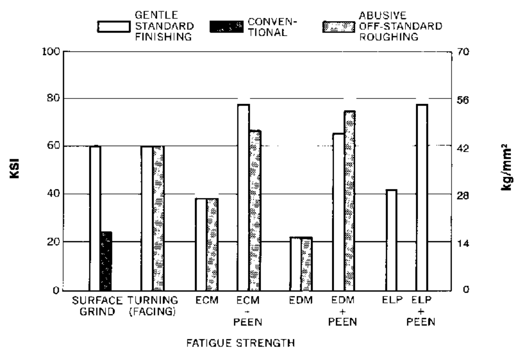


Fig. 9 Summary of High-Cycle Fatigue Behavior on Inconel 718, Solution-Treated and Aged (Rc44)

2.2.3 Electro-Chemical Machining (ECM)

Electro-chemical machining is the controlled dissolution of work piece material by contact with a strong chemical reagent in the presence of an electric current. Even though ECM is considered to be a relatively stress-free process, the reduction in endurance limit is caused by frequently observed surface softening (rebinder effect) and surface imperfections left by preferential attack on grain boundaries. Fortunately, a shot peening post treatment more than restores the endurance limit (see Fig. 10).

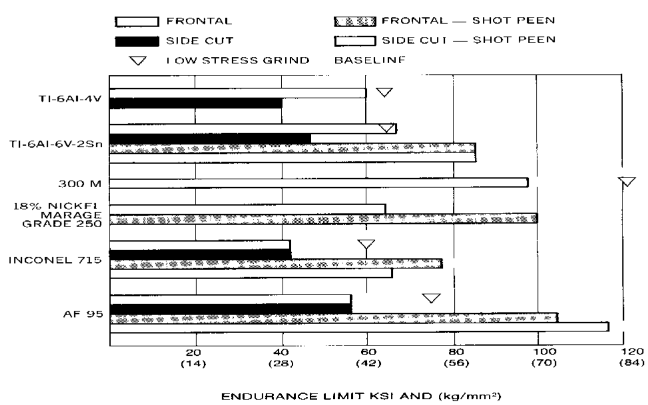


Fig. 10 Summary of High-Cycle Fatigue Response for ECM

2.2.4 Plating

Many parts are shot peened prior to chrome and electro less nickel plating to counteract the harmful effects of plating on the fatigue life of metal parts, which can be residual tensile stresses, hydrogen embrittlement and brittle notch sensitive plate material at the surface. Cracks in the plating can propagate rapidly into the base metal and lead to early failure. However, when the surface of the base metal is compressively stressed, the cracks cannot propagate into the base metal. Figure 11 illustrates this concept and Figure 12 clearly shows the reduction in fatigue resistance experienced on 4340 steel due to plating and the beneficial effect of shot peening *prior* to the plating process.

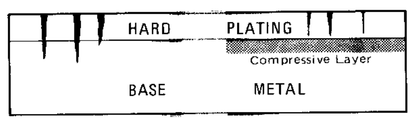


Fig. 11 Plating Cracks Will Not Propagate into Prestressed Base

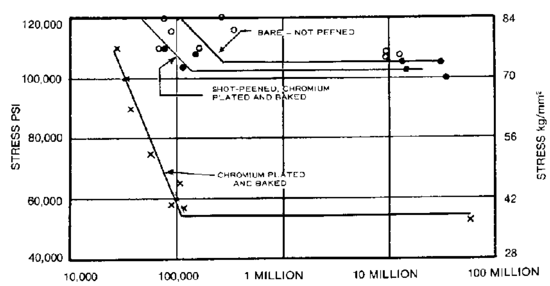


Fig. 12 Cycles to Failure 4340 Steel, 52-53Rc Rotating-Beam Fatigue

Shot peening *prior* to plating is recommended on cyclically loaded parts to enhance fatigue properties. Federal specifications QQ-C-320 and MIL-C-26074A call for shot peening of steel parts that will be chrome or electroless nickel-plated, respectively, where service requires unlimited life under dynamic loads. Other plating processes such as cadmium can also lower fatigue strength unless they are preceded by shot peening.

2.2.5 Anodizing

Anodizing is another application in which shot peening improves fatigue resistance of coated materials. Benefits similar to those shown for plating are illustrated in Figure 13 where the high-strength aluminum base metal was shot peened *prior* to the hard anodize process.

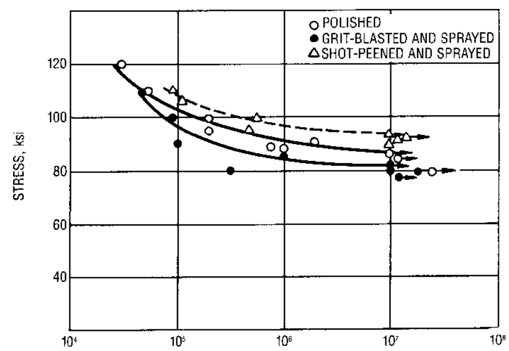


Fig. 13 The Influence of Hard Anodizing and Shot Peening on the Failure Strength of Duralumin (LI)

2.2.6 Plasma

Plasma spray coatings also tend to reduce fatigue resistance. As with other coatings, shot peening is able to recover fatigue debits due to plasma spray processes as shown in Figure 14. Again it should be emphasized that for fatigue improvement, shot peening is performed prior to the coating processes. Additionally, peening after coating is effective in improving the surface finish of plasma-coated parts. Also it can be used to densify and close porosity of the plasma coating.

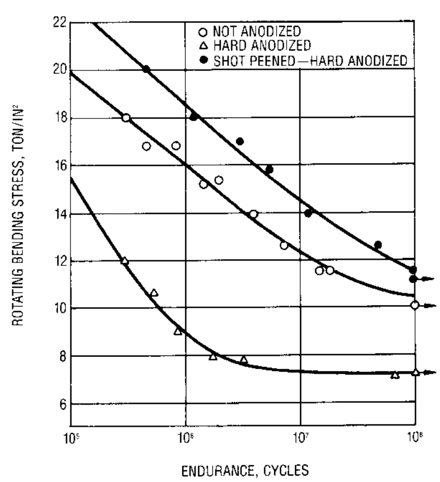


Fig. 14 R.R.Moore Fatigue Strength of Titanium 6AL-4V Polished vs. AS - Sprayed Coating with Pre-spray Conditioning Grit Blast and/or Shot-Peen - METCO 64F

2.2.7 Welding

Heat generated by the welding process often will produce tensile stresses approaching the yield strength of the material. These harmful self-stresses in the heat-affected zone (HAZ) contribute to poor fatigue characteristics of weldments. Improvement in fatigue resistance can be accomplished in two basic steps:

> 1) Improving the weld geometry by grinding the fillet weld tow profile, since fatigue cracks initiate from geometric discontinuities. Figures 15 and 16 show the loss in fatigue strength of A286 and STE690 (a European alloy) caused by welding.
>
> 2) Inducing surface compressive residual stresses in weldments. Shot peening is the preferred method for providing a substantial increase in fatigue resistance. For significant and repeatable improvements, the shot peening must be closely controlled.

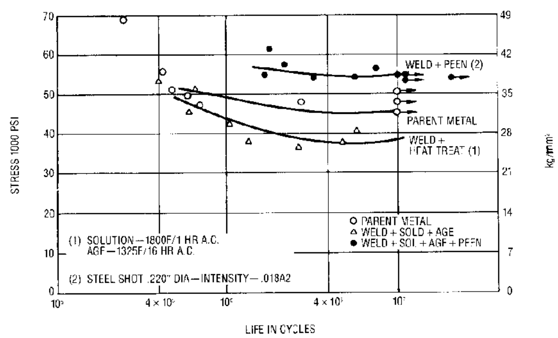


FIG. 15 Effect of Shot Peening on Welded A-286 Fatigue Strength

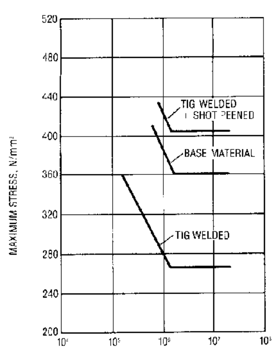


Figure 16 Effect of Shot Peening on Welded STE690 Material

2.2.8 Weld Repair

Fatigue cracks can start in the base metal, the weld material or the heat-affected zone (HAZ). Once detected, the recommended repair scheme is:

1) Reduce the stress concentration by avoiding stray arc strikes, by grinding the weld cracks and by dressing the fillet.
2) Replace the weld metal.
3) Shot peen to induce beneficial compressive stress.

Recent use of the shot peening process in post-weld repair of ball mills suggests that higher intensities, used to induce compressive mean stresses, enhance fatigue resistance.

Number of hours of operation following weld repair:

Not Shot Peened......................................7561 Hours (fatigue cracks developed)

Shot Peened..35,629 Hours (no fatigue cracks)

2.2.9 Decarburization

Decarburization is defined as the loss of carbon from the surface of a ferrous alloy as a result of heating in a medium that reacts with the carbon at the surface. It has been shown that decarburization can reduce the fatigue strength of high-strength steels (240KSI and up) by 70% to 80% (Fig 17, and lower-strength steels (140KSI to 150 KSI) by 45% to 55%.

It is generally accepted that decarburization is a surface phenomenon not particularly related to depth. A depth of .003 inch decarburization can be as detrimental to fatigue strength as a depth of .030 inch. However, the amount of decarburization can have a dramatic influence on fatigue properties of carbon steels.

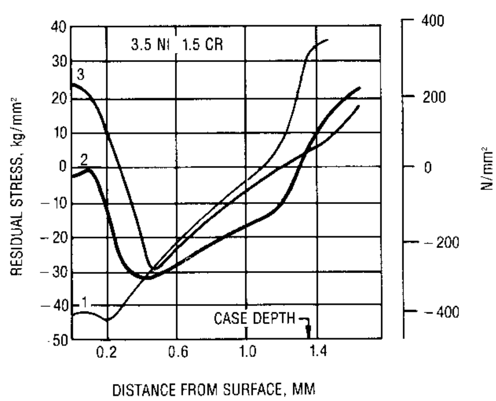


Fig. 17 Effect of Shot Peening on Decarburization

Severe decarburization can induce significant residual tensile stresses in the surface of the part as shown in Figure 18.

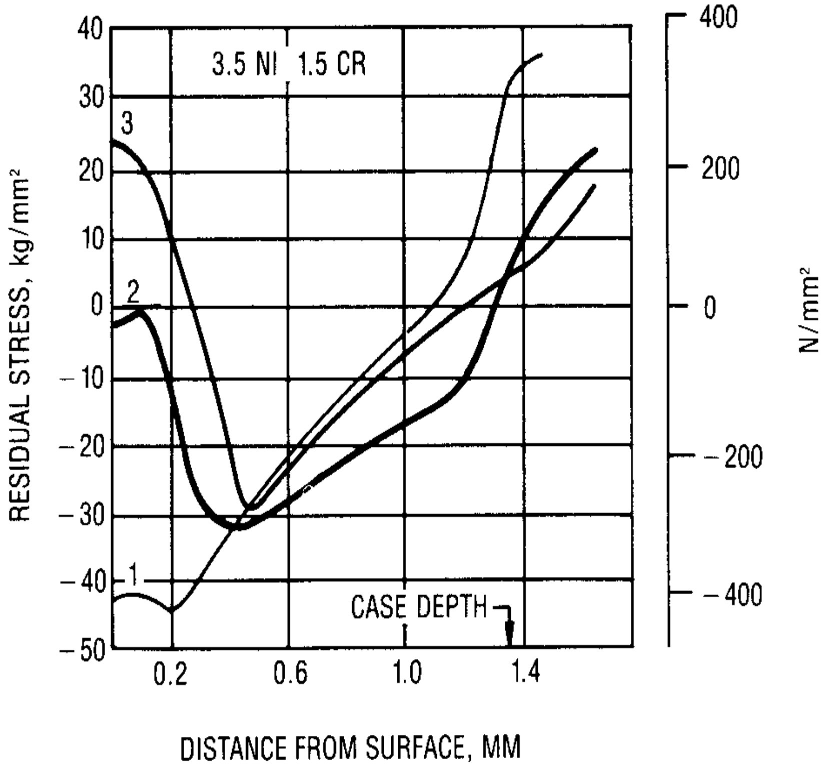


Fig. 18 The Effect of Decarburization on the Residual Stresses Developed in Carburized and Hardened Plates.
The Carbon Content at 0.002mm Was Estimated to Be:
CURVE 1, 1%; CURVE 2, 0.64%; CURVE 3, 0.35%

Shot peening has proven to be effective in restoring most, if not all, of the fatigue strength lost due to decarburization. Because the decarburized layer, though softer, is not easily detectable on quantities of parts, peening can ensure the integrity of the parts in a lot if decarburization is suspected.

3. SERVICE EFFECTS REMEDIED BY SHOT PEENING

3.1 Cavitation Damage

Cavitation damage is the result of high relative motion between a metal and a liquid. If the pressure accompanying a high-velocity motion drops to a vapor pressure, the liquid will vaporize and form a vapor cavity at the metal surface. At a slight increase in pressure, this bubble will collapse, causing a concentrated liquid impact resulting in erosion and pitting of the metal surface. Once initiated, the cavitation damage becomes progressive and cumulative. Shot peening has been shown to be effective in retarding cavitation damage in 1020 steel and 70C brass (Fig. 19). The benefit from shot peening seems to be associated with work hardening. The more work hardening accomplished in the material, the greater the benefit from shot peening. Work hardening would raise the yield strength of the material in the work-hardened area, thus making it stronger and more resistant to damage caused by the collapse of the bubbles.

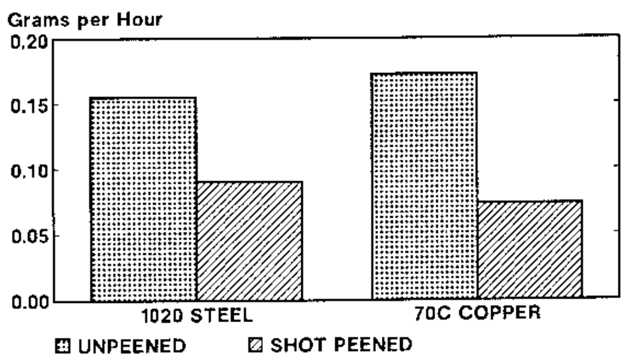


Fig. 19 Rate of Material Loss by Cavitation

3.2 Fretting and Fretting Fatigue

Fretting can develop when the relative motion of microscopic amplitude occurs between two metal surfaces. As the surfaces rub, fine abrasive oxides form, which contribute to the scoring of the surfaces.

Fretting gives rise to one or more forms of damage, such as fretting corrosion, fretting wear and/or fretting fatigue. Fretting corrosion and fretting wear are any corrosion damage and wear damage, respectively, that occur as a direct result of fretting. Surface discoloration, pitting, oxide-layer buildup, seizing and loss of fit are all characteristics of these forms of damage. Fretting fatigue is any fatigue damage that initiates from fretting. The most notable characteristic of this form of damage is a reduction of fatigue strength of the parts (Figure 20 and 21).

Shot peening has proven to be successful in retarding fretting and eventually fretting fatigue by increasing the surface hardening through cold working of the metal and providing residual compressive stresses at the fretting surfaces. The minute pockets that are produced at the surface through shot peening act as oil reservoirs, thus resulting in longer lubricant retention.

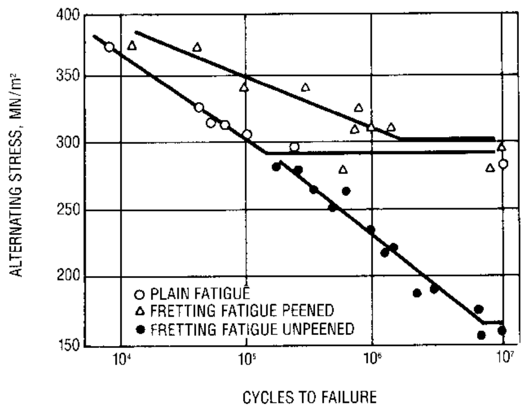


Fig. 20 Rotating-Bending Fatigue Curves for Untreated and Shot-Peened Specimens of Annealed Austenitic Stainless Steel En 58A With and Without Fretting

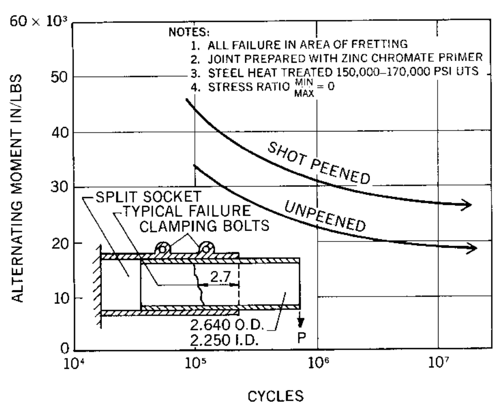


Fig. 21 L-N Curve Clamped Up Joint 4140 Steel

3.3 Galling

Galling is caused by strong adhesive forces whenever an imbalance of electrons exists between two mating metal surfaces. At low stresses, minute junctions form at contacting surfaces and small fragments of metals become detached when subsequent relative movement occurs. At higher stresses, however, much larger junctions are formed and actual seizure may occur, stalling the equipment or "freezing" the action of the part.

The cold-worked densified surface, generally obtained through shot peening, makes the material more resistant to galling. In addition, the shallow indentations caused by the shot act as oil reservoirs and provide improved lubrication throughout the pressure cycle. Also, the residual compressive stress from shot peening retards crack growth and pit formation if only a limited amount of galling occurs.

Shot peening has worked successfully for anti-galling of A.P.I. threads, engine valve stems, and on such materials as Inconel 718 and X750, Monel K-500, stainless steel type 300- and 400-series, 17-7PH, Titanium 6-4 and aluminum. It has also been found that shot peening will reduce scoring on such parts as tappet faces (Ref 45) cams and gears which are in sliding contact under high loads.

3.4 Pitting

Hydraulic wedging action is a lubricated contact that can be understood by examining two rollers, rotating at different peripheral speeds. When the rollers are forced together radially, frictional forces parallel to the surfaces produce tensile stress in one area of each roller surface and compressive stress in another area (Fig. 22). These stresses and the direction of sliding and rolling on the lower speed surface tend to open micro cracks, allowing oil to enter. After the oil is trapped, high pressure builds up as the crack passes under the point of contact, generating high tensile stress at the crack root. This stress causes crack propagation and eventual pitting failure.

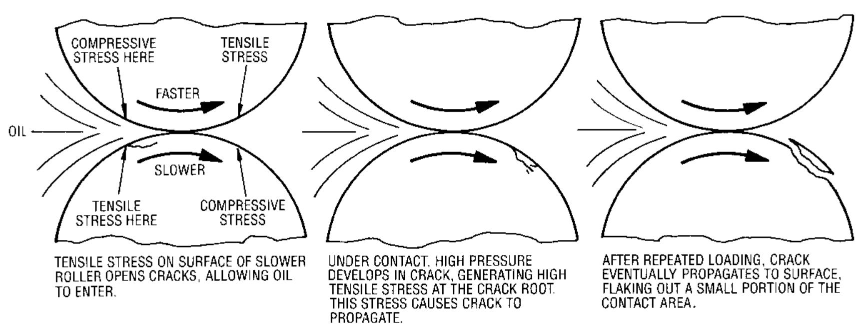


Fig. 22 How Pitting Starts

The opposite effect occurs on the high-speed surface; therefore, pits tend to form more rapidly on the lower-speed surface. Also, plastic deformation in the surface layer of the roller tends to close the cracks, making pitting less likely.

Shot peening has been shown to be beneficial in retarding surface pitting and improving fatigue life of carburized and hardened gears (Fig 23).

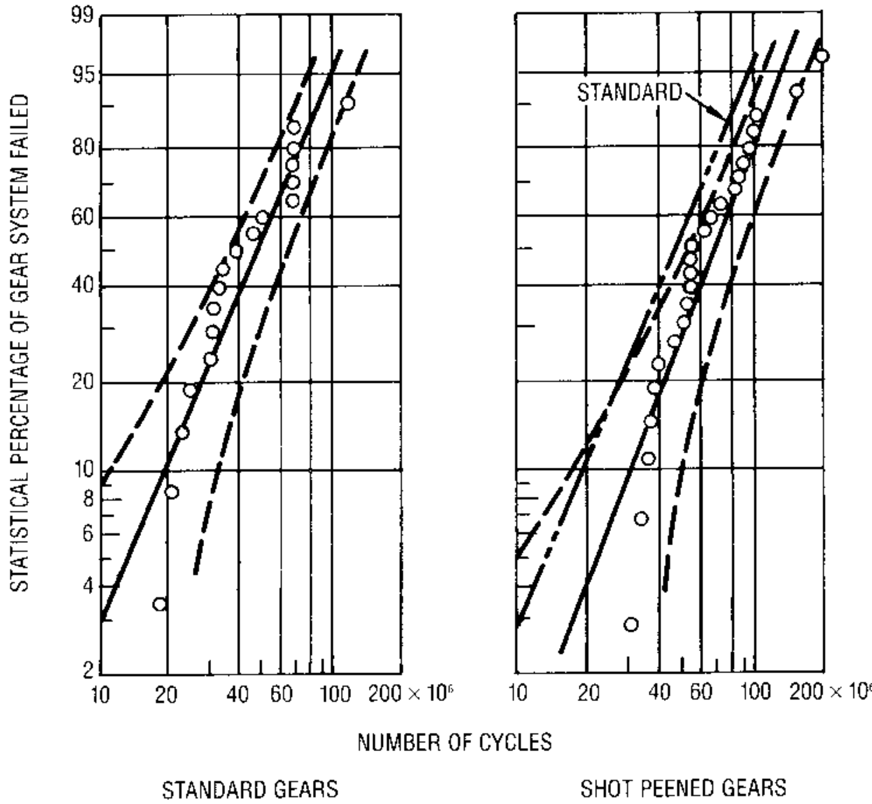


Fig. 23 Comparison of Surface (Pitting) Fatigue Lives of Standard Ground and Shot-Peened Carburized and Hardened CVM AISI9310 Steel Spur Gears, Speed, 10,000 RPM; Lubricant, Synthetic Paraffinic Oil; Gear Temp. 350K (170 f) Maximum Hertz Stress, 1.7X10 N/m (248,000 psi)

Figure 23 shows that shot-peened gears exhibit pitting fatigue lives 1.6 times the life of standard gears without shot peening. Residual stress measurements and analysis indicate that the longer fatigue life is the result of the higher compressive stress produced by the shot peening. The life for the shot-peened gear was calculated to be 1.5 times that for the plain gear by using the measured residual stress difference for the standard and shot-peened gears. The measured residual stress for the shot-peened gears was much higher than that for the standard gears.

3.5 Crack Arrest

The propagation of a crack depends upon stress conditions near its tip. Crack arrest by residual compressive stress is based upon the following factors:

1) A crack will not propagate unless a tensile stress forces it open near the tip.
2) The crack tip will not open as long as a compressive force acts upon it.

Figure 24 shows the concept of compressive crack arrest.

a) Load stress distribution approximated by straight lines.
b) Stress distribution after shot peening.
c) Combined stress distribution obtained by adding load stresses and residual stresses.
d) Distribution under load after a crack has progressed part way into the region of tensile stress. Dashed lines represent the original distribution of figure (c)
e) Crack progressed to the point (I) where the stress in the uncracked loaded part changed from tension to compression. Tension now exists at that point.
f) Crack arrested by the absence of tensile stress.

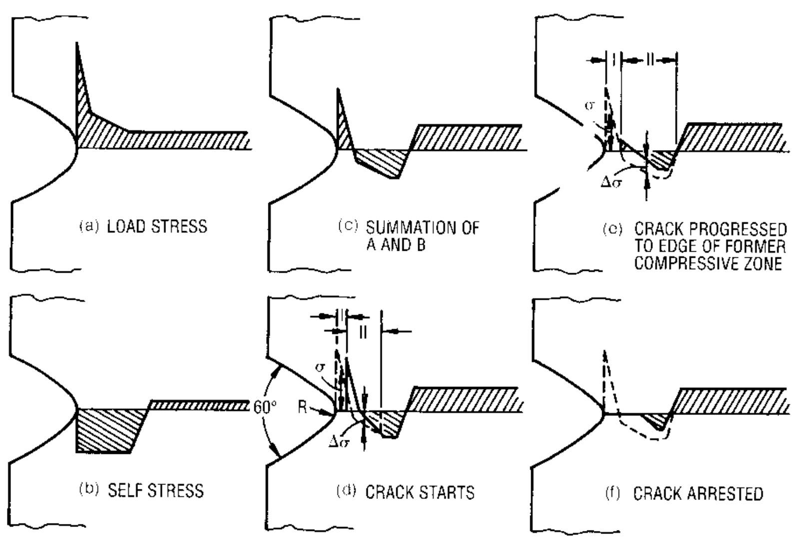


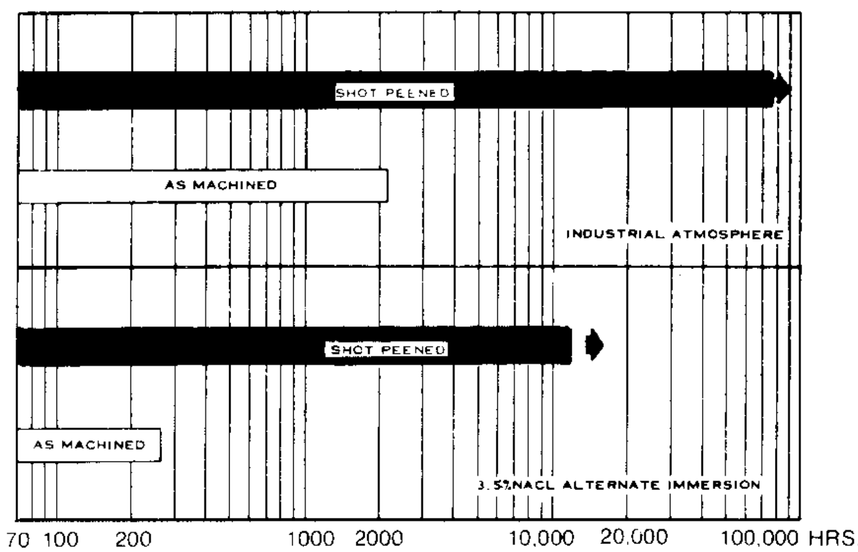
Fig. 24 Crack Arrest by Compressive Self Stress

3.6 Stress Corrosion Cracking

There are many types of corrosion, but perhaps the most catastrophic is stress corrosion cracking (SCC) which is defined as failure by cracking under combined action of corrosion and static tensile stress, either external (applied) or internal (residual). Cracking may be either intergranular or transgranular, depending on the metal and corrosive medium.

Stress corrosion cracking cannot occur in an area of compressive stress.

Higher-strength alloys are generally more susceptible to SCC than lower-strength alloys. Most metals, such as aluminum, magnesium, copper, nickel, steel and stainless steel alloys, are susceptible to SCC given a tensile stress at or above their threshold limits and certain corrosive environments.



Fig, 25 Effect of Peening on Resistance to Stress Corrosion Cracking of 7075-T6

4. PRODUCTS BENEFITTING FROM SHOT PEENING

4.1 Jet Engine Blades

Blades and buckets as well as discs and shafts for aircraft jet engines, stationary gas and steam turbines and compressors are standard applications for shot peening.

Blade roots are peened to prevent fretting, galling and fatigue. Broaching of the fir tree can leave tears, pits or scores which are stress risers. Shot peening to the depth below these surface discontinuities will correct these detrimental effects. Many engine blade roots are shot peened as new parts and re-shot peened upon overhaul to restore the fatigue life.

The airfoils of blades are also commonly shot peened to:

1) retard the harmful fatigue effect caused by pitting,
2) repair foreign object damage (FOD),
3) prevent stress corrosion cracking,
4) retard fretting in tie wire holes, and
5) increase fatigue life in general.

Many coating and plating processes used on airfoils tend to decrease the fatigue life. Shot peening is used to offset these detrimental effects.

It is recommended to re-peen the blades on overhaul of the unit, as the compressive stress induced by shot peening will recover any surface fatigue damage that may have occurred in service, thereby preventing the initiation of propagation of fatigue cracks (Figures 26 and 27). The discs or wheels which support the blades are also peened, especially in the blade slots and the tie-rod bores.

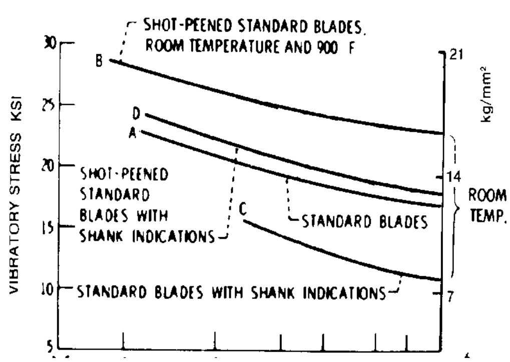


Fig. 26 Suppression of Fatigue Damage of Inconel 713c Turbine Blades by Shot Peening

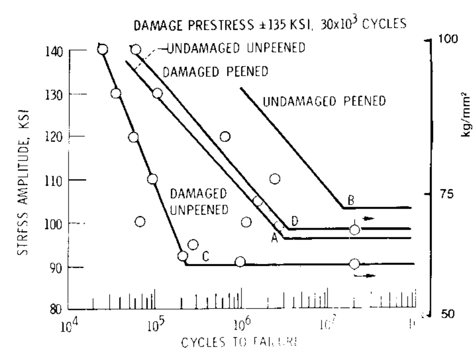


Fig. 27 Shot Peening as a Means of Overcoming Prior Fatigue Damage with 4340 Steel Tested in Rotating Bending

4.2 Connecting Rods

A rough surface in compression will resist failures better than a smooth surface in tension (Figure 28). Note the comparison of polished verses rough forged and shot peened connecting rods in the figure below. It indicates great savings of cost and time (Figure 29). There is usually no advantage in producing a very fine finish prior to peening. If a better surface finish is required, it is permissible to lap, hone or polish after shot peening so long as material removal does not exceed 10 percent of the compressive layer.

The most critical areas of connecting rods are the fillets next to both bores, but the rods are normally shot peened all over prior to machining the bores. Tests have shown that the peened surface protects so well that even scratches made after peening cause no reduction in fatigue strength provided the scratch is less than one quarter of the depth of the compressed layer.

Feed rollers, bearing races and similar parts are peened, maintaining the required surface finish as well as increasing their resistance to galling and fatigue failures. Connecting rods made of various metal alloys, including powder metal, have been shot peened to improve fatigue properties. In addition, fretting and fretting fatigue failures experienced in the bores of the connecting rods have also been prevented by shot peening.

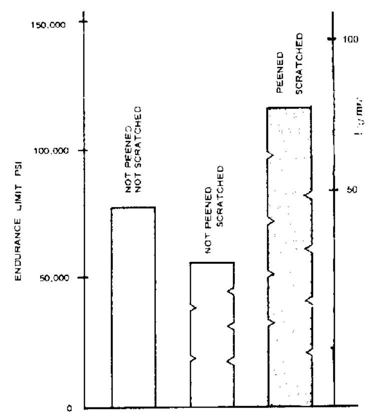


Fig. 28 Effect of Peening and Scratches on Endurance Limit of 4340 Steel at Rc51

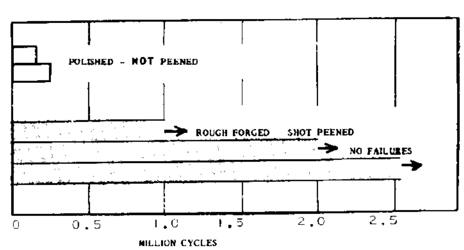


Fig. 29 Fatigue Durability of Fork-Type Connecting Rods

4.3 Crankshafts

The most highly stressed area of a crankshaft is the crank pin bearing fillet (Figure 31). The high stress point is the bottom side of the fillet when the pin is in the top dead-center position during the firing cycle. It is common for cracks to initiate in this pin fillet and propagate through the web of the crankshaft to the adjacent main bearing fillet, causing fatigue failure.

Figure 30 of a 6 cylinder 4340H forged crankshaft shows the unpeened part has fatigue strength of 52 KSI while the shot-peened crankshaft has the fatigue strength of 72 KSI, a 38% improvement.

Current economics emphasize recycling of large crankshafts by reconditioning which basically consists of inspection for cracks; then blending them out by grinding to acceptable limits, even if the original manufacturer has not cold worked the fillets initially. The fillets should be cold worked after grinding. Controlled shot peening is the recommended means of restoring the cold-work effect and the residual compressive stress.

All size crankshafts respond well to shot peening, from small high-speed shafts with journal bearing diameters of 1", to large slow-speed shafts with journal bearing diameters of 6" or more. Experience has shown the process to be effective on forged steel, cast steel, nodular iron, and austempered ductile iron.

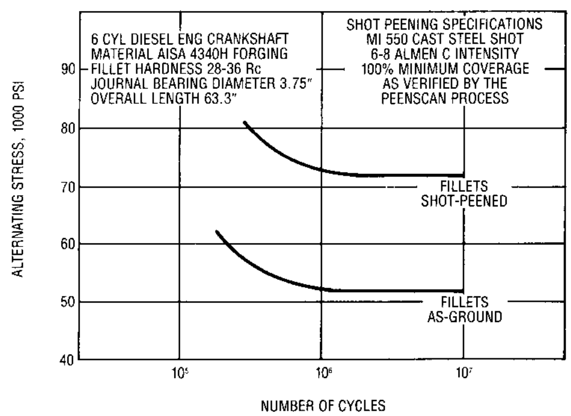


Fig. 30 Increase in Fatigue Strength of Shot Peened Crankshaft

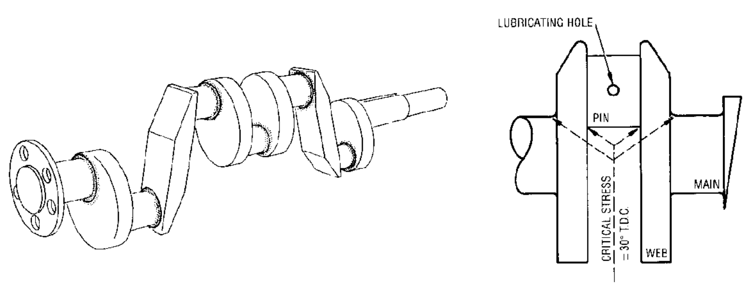


Fig. 31 Crankshaft and Detail

4.4 Gears

Shot peening of gears is one of the more common application of the process. Gearing applications range from automotive, to heavy vehicle, to marine transmissions, to axle drive gears, to small gears used in power tools and to very large gears used in transmissions for large ships and mining equipment.

The fillets at the root of the gear are usually the areas of high stress and should be shot peened. However, it has also been shown that the tiny indentations produced by shot peening on the face of the gear act as very small oil reservoirs which help promote better lubrication, reduce fretting, noise, spalling, scoring and lower operating temperature by reducing friction. Gears which have to be held to very close tolerances may be lapped or honed after shot peening, provided the lapping or honing operation does not remove more than 10% of the depth of the compressive stress induced.

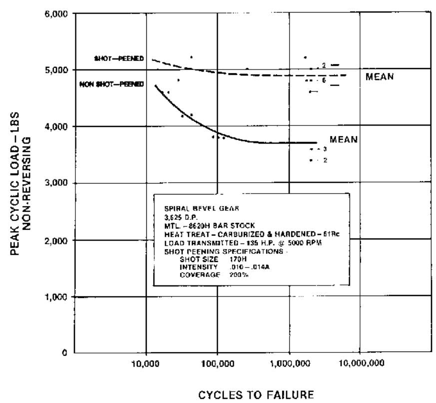


Fig. 32 Increase in Fatigue Resistance of Spiral Bevel Gear

Gears are frequently shot peened after carburizing, as shown in the chart below. It has been found that the life of a case hardened gear, stressed to 80,000 psi (56kg/mm2), increased from 2000,000 cycles before shot peening to 30,000,000 cycles after shot peening. The use of special-hardness (R_C55-62) shot is recommended for peening case-hardened carburized gears in order to produce a higher magnitude of compressive stress.

Increases in fatigue resistance of SAE8620 spiral bevel gears, carburized and hardened to R_C61, are shown in Figure 32. A residual stress profile induced by the same set of peening parameters is shown in Figure 33.

Figures 32 and 34 both show increases in fatigue strength of at least 30% at 10 cycles, which are typical of results obtained by shot peening carburized gears. However, excellent results can also be achieved on through-hardened gears ad gears with induction-hardened teeth and roots. Shot peening can also be used as an inspection tool for "case-hardened" gears. Because of the significant difference in the hardness between case and core, peening the side faces of the gear will show a marked difference in appearance and make the case profile readily identifiable to verify its uniformity.

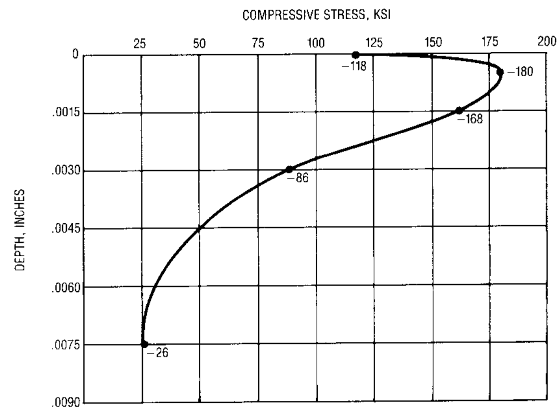


Fig. 33 Stress Profile of Carburized Gear Tooth Root, Ground Then Shot Peened with Special Hardness Shot.

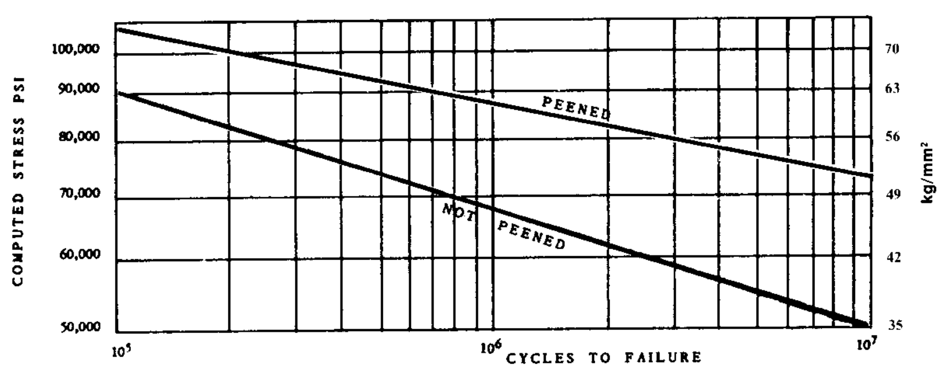


Fig. 34 Fatigue of Carburized Gears

Lloyds of London Register of Shipping, allows an increase in tooth loading for both wear and strength of up to 20% with the use of controlled shot-peened "gearing". Det Norske Veritas of Norway states, "For gears produced according to our usual demand for quality(no grinding notches, no significant surface decarburization etc.), we add 20% to the fatigue limits stated in our rules for shot-peened parts."

4.5 Shafts and Axles

All sizes and many types of shafts and axles are shot peened to improve their fatigue properties. In some instances, peening is required only in keyways, splines, fillets, shear sections or other changes in cross section. Figures 35 and 36 show the benefits of shot peening on rear axles and notched shafts, respectively.

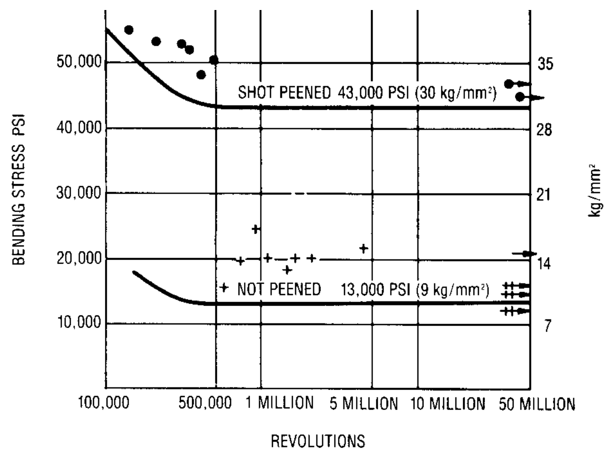


Fig. 35 Fatigue Tests on Rear-axle Shafts

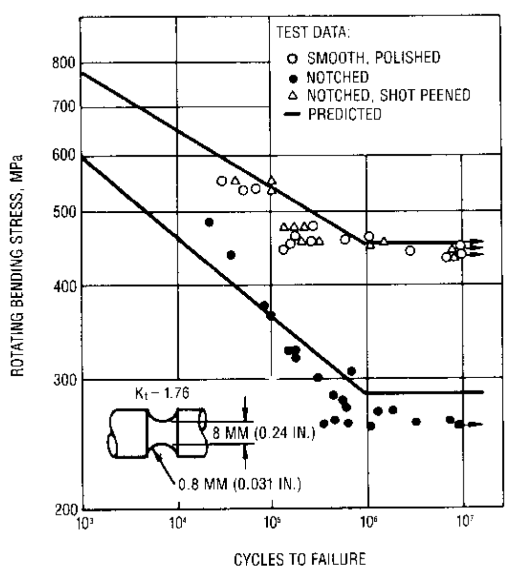


Fig. 36 Fatigue Tests on Notched Shafts

In order to protect the equipment which they drive, many shafts have shear sections designed to fail when the shaft is overloaded. Since the shear section is thinner than the balance of the shaft, it will often be the site of early fatigue failures. By shot peening the shear section of the shaft, the life of the shaft can be increased while retaining the same overload protection provided by the shear section.

4.6 Springs

Compression coil springs are probably the best known and most widely used parts that are shot peened. All automobile engines contain shot-peened valve springs and have done so for forty-five years. Springs made of wire sized as small as .005 inch (.13mm) diameter and as large as 3.0 inch (76.0mm) have been successfully shot peened to increase fatigue resistance. Figure 37 shows the increase in safe stress ranges of coil springs made of various metal alloys. The fatigue resistance of extension springs and coiled torsion springs can also be increased by shot peening.

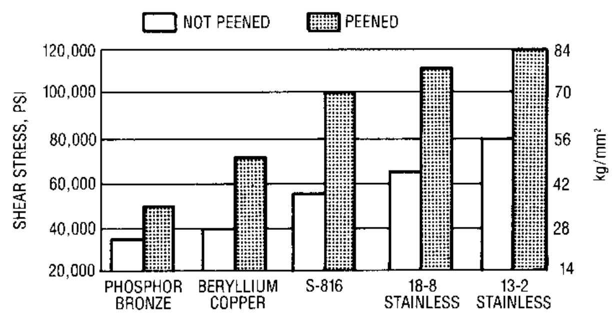


Fig. 37 Safe Stress Ranges for Coil Springs of Various Alloys

4.7 Torsion Bars

Torsion bars are an excellent application for shot peening. Figure 38 shows the increase in fatigue resistance made possible by shot peening torsion bars.

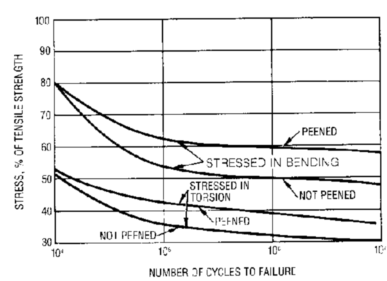


Fig. 38 Comparison of Fatigue Curves Bending Vs. Torsion Loading

5 MATERIALS APPROPRIATE FOR SHOT PENNING

5.1 High-Strength Steels

Increasing use has been made of steel at hardness levels above R_C50 corresponding to tensile strength above 224,000 psi (158kg/mm2) for fatigue applications, such as springs and aircraft landing gear. Figure 39 shows the close connection between shot peening and the use of these strength levels.

Without shot peening, the greatest fatigue strength is obtained at a hardness of around R_C40. At higher hardness levels, the material loses fatigue strength due to increased notch sensitivity. With the addition of shot peening, the fatigue strength increases proportionately in increasing hardness. At a hardness of R_C52, the shot-peened fatigue strength is 144,000 psi (101kg/mm2), more than twice the best unpeened fatigue strength.

This chart shows that it is not sufficient to check the effect of peening at the conditions which were best without peening. Much larger improvement may be obtained by taking full advantage of peening with increased hardness.

The most interesting implication of this data is the permissible use of increased ultimate tensile strength made possible by the use of peening. Normally, strength levels above 200,000 psi (140kg/mm2) without peening are dangerous because of loss of fatigue strength. However, with the addition of peening, the higher-strength levels can be used to withstand higher applied loads at the same time increasing fatigue strength. Excellent examples are impact wrench hammers, anvils and sockets, and percussion drilling tools.

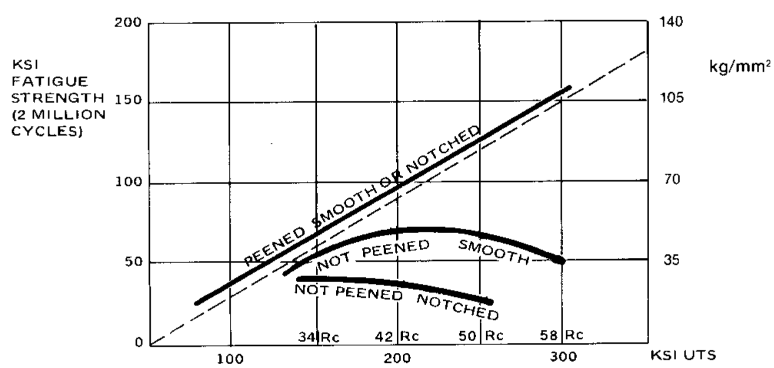


Fig. 39 Comparison of Peened and Unpeened Fatigue Limits for Smooth and Notched Specimens as a Function of Ultimate Tensile Strength of Steel

Testing has confirmed this data and added information that the fatigue strength of peened parts is not impaired by shallow scratches which could otherwise be detrimental to unpeened high strength steel parts.

5.2 Aluminum Alloys

The fatigue resistance of aluminum alloys, commonly used in aircraft structures, can also be improved by the use of shot peening (see Fig. 40).

In recent years, aluminum lithium alloys have emerged, particularly in the aerospace industry. Al-Li alloys include a small percent (normally 2-3%) of lithium which increases durability and lowers density. These advantages result in a significant weight savings of aircraft with no loss to properties. To date, both damage tolerant alloys (similar to 2024) and high-strength alloys (similar to 7075-T6) have been investigated. Shot peening has shown to provide similar increases in fatigue resistance on Ai-Li alloys as with their conventional counterparts. Figure 41 shows fatigue results with Al-Li alloy 2090-T8 compared to the similar alloy 7075-T6. The fatigue results are essentially the same.

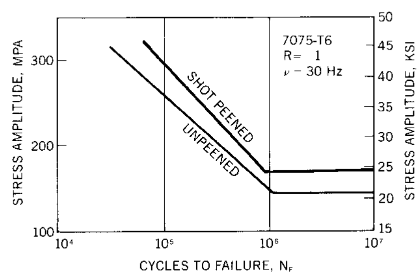


Fig. 40 Results of Reversed Bending Fatigue Tests on Unpeened and Peened Specimens of 7075-T6 Aluminum Alloy

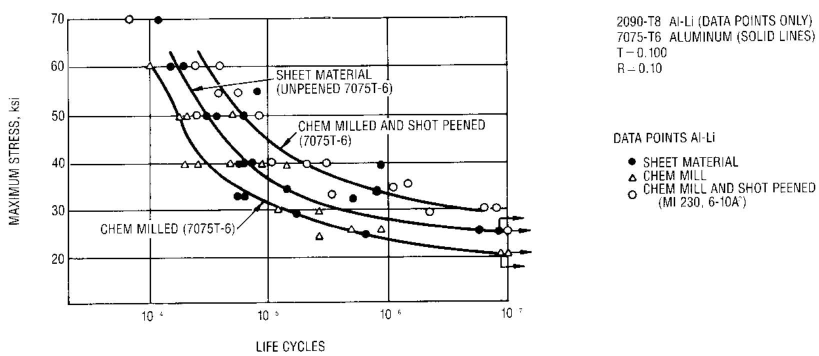


Fig. 41 Comparison of 7075-T6 Vs. Al-Li Fatigue Results

5.3 Austempered Ductile Iron

Although known for many years, austempered ductile iron (ADI) is a material that only today is becoming more widely used. During the past decade, advances in austempering controls have made possible greater exploitation of the unique mechanical properties of ADI. Recent application for ADI include crankshafts, camshafts, gears, and railroad wheels. Figure 42 shows that shot peening provides ADI gear teeth with substantial fatigue strength increases as has been the case with the more commonly used gearing materials. Additionally, shot peening will increase surface hardness of ADI very significantly to promote greater wear resistance.

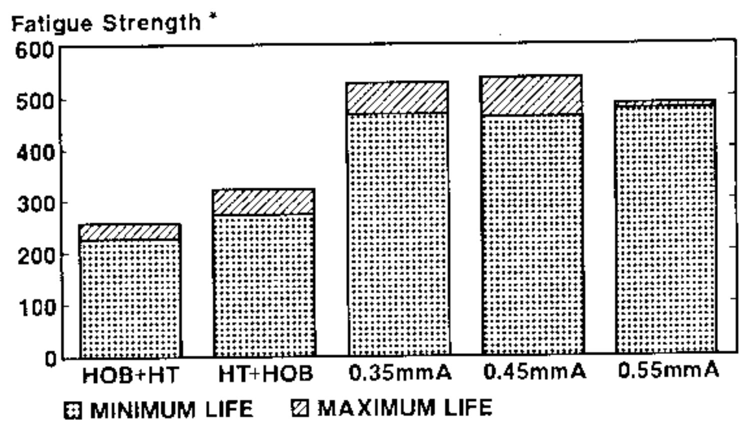


Figure 42 The Effect of Processing Variables on the Bending Fatigue Strength of Austenitic-bainitic (K9805) Gear-teeth: Measured after 10 Loading Cycles.

HEAT-TREATMENT AFTER HOBBING
HOBBING AFTER HEAT-TREATMENT
SHOT-PEENING 0.35mm ALMEN A
SHOT-PEENING 0.45mm ALMEN A
SHOT-PEENING 0.55mm ALMEN A

5.4 Powder Metallurgy (Sintered)

The dynamic properties of sintered (PM) components may be enhanced by shot peening. Improvement in fatigue life is the result of increased hardness and residual compressive stresses. Optimized peening parameters have been shown to raise the endurance limit of sintered steel alloys by 22% and the fatigue life by a factor of ten. This suggests that highly stressed automotive components such as gears and connecting rods should be considered good candidates for sintered steel.

5.5 Titanium

The low-cycle fatigue (LCF) benefit from shot peening varies in degree relative to the applied stress.

Recent data support the notch LCF benefit for dovetail slots in aerospace hardware (Fig. 43).
An evaluation of titanium compressor discs is provided for both baseline and shot-peen data. It may be seen that the shot-peening benefit is evidenced most at the lower stress levels. Typical and minimum (one failure per thousand) curves show an increase of .5x at the high-stress levels to 4x at the lower-stress levels.

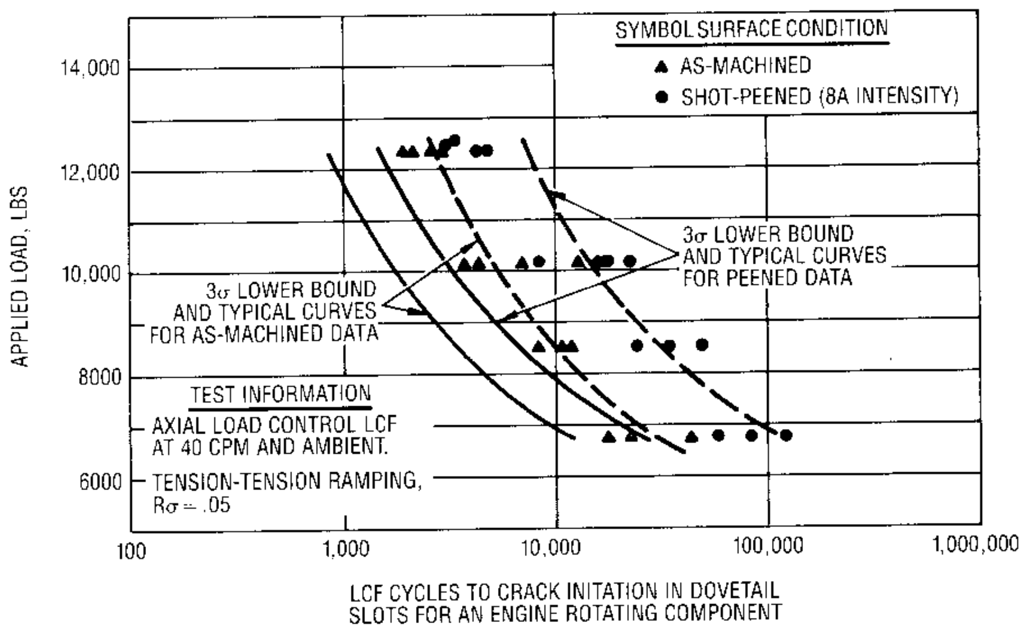


Fig. 43 Notched LCF Benefits to TI 8-1-1 From Shot Peening

6 MISC. PEENING TECHNOLOGY

6.1 Peen Forming

Peen forming is a die-less forming process performed at room temperature. During the process, the surface of the work piece is impacted upon by small, round steel shot. Every piece of shot impacting the surface acts as a tiny peening hammer, producing elastic stretching of the upper surface and local plastic deformation that manifests itself as a residual compressive stress. The surface force of the residual compressive stress combined with the stretching causes the material to develop a compound, convex curvature on the peened side (Fig. 44).

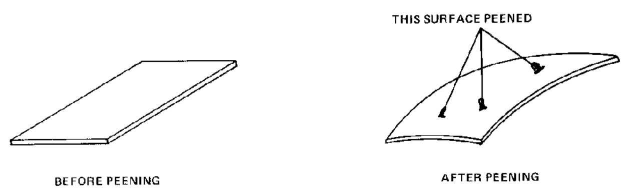


Fig. 44 Compound Curvature Result of Tri-axial Forces Induced by Shot Peening

The process is ideal for forming large panel shapes where the bend radii is reasonably large without abrupt changes in contour. It is best suited for forming curvatures where the radii are within the metal's elastic range.

No dies are required for peen forming; however, for severe forming applications, stress peen fixtures are sometimes used. Peen forming is effective on all metals, even honeycomb skins and ISO grid panels, within certain limitations. A partial list of aircraft using peen formed wingskins is shown is Figure 45.

A6A Gruman	777 Boeing	F-15 McDonnell
EA6B Gruman	S3A Lockheed	F5E Northrup
727 Boeing	P-3 Lockheed	B1B Rockwell
737 Boeing	C-130 Lockheed	A-10 Fairchild
747 Boeing	L-1011 Lockheed	
757 Boeing	MD80 McDonnell	CL-600 Canadair
767 Boeing	MD11 McDonnell	Dash 7 Dehavilland

Fig. 45 Partial List of Aircraft Using Peen-formed Wings

Peen forming is often more effective than rolling, stretching or twisting of metal to develop the required curvatures. Saddle-back shapes are possible and by being a die-less process, material allowance for trimming is reduced, and costly development and manufacturing time required to fabricate hard dies is eliminated. The process is flexible to design changes, which may occur after initial design. By only adjusting the air pressure or wheel speed, it is possible to incorporate curvature changes. Peen forming is accomplished at room temperature. Part size is currently limited to 15 feet wide by 110 feet long (3.0m wide by 24.5m long), the limitation being only availability of existing equipment. Thickness range in aluminum is 0.050 inch to 2.0 inch (1.27mm to 51.0mm); and alloy steel is 0.016 inch to 1.0 inch (.40mm to 25.4mm).

Parts formed by peen forming exhibit increased resistance to flexural-bending fatigue. Another distinct advantage with peen forming, unlike most other forming methods is that all surface stresses generated are of a compressive nature. Although peen-formed pieces usually require shot peening on one side only, the final result causes both sides to have compressive stress. These compressive stresses serve to inhibit stress corrosion cracking and to improve fatigue resistance. Some work pieces should be shot peened all over prior to or after peen forming to further improve fatigue and stress corrosion characteristics. Parts which have been cold formed by other processes are often shot peened to overcome the harmful surface tensile stresses set up by these other forming processes.

6.2 Contour Correction

Just as it is possible to create a desired curvature and shape to components by shot peening, it is also possible to correct the shape and form of parts as well. The shot peening process avoids the unfavorable (tensile) residual stresses produced by other straightening methods and instead produces favorable (compressive) residual stresses. Many companies have correctively peened a great variety of parts such as shafts, tubes, rings, gears, axles, crankshafts, jet engine discs and wing spar extrusions and forgings. Carburized ring gears as large as 48 inches (122 cm) diameter, which were out of round as much as 0.125 inch (3.17mm) have been corrected to within 0.003 inch (.076mm).

Figure 46 is another example of corrective forming by shot peening. The carburized hardened ring gear in this photograph is approximately 6 inches (15.24 cm) in diameter by 2 inches (5.1mc) in width. The concentricity of this gear was between the inner circle and the large division line, corresponding to 80 microns. After the successful corrective forming operation, the ring gear became concentric within 20 microns.

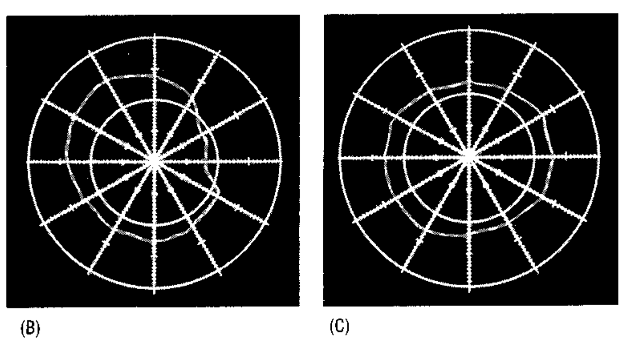


FIG. 46 Contour Correction of Ring Gear
(B) Before Peen Forming (C) After Peen Forming

7. STATUS OF INDUSTRY

A comprehensive report published in 1989 by The National Center for Manufacturing Sciences investigated the art and practice of shot peening. This report, "<u>High Reliability Residual Compressive Stress Processes</u> "(State-of-the Art-Assessment), provides an in-depth review of the peening industry and offers several conclusions for future work. A summary of recommendations is given in the next section.

[Text from section 5.0 Recommendations]

5.0 Recommendations

Based on survey responses and review of the literature, five areas of need have been identified which, if satisfied, would result in significant advancement in the state of the art CRS processing. The following discussions of each of these five recommendations include (1) estimates of time and funds necessary for effective pursuit and (2) assessments of the relative desirability and probability of success. The time and funding estimates are solely opinions of the authors. The assessments of desirability and probability of success were derived from discussions with the NCMS TPC members at a review meeting in June, 1989.

5.1 Development of Non-destructive Means for Crs Process Verification

This need was the most often expressed need among survey respondents. Moreover, survey results clearly showed that, with few exceptions, neither life/endurance nor residual stress testing is being used routinely to verify results of CRS processing. The most probable underlying reason is one of economics. Either the testing itself is deemed too time consuming and expensive or the attendant destruction of the test articles is deemed an economic hardship or both. In the shot peening area, the Almen Strip is employed nearly universally as an indirect means of process verification. This is certainly a better situation than the absence of verification; however, one must recognize the inherent weaknesses of the Almen Strip approach even aside from the issue of broad tolerances in Almen Strips. The AISI 1070 spring steel of the Almen Strip generally does not display the same intensity saturation and coverage responses of the production hardware. In general, there is no established relationship between Almen intensity and the magnitude of mechanical property or residual stress benefit sought for the production hardware. The Almen Strip is a non-discriminate integrator of transferred energy; i.e., different combinations of peening parameters could yield the same Almen intensity, but would likely produce different responses in production hardware.

Survey results also clearly showed a general lack of confidence in the consistency of CRS processing among users. The best evidence for this is that only about one-third of users quantitatively claimed credit for CRS process induced enhancement of hardware life. The major reason for reluctance to claim such credit is the perception of process variability. Certainly this perception indicates a general need for improvement of in-process control of process parameters. Sufficient technology currently exists to accomplish good in-process control; however, the implementation is not meaningful without some direct means of process verification.

With no intent to exclude potential application of other technologies, the authors suggest that either ultrasonic or Barkhausen noise techniques show some promise in this area. A Barkhausen noise technique would have the limitation of being applicable only to Ferro-magnetic materials. While both techniques have the attribute of being non-destructive, it must be noted that both are sensitive to changes in residual stress along with other material characteristics; e.g., grain size and plastic deformation. Thus, they may lack sufficient discrimination to permit direct measurement of residual stress. It is quite possible, however, that they may provide ability to indicate reproducibility, or lack thereof, in CRS processing in spite of inability to isolate effects of process-induced residual stresses.

The cost and timing for development of a non-destructive means for CRS process verifications are estimated to be $1 million and two years respectively.

5.2 Development of Information for Establishing Crs Process Parameter and the Relationship of Those Parameters to Resulting Benefits in Mechanical Properties.

This recommendation stems jointly from recurring responses of survey participants indicating need for information and from the literature review. There may in fact be a wealth of published information in this area. The literature review found well in excess of three hundred technical publications which contained fatigue, stress corrosion and residual stress data from studies involving CRS processing. Most of these were in the shot peening area. These references have been compiled and tabulated in this report; however, a detailed critical review of the data was not within the scope of this survey. As a logical first step in the process of information development, these data should be critically reviewed to assess validity and to establish where gaps in knowledge and data exist. From that information, plans could be drawn for experimental programs needed to bridge at least the most significant gaps. A critical review of published data would likely also result in an enhanced data base for improvement of existing CRS process specifications.

The cost and timing for analysis of available data are estimated to be $40 thousand and six months; generation of additional information to bridge significant gaps would require an additional $500 thousand and two years effort.

5.3 Development of Sensors to Enable Direct Determination and Control of Peening Media Velocity

Fundamentally, shot peening and other impact treatment processes involve the transfer of kinetic energy of a propelled media or strikes into deformation of a work piece upon impingement. To produce this energy transfer in a controlled reproducible manner requires control of numerous process parameters which have been identified in previous sections of this report. It has been concluded from survey responses and literature review that state of the art technologies in sensors and microprocessor control are being implemented with success in the shot peening industry. A notable technological gap exists, however, in the ability for direct sensing and control of media velocity and mass flow rate. As noted in previous sections, there have been publications describing systems based on capacitance sensors which have apparently been successful in direct monitoring and control of media velocity and mass flow rate. One may argue, thus, that the necessary development has already occurred and therefore should not be considered as a major need. As counterpoint to that argument, two very important facts should be noted: (1) none of the development occurred in the U.S., and (2) the developments have not been applied on a commercial basis. On this basis, because of the overall fundamental importance of direct media velocity control, this area is strongly recommended for further development and applications in the U.S.

Such development is estimated to cost $500 thousand and would likely require one year's effort.

5.4 Development of Monitoring Technique to Determine Coverage in Peening Processes

Survey respondents clearly indicated this need in regards to peening processes. Currently, the primary means of determining peening coverage is optically aided visual surface examination, usually at 10x. The drawbacks of this method are (1) the requirement for an experienced observer and (2) the subjective nature of the interpretation, particularly in the coverage range from about 90-100 percent. Some practitioners use a fluorescent paint or dye which is applied to a surface before peening and allowed to dry. During peening, the dried paint is removed from the impingement of the media. The major drawback of this method is the lack of quantitative discrimination. Generally, the fluorescent paint is completely removed significantly before 100 percent coverage is attained. The inverse of this, however, is a definite attribute, i.e., if any fluorescent paint remains adherent on a part after peening, one can be certain that 100 percent coverage has not been attained.

Most likely, state of the art development in the area of peening coverage determination will involve the technologies of vision sensors and artificial intelligence. Implementation of any such development will depend greatly on the economics since competing visual and fluorescent paint methods currently in use are low in cost. Certainly, however, an automated coverage determination system is likely to be economically favorable for high volume, production environments.

Development of a coverage determination system is estimated to cost $500 thousand and would require about one year's effort.

5.5 Peening Intensity Determination

This area is related to the issue of CRS process verification discussed in section 5.1; however, it applies strictly to peening processes. Survey respondents in the peening area clearly indicated a desire for replacement of the Almen Strip which currently is the sole means for indicating peening intensity. The major objection of the Almen Strip is based on the time consuming iterative process *of adjusting process parameters until the given desired Almen intensity is attained and the re-verification required after peening has been performed. There are also technical issues of differences in saturation response between given hardware material and the AISI 1070 steel from which the Almen Strip is made. These things taken together make replacing the Almen Strip highly desirable. No specific suggestions for such a system were uncovered in the survey, but clearly speed and low cost are key desirable attributes.*

Such development would likely require $500 thousand to $1 million in funding and two to three years' investigation.

5.6 Feasibility Assessment and Ranking

Estimates of costs and timing for each of the recommended development areas have been given in sections 5.1 through 5.5. After completion of the survey, the TPC committee met to review and discuss results. Included in that meeting was a discussion of specific desirability and feasibility (probability of success) of the five technical development areas. The consensus of TPC and Metcut personnel on these points is presented on page 41. With regard to the ranking of desirability, not that these are <u>relative</u> rankings among the areas identified. Developments in all five areas were deemed highly desirable in absolute terms.

An alternate presentation of the same information is given graphically on page 42. Clearly, it is seen that NDE Process Verification ranked highest in relative desirability, but lowest in probability of success. The Velocity Monitor and Intensity Monitor both ranked moderately high in relative desirability and highest in probability of success.