Effectiveness of Shot Peening Process in Wide Range of Applications

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The main advantage of using shot peening process is to increase the fatigue strength of components subjected to high alternating stresses. The fields of application for shot peening include all metallic components, which are subject to fluctuating and fatigue loads. Some common fields of shot peening application are:

1. Vehicles and agricultural machinery.
2. Power drive and transmission system.
3. Internal combustion engines.
4. Steam and gas turbines.
5. Aviation equipment.
6. Chemical equipment.

The shot peening can improve the performance of the parts through:

1. Usage of the abrasive effect.
2. Removal of stress concentrations.
3. After-machining process.
4. Wear reduction on sliding surfaces.
5. Reduction of the danger of stress corrosion cracking.
6. Straightening or forming of metallic components.
7. Surface stabilization before chromium plating.

Increased fatigue strength due to shot peening has been firmly established by extensive fatigue tests on a wide variety of machine parts. The process is used very extensively on leaf springs, coil springs, torsion bars and other machine parts.

A gain in fatigue strength can be obtained even under poorly chosen peening conditions for a particular application, and even under poorly controlled operating conditions of the peening machine. In spite of this adverse combination, sufficient increase in fatigue strength may be obtained to justify the use of shot peening in that particular application. Shot peening is economical and enviromuental friendly. It leads to significant improvements of the mechanical properties of work pieces. Table 1 gives numerous applications of shot peening [1].

Table 1: Improvement in Fatigue Life of Parts by Shot Peening

Type of Part	Applied Stress	% Increase in Service Life
Pins	Alternate Bending	400 — 1900
Shafts	Torsion	700
Gearbox Shafts	Service Life Tests	80 —
Crankshafts	Service Life Tests	300, variable
Aircraft Link Rods	Push / Pull	105
Connecting Rods	Push / Pull	45
Leaf Springs	Dynamic Stresses	100 — 340
Helical Springs	Service Life	3500
Torsion Bars	Dynamic Stress	140 — 600
Cardan Coupling Shafts	Alternate Bending	350
Gears ..	Service Life Tests	1.30
Tank Tracks	Service Life Tests	1100
Weldments	Service Life Tests	200
Valves	Service Life Tests	700
Rocker ArmS	Service Life Tests	1320

Other advantages of using shot peening are:

1. Permits design of lighter weight and lower cost components.
2. Prevention of stress corrosion.
3. Formation of lubrication pockets.
4. Compensates manufacturing related surface defects.

1 Shot Peening in Gear Design

Shot peening is an excellent means of increasing beam strength of all types of gears in which high load carrying capacity is required [2]. Beam strength is the resistance of a tooth to breakage. A newly manufactured unpeened gear contains concentrations of residual tensile stress induced during manufacturing. The highest concentration of stress is in the tooth fillets at the gear roots (Fig 1). This area is also highly loaded when a gear is running and subjected to bending fatigue failure. If the combination of applied load and residual tensile stress is high enough, the gears fail prematurely (Fig. 2) [3].

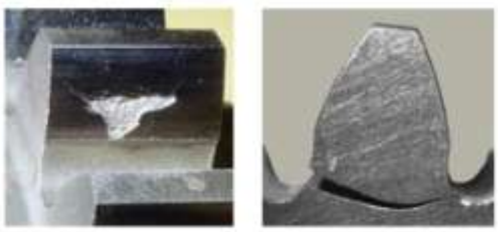

Fig. 1: Failure of Gear Tooth

Fig. 2: Failure of Pinion

The shot peening treatment is applied generally to the tooth fillets only, although sometimes the entire tooth profile is shot peened. In the latter case, the resulting dimples provide, in addition to improved stress characteristics, a beneficial effect on lubrication. They act as lubrication pockets that aid in maintaining a full film thickness between meshing teeth.

Gear manufacturers generally prefer not to uprate gears that have been shot peened. They look on shot peening, which is fairly inexpensive, as added insurance in getting maximum operating life (Fig 3). Shot peening is seldom specified in original gear design, yet it can improve the life and load carrying capacity of gears by as much as 200 % often without adding appreciably to cost.

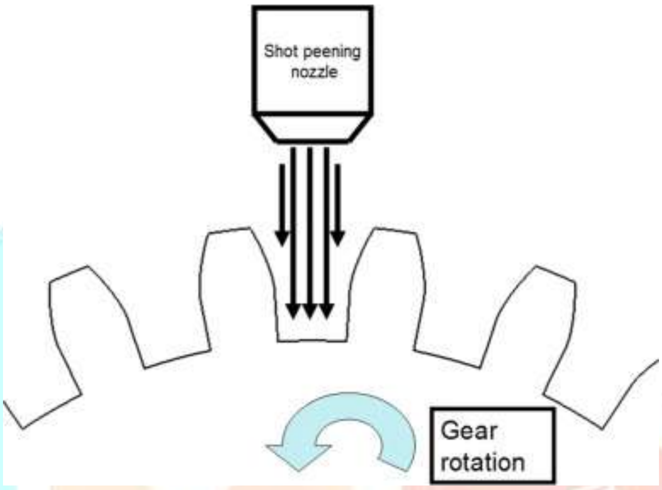

Fig. 3: Peening Arrangement for Gears

In an experimental study done by Kotoji, Katsuyuki and Hirohito [4], two kinds of steels *A* and *B* with different chemical compositions were quenched and tempered to a hardness level of 200 HV. Gears were then machined from them with the following specifications: module = 3, number of teeth 36, helix angle and hand 17° right hand, pressure angle 14° 30' and over-ball diameter 123.6 mm. Six kinds of gears were made. Gears I to IV were made of steel *A* while the gears V and Vi were made of steel B.The surface treatment techniques adopted were Vacuum Carburizing (VC), Contour Induction Hardening (CIH) and Double Shot Peening (DSP). After machining, the gears were surface treated with these combined treatments. Table 2shows the combined surface treatments for each gear.

Table 2: Combined Surface Treatment of Various Gears

Gear	**I**	**II**	**III**	**IV**	**V**	**VI**
Steel	A	A	A	A	B	B
Surface Treatment	VC	VC + DSP	VC + CIH	VC + CIH + DSP	CIH	CIH + DSP

Fig. 4 shows S-N curves of all the gears except gear III, which was not fatigue tested. The stress range at the fatigue limit of various gears is summarized in Table 3. It can be said tha.t the difference in the fatigue limit resulted from the different compressive residual stress distribution of various gears. The conclusion is that double shot peening played a key role in increasing the fatigue limit [4].

Table 3: Stress Range of Various Gears LI

Gear	Stress Range at Fatigue Limit, MPa	% Increase
I	883	-
II	1931	118 over I
IV	2207	150 over I
V	1256	-
VI	1710	38 over V

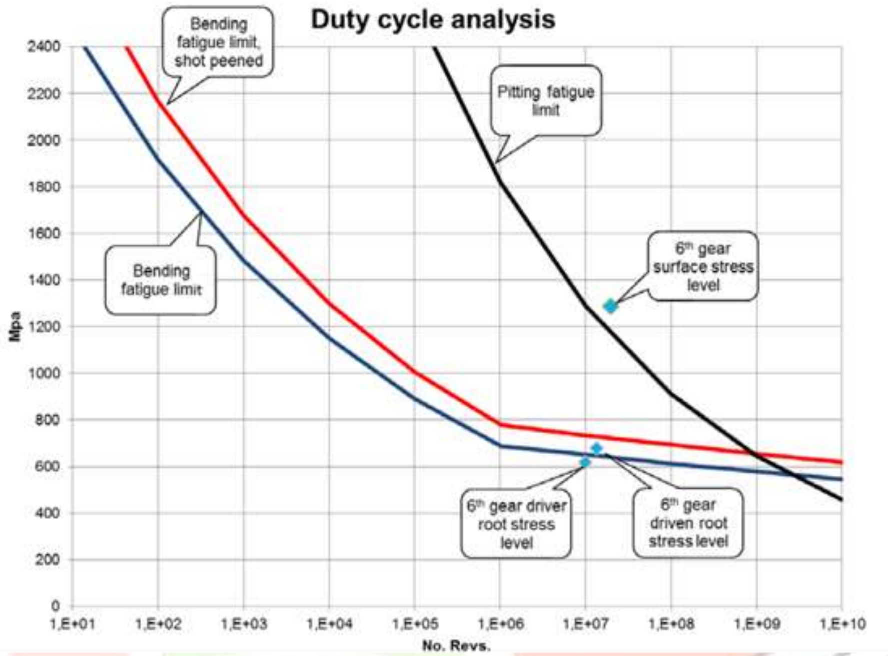

Fig. 4: S-N Curves of Various Gears

At the Dingolfing plant near Munich, BMW manufactures all gear components for passenger cars and motorbikes. Production can be both — single and mixed product runs (parts for passenger cars and motor bikes). After hardening and annealing, all gear parts are shot peened to increase vibration strength, resistance against stress cracks and vibration crack corrosion. Requirements are complex to a certain extent: root and tooth flanks of the parts have to be shot peened while areas require only descaling or deburring.

2 Shot Peening for Welds

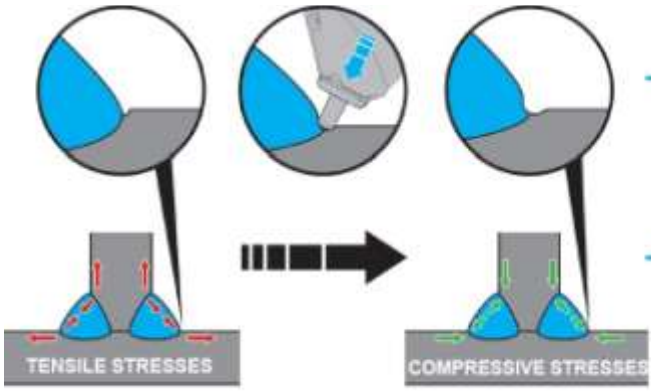

Fig. 5: Manual Peening of Welds

A study done through the SAE Fatigue Design and Evaluation Committee showed what shot peening can do for welds compared to welds that didn't have this operation done. The study claimed that the regular welds would fail after 2,50,000 cycles, while welds that had been shot peened would fail after 2.5 million cycles, and that too outside the weld area. This is part of the reason that shot peening is a popular operation with aerospace equipment parts. However, the beneficial stresses that are induced on these parts can wear off due to higher temperatures [5].

The analysis of fatigue test results of improved welded joints proposed by Huther*et al.* [6] involves more than 300 sets of results. The analysis concerns the four improvement techniques which have given rise to the greatest number of studies: burr grinding, TIG dressing, hammer peening and shot peening. In this study, different parameters have been analyzed such as the type and thickness of the welded joint, the yield strength (230 <σy, <800 MPa) and the stress ratio *R* (-1 <*R* <*0.5).* In each case, the proposed improved S-N curves enabled to compare the behavior of the welded joint (Fig. 6). Table 4 compares the design stress, S_{Rk}, (in MPa) statistically determined at 2x10^6 cycles for shot peened specimens. Depending on the welded detail, the ratio S_{Rk}/S_{Rk} *(AW)* varies between 1.5 and 2.5 (improvement range: 50-150 **%).**

Table 4: Comparison of Design Stress for Shot Peened and As-Welded Specimens

Joint Type	σy	M	Δσ	S_{Rk}	S_{Rk}(Aw)	S_{Rk}/S_{Rk} (Aw)
Butt	>600	9	326	226	90	2.5
Cruciform	<400 >600	9	278	220	90	2.4
T - Joint	<400	9	196	144	71	2.0
	>600	9	232	146	71	2.0
Longitudinal Attachment	<400	5	123	95	63	1.5
	>600	5	148	121	63	1.9

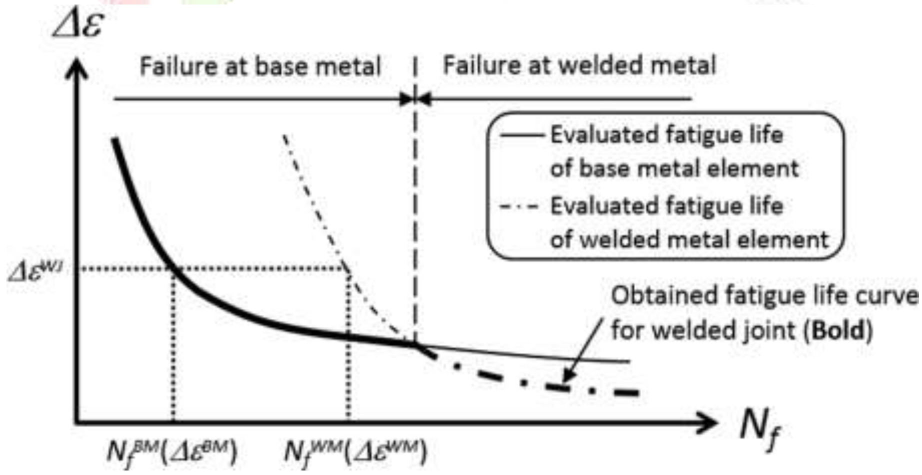

Fig. 6: Fatigue Strength of Welded Joints in Steel E460 [6]

Shot peening improves property performance of welds and weldments by canceling residual tensile stresses that develop in surfaces as welds cool and replacing them with compressive stresses. Compressive stresses raise resistance to fatigue, stress corrosion, and inter-granular corrosion. Testing shot-peened parts, researchers have demonstrated that peening raises fatigue resistance of fillet welds in carbon steel and butt welds in constructional alloy steel by 20-40 %, and can double fatigue resistance of butt welds in aluminum plate and 18 % Ni maraging steel. Researchers at Rockwell International (Atomic Division) found that shot peening prevents stress corrosion cracking of weldments in austenitic stainless steel [7].

If shot peening process is applied in combination with some other treatment to modify the weld profile like TIG-dressing, disc grinding or burr grinding, its effectiveness can be increased, since shot peening will act on a surface where defects and imperfections have already been removed and the weld profile has been geometrically improved. But these very good results can be achieved only after an accurate investigation in the case of interest, that is to say that the choice of shot peening parameters should be chosen bearing in mind the material, the type of welded detail, the analysis of the stress state under the in-service load. In this case the fatigue behavior of welded parts will be similar to the one of monolithic notched parts, and the fatigue limit much higher, making welding more convenient in respect to other joining techniques.

3 Shot Peening for Lighter Components

Instead of designing a component with **a** larger cross sectional area for better load carrying capacity, it is better to go in for a smaller cross sectional area component undergoing shot peening, thereby reducing the weight of the component.

Today in the automotive industry, all chassis, valve springs, many gears and shafts are shot peened. Without shot peening, these parts would have to be 30-50 % heavier, increasing the weight of an automobile by as much as several hundred pounds. The weight savings made possible by use of shot-peened parts are of great importance in the aircraft industry for engine parts, propellers, landing gear, and similar items subject to repeated loading. Other industries requiring a high strength to weight ratio, such as the oil industry, also rely heavily on shot peening. An important recent development is shot peening of ultra-high strength steels for improved fatigue-life characteristics [8].

The reduction of vehicle weight by using light-weight structural alloys such as those based on magnesium, aluminum and titanium, for body as well as suspension parts, is one of the most promising ways to reduce fuel consumption and improve driving performance. Superior fatigue properties of the materials are an important requirement for these applications. Since shot peening is known as a low cost finishing treatment that is able to markedly improve the fatigue life of many structural materials such as steels and cast irons, the effect of shot peening on the fatigue performance of the more expensive light-weight alloys is of particular importance for automotive applications [9].

4 Shot Peening for Springs

Fatigue tests on springs which had been previously static tested showed peened springs to have longer life than unpeened ones. The tests also indicate that plain carbon steel springs are at least comparable to alloy springs in fatigue. However, alloy springs are justified on the basis of higher harden ability, higher elastic limit and greater impact resistance. The two main methods for improving spring performance are shot peening (Fig.*7)* and scragging. Shot peening affects surface tensile stresses by developing residual compressive stresses, thus increasing the endurance of the part.

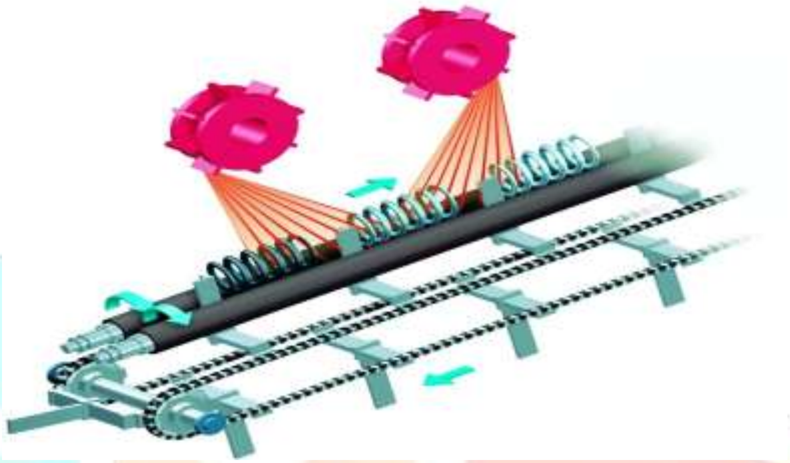

Fig. 7: Shot Peening of Coil Springs

In order to obtain best performance in hot wound springs, both for fatigue life and minimum setting in service, the spring should have negligible decarburization, be accurately wound, have evenly spaced coils, be heat treated correctly and adequately shot peened, and should be pre-set before service.

The industrial shot peening of springs is performed in batch type equipment where a centrifugal wheel is used to propel the shot. In an industrial study, a machine normally working with steel shot was adapted to work with ceramic shot [10]. The main modifications to the equipment were the control of the mass flow with ceramic shot and adjustment of the wheel rpm. By using ceramic versus steel shot in a double peening process, an increase of *25 %* of durability for 90 % reliability achieved on highly loaded torsion springs.

Even after the optimal shot configuration and intensity are established for a given application, it is also possible in some cases to achieve the same or better durability with a single ceramic peening versus duplex peening with steel shot or even duplex peeñing with steel followed by ceramic [10]. Because of the very high residual stresses that can be achieved at the surface without increasing the roughness, ceramic shot is especially efficient in applications where the fatigue failure actually starts at the surface of the spring wire (Fig. 8).

Fig. 8 Failure in Coil Spring

5 Shot Peening for Automobiles

At present, improvement of the fatigue limit of automotive components is a top priority of the automobile industry. The demand is especially high for automobiles that are environment friendly and fuel-wise economical. To improve the fatigue limit of automotive components, the following three methods are currently in common use:

1. Minimize surface roughness.
2. Increase hardness of the material.
3. Introduce a large compressive residual stress at the surface.

Although the second method is a reasonable alternative, it is difficult to apply to the automobile parts with hardness as high as 600-700 HV. Fatigue limit is proportional to hardness up to 400-500 HV. Above 500 HV, fatigue limit does not increase with hardness, rather it decreases. Therefore, it is not appropriate to increase hardness further for components such as gears and springs. The third method of shot peening is used widely for this purpose. Some of the applications of shot peening in automobile field include:

5.1 Connecting Rod

When building a high performance engine, great attention is paid to the connecting rods, eliminating stress risers by such techniques as grinding the ed.ges of the rod to a smooth radius, shot peening to induce compressive surface stresses in order to prevent crack initiation, balancing all connecting rod / piston assemblies to the same weight and magnafluxing to reveal otherwise invisible small cracks which would cause the rod to fail under stress (Fig 9).

Fig. 9 Failure of Connecting Rod

5.2 Automotive Axle Shaft

All vehicles have some type of axle shaft-differential assembly incorporated into the drive transmission line. Rear wheel drive is a common form of engine-transmission layout used in automobiles. Rear wheel drive means the power from the engine and the transmission goes to the rear wheels.

Axle shafts are used in automobiles to connect wheel and differential at their ends for the purpose of transmitting power and rotational motion. In operation, axle shafts are generally subjected to torsional stress and bending stress due to self-weight or weights of components, or possible misalignment between journal bearings. Thus, these rotating components are susceptible to fatigue by the nature of their operation (Fig. *10).* The fatigue failures are generally of the torsional, rotating-bending, and reversed (two-way) bending type. Fatigue failures start at the most vulnerable point in a dynamically stressed area particularly where there is a stress raiser [11].

Fig. 10: Failure of Axle Shaft

The stress raiser may be mechanical or metallurgical in nature, or sometimes a combination of the two. Mechanical stress raisers are non-uniformities in the shape of the shafts such as step changes in diameter, sharp corners, keyways, grooves, threads, splines and surface discontinuities like seams, notches and machining marks. Metallurgical stress raisers may be quench cracks or weld defects. The microstructure of the shaft material also plays a vital role not only in the initiation of fatigue failures but also during the progressive growth of the fatigue crack to cause failure of the component.

6 Shot Peening for Hardened Parts

The fatigue strength can be compared with ultimate tensile strength for both smooth and notched metallic specimens. At higher strength / hardness levels, materials lose fatigue strength due to increased notch sensitivity and brittleness. With the addition of compressive stresses from shot peening, however, metal fatigue strength increases proportionately to increasing strength / hardness.

Today, many automobile parts, after being subjected to hardening processes such as quenching/tempering or carburizing, are chrome-plated or otherwise surface-treated to improve their durability, wear-resistance and corrosion-resistance. To determine the possible effects of the shot peening process on characteristics such as fatigue strength when it is applied to partswhich are carburized and then hard chrome-plated, a series of tests was conducted [13].

Case 1: Carburized Hardened

Case 2: Case 1 + Shot Peening (Steel Shot, 0.41 mm A)

Case 3: Case 1 -F Cr Plating (Hard Chrome, 40im)

Case 4: Case 1 ± Shot Peening + Cr Plating

Case 5: Case 1 -F Cr Plating + Shot Peening

Case 6: Case 1 ± Tufftride

Case 7: Case 1 + Cr Plating + Baking (2000 C)

1. When carburized hardened and chrome-plating were performed on parts (Case *3),* a 20 % loss in fatigue strength resulted as compared with parts which were carburized hardened but not shot-peened (Case 1). When shot-peening and then chrome-plating of carburized hardened parts was done (Case 4), or when shotpeening was done in the final manufacturing process (after chrome-plating) (Case *5),* the fatigue strength could be maintained at a level almost equivalent to what was obtained in Case 1.

2. When the parts were heated to 200° C for *3* hours after chrome-plating (Case 7), the hardness decreased to some extent, so fatigue strength and pitting resistance decreased. However, when shot peening was done before or after chrome-plating (Case 4 or *5),* it was possible to obtain parts having hardness, fatigue strength and pitting resistance well comparable with those resulting in Case 1. These favorable results were considered to be attributable to the compressive residual stress due to shot-peening, which prevents crack propagation.

3. When tufftriding (liquid nitriding) was applied to carburized hardened parts (Case 6), both corrosion resistance and wear resistance improved without any loss in fatigue strength, in comparison to Case 1. Furthermore, even higher fatigue strength could be expected if a proper shot-peening is selected.

7 Shot Peening of Bicycle Frames

Shot peening has four major benefits in the crafting of titanium bicycle frames:

1. Fatigue life is enhanced significantly increasing the useful life of the frame.
2. The frame is stress relieved so that all the component parts work together.
3. Surface hardness is enhanced increasing resistance to scratches.
4. Provides an aesthetically pleasing finish.

The process of butting and welding titanium tubes to make a frame is known to create tensile stresses in the frame material. Tensile stresses make the area in question want to pull itself apart. This is a bad property to impart to a bicycle frame as any minor notch or micro crack in the frame will propagate and further compromise the material. The induced tensile stresses are most concentrated in the heat affected zone — the area of the welds. Thus, strength is compromised precisely where one would like it to be the greatest.

Shot peening of welded titanium joint substantially increases both fatigue strength and fatigue life as compared to the same joint which is not shot peened. Shot peening imparts residual compressive stress which counteracts the residual tensile stress, which is created in the process of cutting, grinding and welding. Typically, fatigue strength of a welded titanium joint after shot peening is *double* that without shot peening. By shot peening the frame after it is welded together, the stresses in the material are relived, providing compressive qualities, which are known to reduce micro cracking and enhance fatigue life. Without stress relieving, each of the tubes will retain tensile stresses which tend to conflict with one another. Stress relieving allows the component tubes of the frame to work together as designed, acting as a unified structure rather than a collection of competing parts [14].

8 Shot Peening in Aerospace Applications

The aerospace structures are designed by following the damage tolerant methodology. This implies that critical elements are periodically inspected, visually or by some nondestructive technique, to assess presence of growing fatigue cracks and to evaluate if their presence can be tolerated until the next inspection. Shot peening is applied to new as well as used components, to create a favourable residual stress field where fatigue damage is developing.

The importance of surface treatment is fundamental to diminish the frequency of the inspections, which is in delaying fatigue crack growth. This is an important objective, since it allows for considerable savings. This is a key factor that drives manufacturers and researchers to start and develop new research programs aimed at obtaining structures that are ever more safe, light, reliable and economic. Following are some of the success stories for aerospace applications:

8.1 German Aero Engine

Rolls-Royce Deutschland (RRD) is German aero engine manufacturer with the complete responsibility for design, manufacturing, validation and in-service support for engines. Within component manufacturing, besides complex machining operations, a series of special processes such as controlled shot peening are applied. Controlled shot peening is applied mainly at critical rotating parts to introduce compressive residual stresses at the surface to obtain increased life of the component. Basic process parameters that determine the residual stresses achieved are the shot mass, velocity and the coverage [15].

8.2 Reduction in Airframe Weight

Reducing airframe weight is an extremely important consideration in the engineering of both military and commercial aircraft. Apart from static strength, the primary concern in aircraft engineering is fatigue strength, which, if improved, can mean significant savings in airframe weight. The fatigue strength *of* components can be improved in specific instances by shot peening. The chief aim of the study done by Franz and Olbricht [16] was to optimize the shot peening process to improve the fatigue strength of the titanium alloy Ti-6A1-4V. According to the literature, the peening of titanium alloys is a particularly sensitive process and has also been known to result in increased fatigue strength. Practice has shown that fatigue strength is dependent **upon** the type of cyclical loading, component form, material and certain secondary factors. One of these factors is the surface, which has been subjected to various treatments and processes and provided with protective coatings.

Shot peening changes the properties of near-surface layers, depending upon the condition of the material. The extent of the change can be determined in terms of certain characteristic values or parameters, and is also related to the original values for these parameters. The three most important parameters are: residual stresses, work-hardening and surface topography or morphology. Also to be taken into considerations are phase transformations and the implantation of shot-peening media. Changes in the parameters, whether positive or negative, are in part responsible for the change in fatigue strength, depending upon the materials prior condition and the type of stress applied. By cutting all the specimens from a plate in essentially the same way, it was ensured that the microstructure was approximately the same in all the specimens and would manifest itself solely in the statistical distribution of fatigue strength values [16].

The robotic shot peening system has successfully been used for the peening of several components on military and commercial aircraft. The CF-i 8 aircraft is a multipurpose, high-performance twin-engine fighter acquired by the Canadian Department of National Defense starting in 1982 to handle air-to-air or ground-attack roles. The CF- 18 structure is made of several thick, machined components that are sometimes shot peened to improve the fatigue life. During the assembly of the aircraft, a few critical locations on the wing carry-through bulkheads were peened to improve the fatigue life of the aircraft. The peening was performed to an intensity of 6-10 *A*with steel shot [17]. A second peening, to the same intensity hut using glass beads, was also performed on some of the most critical locations in order to obtain the best possible fatigue life. The use of ceramic beads was prompted by Original Equipment Manufacturer (OEM) test results that showed an increased fatigue life over glass beads. The robotic shot peening system is a new tool to ensure optimum fatigue life improvement on the CF-18 at difficult to access locations. The robotic shot peening system offers a peening of exceptional quality in a process that is controlled, accurate, and repeatable even in confined areas.

8.3 Auxiliary Power Unit Exhaust Ducts

One particular type of Auxiliary Power Unit is used to provide power to an aircraft when it is on the ground with the main engines turned off. The tubular exhaust ducts are a high temperature 8009 aluminum alloy welded in an end-to-end design. Tension-tension fatigue tests measured fatigue strength of 23 ksi (156 MPa) at 3,000 cycles in the as-welded condition. Glass bead peening of the welds resulted in a 13 % fatigue strength improvement to 26 ksi (180 MPa).

8.4 NASA Langley Crack Growth Study

Engineers at NASA performed a study on crack growth rates of 2024-T3 aluminum with and without shot peening [18]. The samples were tested with an initial crack of 0.050 (1.27 mm) (damage tolerance rogue flaw) and then cycle tested to failure. It was found that crack growth was significantly delayed when shot peening was included. Table 5 shows par cent increase in average life cycle as a result of shot peening. This test reflects conditions that are harsher than real world conditions. Real world conditions would generally not have initial flaws and should respond with better fatigue life improvements at these stress levels.

Table 5: Effect of Shot Peening on Crack Growth Rate of Aluminium [18]

Net Stress (ksi)	No. of Tests	Non-Shot Peened	Shot Peened	
		Average Life Cycles	Average Life Cycles	% Increase
15	2	75,017	253,142	237
20	3	26,029	47,177	81

8.5 Turbine Engine Fan Disks

In 1991, the Federal Aviation Authority (FAA) issued an airworthiness directive that required inspection for cracks in the, low pressure fan disk. At the time, over 5,000 engines were in use on business jets in the United States and Europe. The FAA required that engines that did not have lance (shot) peening following machining in the fan blade dovetail slot be inspected. Those engines having fan disks without lance peening were required to reduce service life from 10,000 to 4,100 cycles (takeoffs and landings). Disks that were reworked with lance peening as per AMS 2432 (Computer Monitored Shot Peening) prior to 4,100 cycles were granted a 3,000 cycle extension.

8.6 Turbine Engine HP Compressor Rotors

Two leading companies in the manufacture of jet turbine engines jointly manufacture high pressure compressor rotors. Separate pieces are machined from forged titanium (Ti4Al-6V) and then welded together. Testing produced the following results (Table 6): Initially, shot peening was used as additional insurance from failure. After many years of failure free service, coupled with innovations in shot peening controls, shot peening has been incorporated as a full manufacturing process in engine upgrades.

Table 6: Effect of Shot Peening on Life **of Compressor Rotors**

Treatment	Life Cycles
As Welded	4,000
Welded and Polished	6,000
Welded and Peened	16,000

9 Shot Peening in Chemical and Petrochemical Applications

Shot peening has proved its effectiveness in extending the service life and enhancing the performance of metal components by protecting them against fatigue, fretting fatigue, stress corrosion cracking and a variety of other failure mechanisms. Following are some of the applications for chemical and petrochemical industries:

9.1 Chemical Handling Equipment

Shot peening has been utilized as a cost savings measure for construction of chemical handling equipment. In cases where ammonia dr chloride based solutions were to be contained, a lower cost Stress Corrosion Cracking (SCC) susceptible material was selected with shot peening rather than a more expensive non-SCC-susceptible material. Even with the additional shot peening operation, construction costs were less than using the more expensive alloy. Table 7 demonstrates the effectiveness of shot peening in combating SCC for those stainless steel alloys listed. A load stress equivalent to 70 % of the materials yield strength was applied.

Table 7: Effect of Shot Peening on Life of Different Stainless Steels

Material	Test Life (Hours)	
	Not Peened	Peened
316 SS	11.3	1,000 No Failure
318 SS	3.3	1,000 No Failure
321 SS	5	1,000 No Failure

9.2 Offshore Steel Structures

A Norwegian research program concluded that the combination of weld toe grinding and shot peening gave the largest improvement in the life of an offshore steel structure (Table 8). This corresponds to more than a 100% increase in the as-welded strength at one million cycles. Other research shows that the improvement in weld fatigue strength from shot peening increases in proportion to the yield strength of the parent metal.

Table 8: Effect of Shot Peening on Fatigue Strength of Offshore Steel Structures

Steel Condition	Fatigue Strength at 1,000,000 Cycles
Base Material	50 ksi (340 MPa)
As Welded (only)	20 ksi (140 MPa)
Weld Toe Ground (only)	26 ksi (180 MPa)
Weld Toe Ground and Peened	44 ksi (300 MPa)

10 Shot Peening in Processing Applications

The application of shot peening in various processing industries can be given as:

10.1 Food Industry Cheese Molds

The cheese / dairy industry has found that uniform dimples provide a surface that can advantageously replace other surface treatments. The textured surface from shot peening often has a lower coefficient of sliding frictioi that is necessary for cheese release properties on some food contact surfaces. The dimples act as lubricant reservoirs for fat or other substances allowing the cheese product to slide easier through the mold on the peaks of the shot peening dimples. Testing has shown that shot peened finishes meet or exceed necessary requirements for cleaning in terms of microbial counts. This is due to the rounded dimples that do not allow bacteria to collect and reproduce. Sharp impressions left from grit blasting, sand blasting or broken media have proven to be less cleanable and have a much greater tendency for bacteria to collect and reproduce. Both glass beaded and stainless steel media have been used successfully in this application.

10.2 Pneumatic Conveyor Tubing

Pneumatic conveyor tubing can be up to ten inches in diameter and is usually made of **a** stainless or aluminum alloy. It is used to transport plastic pellets at the facilities of molding companies or at various production, blending and distribution sites. Transported pellets degrade when contact is made with internal piping surfaces. The velocity of the pellets results in friction, heat and lost production. Directional shot peening has been found to be much superior to other internal treatments of the tubing, it is often more economical and can be applied on-site. The directional surface finish has the added benefit of work hardening (when stainless steel or aluminum piping is used), thus extending the life of the surface treatment. Table 9 shows test results from six different internal pipe treatments. A lower value of fines per 100,000 lbs conveyed is desirable. The directional shot peening resulted in one third of the fines of the next closest finish.

11 Shot Peening in Transportation Applications

Shot peening plays an important role in strengthening the metallic parts in various transportation systems. For example, a brake pin is part of **a** hydraulic brake assembly used in a mass transit train system. In a study, the undercut sections near the chamfered end were designed to fail in the event of axial overload. During the investigation of premature failures it was found that a bending load was also occurring. The combined axial and bending load when simulated in test conditions caused fatigue failure between 150000-2,600,000 cycles. After shot peening was added to the brake pin, all test specimens exceeded 6,000,000 cycles without failure.

Table 9 :Effect of Shot Peening on Pneumatic Conveying Capacity

Treatment	Fines (gm/100,000 lb conveyed)
Directional Shot Peened	1629
Smooth Mill Finish	4886
Spiral Groove Pipe	6518
Sandblasted Pipe	7145
Polyurethane Coated	7125
Medium Scored Pipe	13887

12 Shot Peening in Power Generation Applications

Shot peening plays an important part in the production of gas turbine compressor blades and low pressure steam turbine blades. The process and peening parameters for the shot peening of the component blade are specified in such a way that they lead to optimum fatigue strength. Only numerically controlled shot peening machines allow a reproducible shot peening with the established optimum parameters. The quality of the end product blade is greatly improved by shot peening because the improvements in fatigue strength obtained are used only as a technique to increase the component service safety but not to increase the allowed service loads.

Gas turbine compressor blades and steam turbine blades at ABB are mainly made out of the 12 % Cr-steel (X2ICrMoV121) or the titanium alloy Ti-6A1-4V with only a few exceptions. These blades operate world wide under various climatic conditions. If the decision is made to shot peen a particular turbine blade type, the shot peening parameters are determined. The desired distribution of residual stresses is chosen depending on the steel shot. This distribution is characteristic of the component material. However, not only the material behavior during shot peening of components is important, but it has to be checked in a second step whether the chosen residual stress distribution is compatible with the geometric conditions. Practically speaking this means consideration of the smallest radius in the blade root or transition between airfoil and root. If notched specimens or components are shot peened with the right shot and the right intensity, the improvement of fatigue strength obtained is higher than for smooth specimens or sections of components at the same load. For example, investigations with several microstructures of the titanium alloy Ti-6A 1 -4V have shown that the increase in fatigue strength after shot peening depends more on the retardation or prevention of propagation of surface micro cracks due to the compressive residual stresses than on the prevention of crack initiation as is the case for austenitic alloys. If a notch is present, this crack retardation effect is even more pronounced due to the stress gradient.

Following are some of the important examples of using shot peening for power generation applications:

12.1 Feed Water Heaters

Large thermal fatigue cracks were discovered in eight high pressure feed water heaters used in a power generation application [58]. These units operated in both an elevated temperature and thermal fatigue environment. Startups and shutdowns caused thermal fatigue. Steady state operation was at 480-660 °F(250-350 °C). The cracks were circumferential in the weld heat affected zone between the water chamber and tube sheet. Fatigue cracking was attributed to years of service and 747 startups and shutdowns of the unit. This caused concern about the remaining life of the units. The cracked locations were machined and shot peened. Subsequent inspections showed that no additional fatigue cracks developed after five years of service and 150 startup and shutdown cycles.

12.2 Diaphragm Couplings

Metal diaphragm couplings are often used in turbo machinery applications. These couplings accommodate system misalignment through flexing. This flexing, or cyclic loading, poses concerns for fatigue failures. Researchers concluded that the ElectroChemical Machining (ECM) process produces parts that are geometrically near-perfect. However, they found under electron microscope scanning that small cavities sometimes developed onthe surface of a part as a result of ECM. These cavities apparently generate stress concentrations that lead to premature failures. Shot peening after ECM was able to overcome this deficiency and has significantly improved the endurance limit of the diaphragm couplings.

12.3 Turbo Machinery Blades and Buckets

A very common fretting environment is the dovetail root of turbo machinery blades. Shot peening is commonly used to prevent fretting failures of *these* roots. The tight mating fit coupled with demanding loading conditions require that the surfaces be shot peened to prevent failure associated with fretting. Many turbine and compressor blade roots are shot peened as OEM parts and re-shot peened upon overhaul to restore fatigue debits otherwise lost to fretting. The discs or wheels that support the blades should also be peened.

13 Shot Peening in Medical Applications

Application of shot peening for medical equipment and accessories is **a** new area of research. Shot peening with steel shot followed by **a** cleaning process with glass beads is commonly used as surface finish in the production of modular hip end prostheses [19]. Zirconia beads offer higher hardness and strength/fracture resistance than glass beads. The surfaces of Ti-A16-V4 rods were shot peened with zirconia shot using different Almen intensities and coverage. A field emission scanning electron microscope was used for the detection of the residual particle contamination on the surfaces. The near-surface residual stress distributions induced by the shot peening processes were measured by Xray diffraction.

Rods of Ti-A16-V4 with diameters of 8 and 15 mm were shot peened with zirconia shot. The shot used was Zirshot Z425, Saint-Gobain ZirPro, LePontet with a grain size of 0.425-0.600 mm. The outstanding properties of Zirshot are the high hardness and strength / fracture resistance. The shot peening parameters are given in Table 10.

Table 10: Shot Peening Parameters for Medical Components [19]

Intensity (mm A)	Coverage (Passes at 2xt 98%)	Shot Amount (kg)	Air Pres. (Bar)	Sample Dia. (mm)
0.15	2	1.4	4.5	15
0.15	4	2.8	4.5	15
0.18	2	1.4	6.0	15
0.18	4	2.8	6.0	8

Experimental results show that shot peening with both steel and zirconia shots induces the desired residual stress states of the implant components. However, particle contamination of the surfaces must be avoided for physiological reasons as well as for reasons of wear, fretting fatigue, and corrosion of the implant material. The standard shot peening processes, however, lead to a contamination of the surfaces with glass or zirconia particles. Therefore, a shot peening process was suggested with steel shot and subsequent removal of the ferrous contaminations by a pH-dependent chemical cleaning procedure. This procedure employs the favorable topography of shot peened surfaces with regard to the biocompatibility of the implants and allows avoiding any ferrous particle contamination of the implant surfaces.

14 Shot Peening of Stainless Steel

Due to its excellent corrosion resistance, austenitic 316L stainless steel is successfully used in a wide range of environments such as chemical, petrochemical, nuclear and food industries. However, it presents relatively low strength and poor wear resistance. Therefore it is very important to improve these properties by applying surface treatment prior to applications. The fatigue behavior of austenitic stainless steels treated by several methods has been reported but still very limited surface modification techniques can be applied without any loss of the advantages such as corrosion resistance and ductility [20]. The fatigue lifetime improvement for different treatment conditionsfor an applied stress of 380 MPa and 400 MPa respectively.

To avoid too much time consuming experiments, fatigue tests were stopped at a limit of $N = 2x10^6$ cycles. For fatigue lifetime determination, the criterion of complete separation of the specimen was used except when the lifetime exceeded the limit number of cycles. The lifetime of the nano-structured stainless steel is increased considerably compared with the untreated material. In the case where shots of 2 mm diameter were used to prepare the surface nano-crystallization, the benefit on the lifetime improvement is rather low for the high stress amplitude used here, With the use of 3 mm shot, the effect is more pronounced since through nano-crystallization treatment the yield stress is greatly improved and still good ductility can be observed (Table 11).

Table 11: Mechanical Properties of SS **After Shot Peening**

Treatment Time (mill)	0.2% Yield Strength (MPa)	UTS (MPa)	Total Elongation
5	510	710	43
15	665	750	22
30	725	784	15

15 Shot Peening of Agricultural Equipments

Critical components of agricultural equipment come into direct contact with soil / crop or some vital parts of a mechanism. These components are exposed to fatigue, wear and impact and therefore require certain level of hardness, toughness and fatigue resistance. The consequences of impact, fatigue and wear are serious in terms of both replacement cost (parts, labor and down time) and its effect on timeliness of field operations. Further, cost, higher speed of operation, higher reliability and durability of wearing parts demand greater attention to the structural design of implements employing minimum metal or lighter weight and yet ensuring an adequate fatigue life of key components [21]. Shot peening process can be used for agricultural equipment to make it cost-effective and techno-economically acceptable to agricultural equipment manufacturers.

16 Shot Peening of Soil Engaging Tools

Abrasive wear is a micro fatigue phenomenon occurring in soil engaging tools. From cost consideration, these tools are made of cheaper carbon steels. To enhance wear resistance and tool life of these steels, the effect of shot peening, coating and coating with post shot peening was studied. Shot peening was carried out on the test pieces using pressure peening system. The peening system had one nozzle and a reciprocating arrangement for nozzle holder. The work piece was fixed in front of the nozzle for shot exposure. Peening pressure was 0.589 MPa, nozzle bore 6.0 mm, shot size S *330* (0.825 mm), shot hardness 45-50 HRC, stand off150 mm, average mass flow 0.4 tph, angle of impingement near to 900, coverage 98 % and peening intensity 0.3 *5-0.45 A*. Shot peening C after coating has shown considerable improvement on abrasive wear resistance [22].

Design of experiment

The following treatments were decided to be performed on the test specimens:

T1 = Virgin sample (SAE-i022) (Ti — stands for treatment one).

T2 = Virgin and shot peened.

T3 = Virgin and coated with material I (self fluxing alloy of Ni-Cr-Fe-Si-B).

T4 = Virgin and coated with material II (ceramic material which is a combination of $A1_2O_3$ - TiO_2).

T5 = Virgin and coated with material III (super performance stainless steel).

T6 = Virgin coated with material I and again shot peened.

T7 = Actual blade material sample (En 42).

To make a comparative study of all the test specimens subjected to different treatments, they were tested (run) for fifty hours simultaneously in the wear test machine, so that all the samples could be subjected to same operating/ environmental conditions. Percentage wear of test pieces after different treatments are given in table 12.

Table 12: Effect of Various Surface Treatments on Abrasion Wear [22]

Treatment	Mass of Blades (gm)		Wear (%)
	Before Test	After Test	
T1	55.23	51.78	0.054 (6.25)
T2	55.14	51.92	0.051 (5.84)
T3	56.467	56.433	0.000406 (0.06021)
T4	49.104	49.069	0.000458 (0.07127)
T5	48.867	48.388	0.005727 (0.9802)
T6	52.838	52.821	0.000138 (0.03217)
T7	70.87	67.49	0.041 (4.77)

17 Shot Peening in Repair Work

All peening treatments improve the fatigue life of components, but when rework (repeening) on a damaged component is to be done for life extension, optimizing of the peening parameters is a must. Poor control of peening procedure, or unnecessary over peening can result in a relatively poor fatigue life. Over peening may result in introduction of surface damage in the form of laps / folds due to impact extrusion of the material parallel to surface. There may be an apparent improvement in the surface finish of a repeened component, hut reduction in fatigue life may occur due to surface defects originating from the preceding peening, i.e., deeper laps / folds being hammered deeper.

In general, lighter peening media like hard plastics, glass or ceramic beads may dramatically improve the fatigue performance as compared to steel shots and thereby reduce the scatter. Specially in the case of aluminium alloys, steel shot peening can be quite detrimental to the fatigue performance and needs optimizing and monitoring of the peening parameters due to relative softness. Uncontrolled peening may introduce surface damage, which can promote fatigue cracking *[23].*

A double peening can also be carried out. The first run is performed with a small shot to assure the treatment and to open even sharp arid deep defects. The second run with a larger shot must then be performed to reach a high Alrnen intensity, i.e., a large affected depth. In all cases coverage rate higher than 100 % must be realized, 200 % is recommended.

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