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Controlled Shot Peening of Automotive Components

N. Kenneth Burrell
Metal Improvement Co., Inc.

ABSTRACT

The controlled shot peening process is by no means new to the automotive industry. This process is routinely used on many mechanical components to increase fatigue life. In other cases, shot peening is used selectively to overcome unexpected service failures or to allow the use of existing designs in higher stress applications. Some of the more common applications of the shot peening process are engine valve springs, suspension springs, crankshafts, connecting rods, and various transmission components. Much data have been gathered on these and other components which indicate the significant increase in fatigue strength that can be realized as a result of this cold working process. Several examples of these improvements will be discussed, together with supporting S-N curves. Also discussed will be the use of new generation shot peening equipment employing microprocessor control and continuous monitoring of process variables to assure complete repeatability of the process. Improved inspection techniques will be included.

THE PURPOSE OF THIS PAPER is to review fatigue data developed on many components and furnish design engineers with data relative to the effect of the controlled shot peening process on various components that will allow the salvage of existing designs or allow the use of existing designs at higher stress levels.

A discussion of shot peening is really a discussion of residual stress. Residual stress is any stress contained within a part after completion of all manufacturing operations, without any external forces being applied. Most metal parts will contain residual stresses from the manufacturing processes. For example, severe grinding or machining can result in high surface residual tensile stress. Welding will produce high residual tensile stresses in the heat affected zone adjacent to the weld. Cold formed parts, such as springs or formed stampings, will also contain residual tensile stresses.

It is generally recognized that fatigue cracks initiate only in an area of tensile stress, and will normally initiate at the surface of the part. Consequently, if the surface of a metal part contains residual tensile stress, the result will be a lowering of fatigue life. Conversely, if the surface contains residual compressive stress, the fatigue life will be improved.

Shot peening is a cold working process performed by bombarding the surface of the part with small spherical media, the end result being to produce a thin layer of high magnitude residual compressive stress in the surface. The maximum magnitude of this compressive stress will normally be 50-60 per cent of the ultimate tensile strength of the material and will be at maximum slightly below surface. The compressively stressed surface resulting from the shot peening process will negate or minimize applied tensile stresses and resist the initiation of fatigue cracks, as shown in Figure 1.

There are many occasions when a design engineer would prefer to use a high strength steel to minimize size and weight. However, there is always concern about the notch sensitivity of high strength steel in a fatigue critical application. The data shown in Figure 2 (1*) suggests that if shot peening is considered, the high strength steels can be successfully used in these applications.

*Numbers in parentheses designate References at end of paper.

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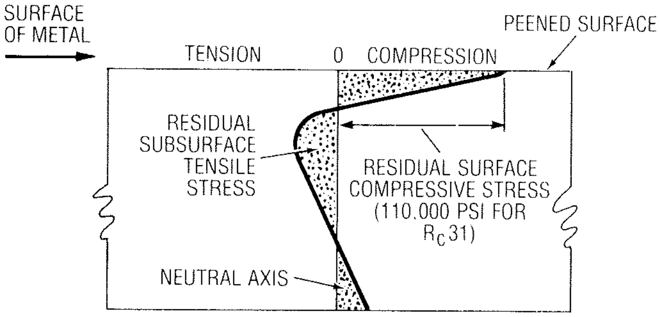
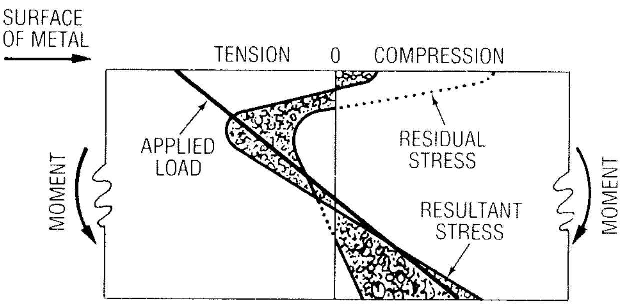


(a) INDUCED COMPRESSIVE AND TENSILE STRESSES IN SHOT PEENED METAL WITH NO EXTERNAL LOAD



(b) STRESSES IN SHOT-PEENED METAL WITH APPLIED BENDING MOMENT

Fig. 1

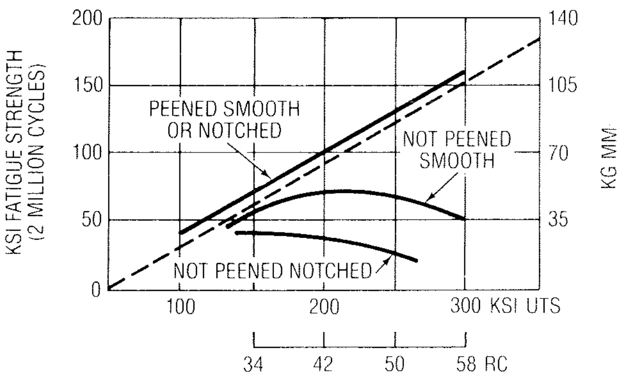


Fig. 2. COMPARISON OF PEENED AND UNPEENED FATIGUE LIMITS FOR SMOOTH AND NOTCHED SPECIMENS AS A FUNCTION OF ULTIMATE TENSILE STRENGTH OF STEEL.

When considering shot peening on high strength steel, it must be remembered that shot peening is a cold working process, and therefore, the peening media must be at least as hard as the target part to achieve optimum results. Normal peening shot is generally in the hardness range of 45-48Rc. If the part to be shot peened is harder than this value, special hard shot in the range of 55-62Rc should be specified. The use of harder media on high strength steel will result in a higher magnitude of residual compressive stress, as shown in Figure 3.

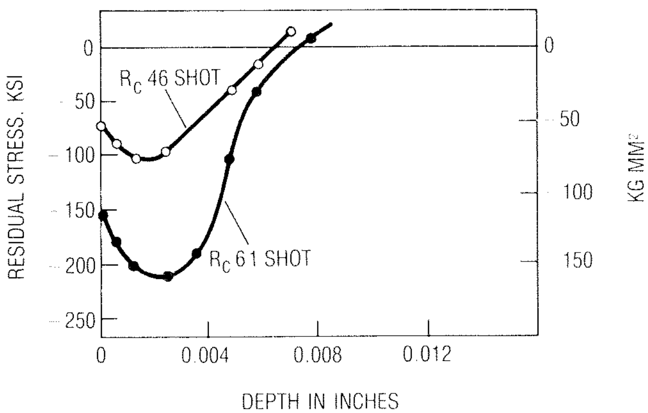


Fig. 3. PEENING 1045 STEEL AT R_C 62 WITH 330 SHOT

Shot peening is, and has been, used as a production process on a large number of automotive components. A partial list of these applications is shown below:

Valve Springs	Piston Rings
Brake Springs	Transmission Gears
Suspension Springs	Transmission Shafts
Rocker Arms	Clutch Plates
Valves	Drive Shafts
Connecting Rods	Differential Spiders
Connecting Rod Bolts	Differential Side Gears
Crankshafts	Differential Housings
Piston Pins	Axles

Data on a number of these applications will be discussed.

SPRINGS

Springs respond more dramatically to the shot peening process than most metal parts because of the high residual tensile stresses resulting from the forming operation. Much testing has been performed to determine how much improvement can be expected from helical and flat springs. Figure 4(2) shows the allowable fatigue strength in the peened and unpeened condition for helical springs coiled from oil tempered wire. It should be noted that these shot peened springs can be used at 65-70 per cent higher stress levels than the unpeened springs.

Table 1 indicates the improvement found in the fatigue testing of helical springs formed from various materials.

Automotive leaf springs respond well to the shot peening process as can be seen in Figure 5(3). In this example, it can be seen that the shot peened springs, cyclically stressed to 150,000 psi, show no failures at over one million cycles as compared with unpeened parts at 100,000 cycles.

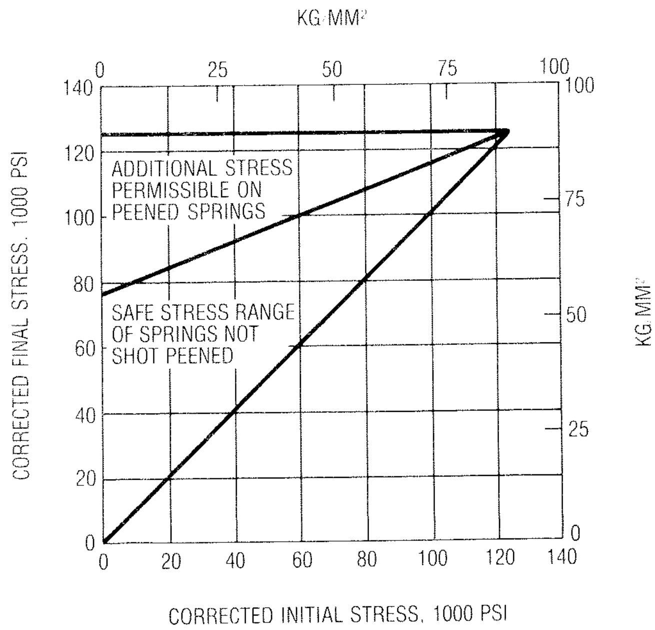


Fig. 4 SAFE STRESS RANGES FOR COIL SPRINGS (.207 DIAMETER STEEL)

Description	Test duration millions of cycles	Fatigue Strength Not peened	Fatigue Strength Peened	Improvement
Music wire, 0.039 in. dia.	0.4	120,000 psi	190,000 psi	58%
Oil tempered, 0.207 in. dia.	10	85,000	120,000	41
Hot coiled 1095, 3/4 in. dia.	2	60,000	90,000	50
Beryllium copper, 0.148 in. dia.	10	40,000	78,000	95
Stainless 18-8	10	80,000	120,000	50
S-816	10	55,000	100,000	81

TABLE 1. INCREASES IN FATIGUE STRENGTH IN HELICAL SPRINGS

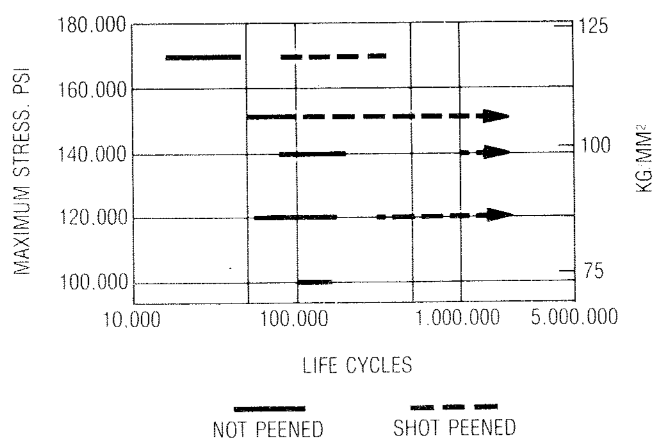


Fig. 5. LIFE TEST RESULTS ON AUTOMOTIVE LEAF SPRINGS

GEARS

After springs, gears are probably the most common application of shot peening in the automotive industry. The majority of these applications involve carburized and hardened steel, having a surface hardness of 58-62Rc, although shot peening is commonly specified on induction hardened and through hardened steel as well as austempered nodular iron gears.

Gear failures fall into two main categories. The most common type of fatigue failure, and the one for which most testing has been performed, occurs in the root radius between the teeth. Figure 6(4) shows the results of fatigue testing carburized and hardened planet gears fabricated from 4118 steel. The results indicate an increase in fatigue strength of 25-30 per cent as a result of shot peening.

Surface fatigue is another cause of gear failure, and is usually identified as pitting or spalling. Not much component testing has been performed to date to determine the effect of shot peening on this type of failure. One such work was performed by the NASA Lewis Research Center, which showed shot peening to increase the surface fatigue life by 160 per cent as shown in Figure 7(5). Other limited component testing has been conducted within industry for which no data has been published. In these cases, by varying the shot peening parameters, increases in surface fatigue life of as much as 300 per cent have been observed.

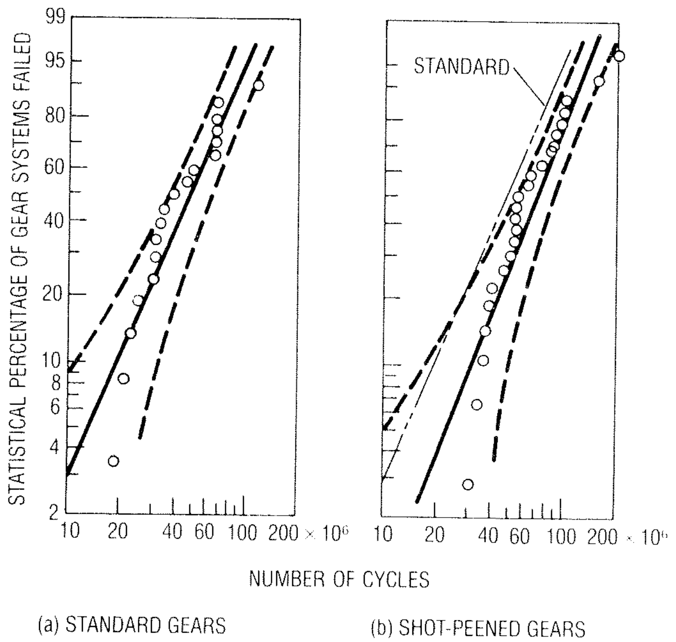


Fig. 7 COMPARISON OF SURFACE (PITTING) FATIGUE LIVES OF STANDARD GROUND AND SHOT-PEENED CARBURIZED AND HARDENED CVM AISI 9310 STEEL SPUR GEARS. SPEED, 10,000 RPM; LUBRICANT, SYNTHETIC PARAFFINIC OIL; GEAR TEMPERATURE, 350 K (170 F); MAXIMUM HERTZ STRESS, 1.7×10^9 N/m^2 (248,000 PSI).

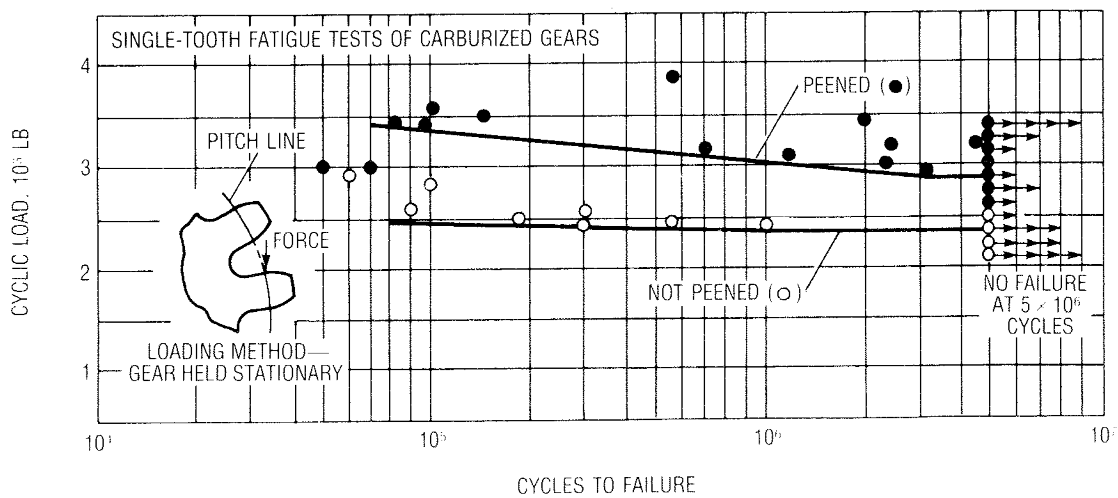


Fig. 6 CARBURIZED PLANET GEARS (4.8 DP WITH 1.4-IN. FACES), FROM THE SAME 4118 STOCK, SHOWED INCREASED LOAD CAPACITY WHEN SHOT PEENED

CRANKSHAFTS

Shot peening of crankshafts is a lesser known application of the process. As a result of the tendency of industry to increase the horsepower of existing internal combustion engines through turbocharging and aftercooling, much higher stresses have been imposed on the crankshaft. Fatigue failures will usually initiate in one of the journal bearing fillets, but occasionally in one of the main bearing fillets. Shot peening has frequently been used as a production process to significantly increase the fatigue strength of this type of part.

Much testing has been performed to verify the fatigue improvement to be expected by the shot peening process. Figure 8(6) shows the results of a fatigue test on a six cylinder, diesel engine crankshaft. The increase in fatigue strength in this case was approximately 40 per cent.

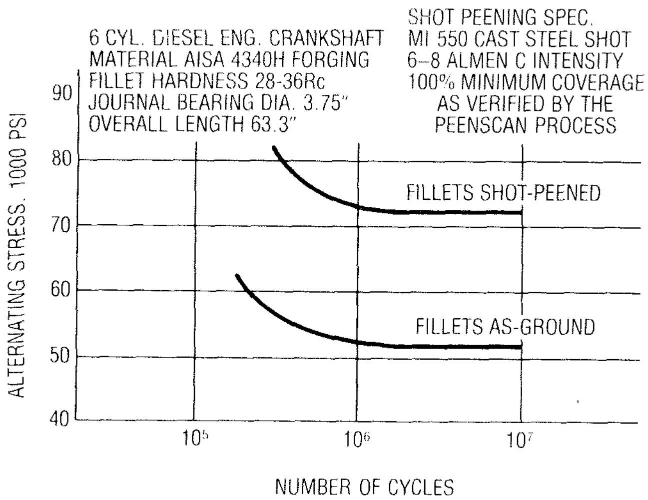


Fig. 8

CONNECTING RODS

For the same reason mentioned in connection with crankshafts, it frequently becomes necessary to increase the fatigue strength of connecting rods used in internal combustion engines. Polishing has been tried to improve the as-forged finish and remove other surface discontinuities which act as stress risers. This is somewhat effective, but as seen in Figure 9(7), shot peening is a preferable process from the standpoint of fatigue results.

The initiation point of fatigue on a connecting rod is generally in the I beam section of the rod. Since no machining is performed in this area, connecting rods are normally shot peened in the as-forged condition to eliminate costly masking operations.

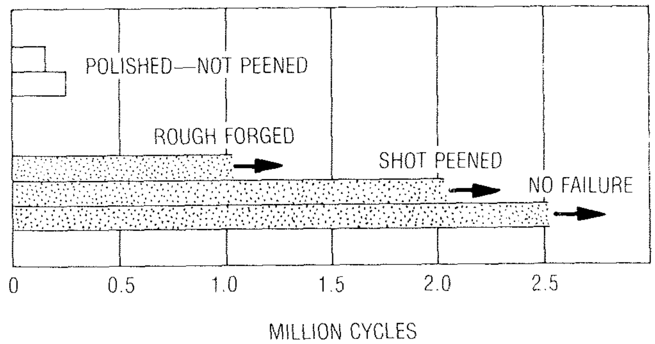


Fig. 9. FATIGUE DURABILITY OF FORK TYPE CONNECTING RODS

AXLES

Because of the abuse to which they are subjected, axle shafts are prime candidates for fatigue failure. The initiation site for fatigue failure may occur in many areas, but usually in splines, keyways, or the major change in cross section where the major diameter of the shaft meets the flange. Often it is this last area which fails because that portion of the axle remains in the as forged or as cast condition, and therefore has a rough surface. Figure 10(8) shows the results of fatigue testing on automotive rear axles. In this case, the fatigue strength as a result of shot peening was increased from 13,000 psi to 43,000 psi.

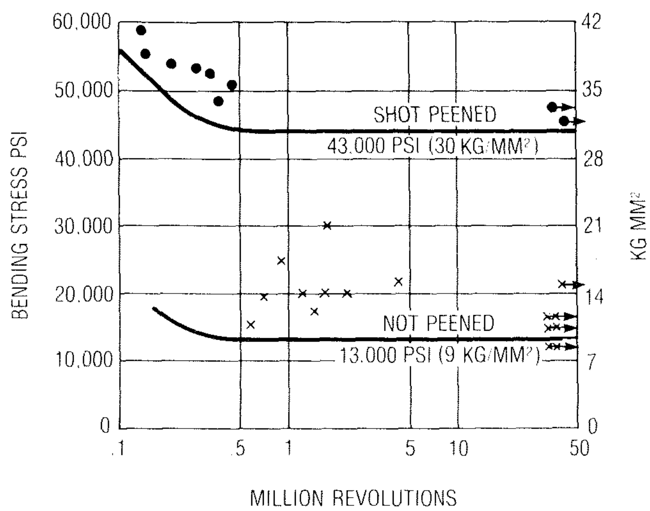


Fig. 10. FATIGUE TESTS ON REAR AXLE SHAFTS

CONTROL OF THE SHOT PEENING PROCESS

Many people in industry mistakenly equate blast cleaning with the shot peening process because they both consist of impelling media against the surface of a metal part. However, the processes are quite different. Blast cleaning is intended to remove contaminants from the surface with the result being a clean part. Little or no attention is given to the intensity of the blast, the condition of the media, or whether the surface of the part has been exposed to complete impingement. In contrast, shot peening is a well-controlled process with all of the shot peening parameters specified. The primary concern is repeatability to ensure the same results for all parts. In recent years, to verify results, some manufacturers have required that minimum surface residual compressive stresses be present on their shot peened parts, and periodically check sample parts with various types of X-ray diffraction equipment.

Various control measures are taken to assure repeatability of process which will result in greater assurance of product reliability.

The first step in assuring optimum results starts at the drawing board with the process specifications. The process specifications which include media type, size and hardness, as well as intensity and coverage, will depend on the part geometry, material, hardness, surface condition and mode of failure. Once the specifications are selected, there must be a means of measuring the process variables to be certain they are being maintained.

INTENSITY - The intensity of the shot peening process is a measure of the kinetic energy being delivered to the part and is a product of the mass and velocity of the media. This intensity governs the depth of the compressively stressed layer. The depth of the compressive layer can be critical. If the design engineer is confronted with a thin section part, the concern is to limit the depth of compressive layer such that no more than 20 per cent of the cross section will be placed in compressive stress to avoid excessively high core tensile stresses and possible distortion of the part. Surface condition is often of concern. If a rough machined surface is present the intensity must be sufficient to assure a depth of compressive stress greater than the surface discontinuities created by the machining. In addition, some parts in service are subjected to foreign object damage. If the design engineer can anticipate this condition he can specify an intensity high enough to counteract the effect of this potential damage.

The intensity of the shot peening process is measured by the Almen strip. This is a flat strip stamped from 1070 spring steel and heat treated to a hardness of 44-50Rc. Three different Almen strips may be used, depending upon the intensity range, as shown in Figure 11 (9).

The Almen strip is mounted in an Almen block, which is a rigid 3/4-inch thick steel block, and is located in the same plane as the critical area to be shot peened. It should be noted that the Almen strip should not be directly mounted to a part unless it is totally flat and is of sufficient cross section that no distortion can occur as a result of the peening effect. After exposure to the shot stream, the Almen strip will have a curvature which is convex on the peened surface. The degree of curvature will be proportional to the peening intensity and this arc height is measured on the Almen Gauge shown in Figure 11(9).

MEDIA - All shot peening media, whether it be cast steel, gladd bead, or ceramic, will deteriorate after some period of use, some more rapidly than others. When this occurs, intensity levels are diminished due to the lower mass of broken particles. More important is the potential for surface damage due to the impacting of these broken particles on the surface of the part.

The military specification for shot peening places a limit on the amount of broken or deformed particles allowable in the shot peening machine. Table 2 is a table showing these limitations for cast steel shot. When using glass or ceramic media, there are also limitations on the allowable amount of broken particles, and because there are no means to separate broken from good media, the entire machine load must be discarded when the allowable limits are exceeded. In the case of cast steel shot there is sizing and shape classification equipment in general use which allows the broken media to be separated from that which is still usable.

COVERAGE - Achieving full peening coverage on the surface of the part is of paramount importance to developing a uniform layer of compressive stress and achieving repeatability of results on all parts. Complete coverage is the full obliteration of the original surface as a result of the impacting of the media.

Visual inspection for this condition can be difficult, particularly on hard parts where the indentations are minute, or where the geometry of the part makes inspection difficult, such as the I.D. of tightly wound springs, or very small radii such as found in threads. To make the inspection job easier, the Peenscan process was developed many years ago, and is recognized in the Military Specification as an alternative means of inspection to the 10X glass. This process utilizes a tracer dye which fluoresces under ultra-violet light. The part to be shot peened is coated with this material in the area to be peened. During the shot peening process the dye will be removed

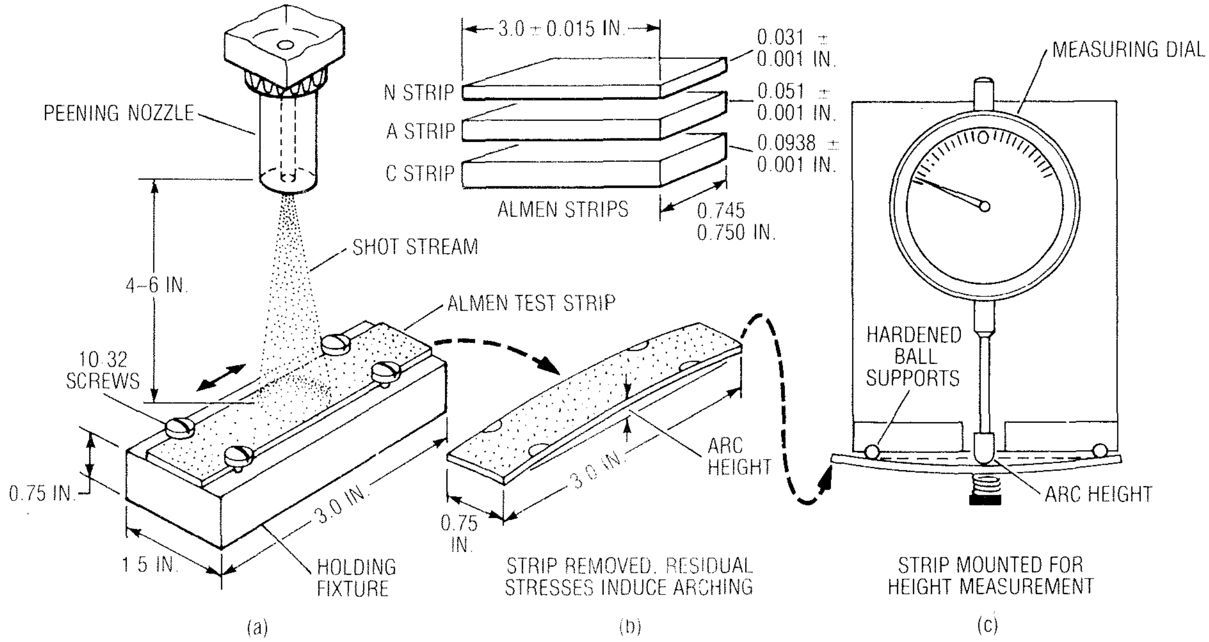


Fig. 11 THE SHOT STREAM LEAVES RESIDUAL STRESSES THAT MAKE THE ALMEN TEST STRIP ARCH UPWARDS. THE ARC HEIGHT SHOWS PEENING INTENSITY

Peening Shot	All pass U.S. screen size	Max. 2% on U.S. screen	Max. 50% on U.S. screen	Cumulative min. 90% on U.S. screen	Max. 8% on U.S. screen	Max. number of deformed shot acceptable
930	5 (.157)	6 (.1320)	7 (.1110)	8 (.0937)	10 (.0787)	5 per area 1 inch square
780	6 (.132)	7 (.1110)	8 (.0937)	10 (.0787)	12 (.0661)	5 per area 1 inch square
660	7 (.111)	8 (.0937)	10 (.0787)	12 (.0661)	14 (.0555)	12 per area 1 inch square
550	8 (.0937)	10 (.0787)	12 (.0661)	14 (.0555)	16 (.0469)	12 per area 1 inch square
460	10 (.0787)	12 (.0661)	14 (.0555)	16 (.0469)	18 (.0394)	15 per area 1 inch square
390	12 (.0661)	14 (.0555)	16 (.0469)	18 (.0394)	20 (.0331)	20 per area 1 inch square
330	14 (.0555)	16 (.0469)	18 (.0394)	20 (.0331)	25 (.0280)	20 per area 1/2 inch square
280	16 (.0469)	18 (.0394)	20 (.0331)	25 (.0280)	30 (.0232)	20 per area 1/2 inch square
230	18 (.0394	20 (.0331)	25 (.0280)	30 (.0232)	35 (.0197)	20 per area 1/2 inch square
190	20 (.0331)	25 (.0280)	30 (.0232)	35 (.0197)	40 (.0165)	20 per area 1/2 inch square
170	25 (.0280)	30 (.0232)	35 (.0197)	40 (.0165)	45 (.0138)	20 per area 1/2 inch square
130	30 (.0232)	35 (.0197)	40 (.0165)	45 (.0138)	50 (.0117)	30 per area 1/4 inch square
110	35 (.0197)	40 (.0165)	45 (.0138)	50 (.0117)	80 (.0070)	40 per area 1/4 inch square
70	45 (.0165)	45 (.0138)	50 (.0117)	80 (.0070)	120 (.0049)	40 per area 1/4 inch square

TABLE 2. CAST SHOT NUMBERS AND SCREENING TOLERANCES

gradually in proportion to the percentage of peening coverage and will not be fully removed until complete coverage has been achieved. This process is generally used during machine set up, and in the case of long-running production jobs, a periodic check will be made to assure that full coverage is being maintained.

EQUIPMENT - Because of the exacting controls required, all shot peening must be performed automatically. This means the machine used must provide means for propelling shot by air pressure or centrifugal force against the part and mechanical means for moving the part through the shot stream in either translation or rotation, or both, as required. The machine must be capable of consistently reproducing the intensity and coverage requirements.

In some industries today, particularly the aircraft industry, there is greater use being made of shot peening as a design tool, and there are indications that this trend will continue and broaden into other industries. When shot peening is used in this manner, particularly where safety considerations are present, repeatability and absolute process control become imperative. The only way this can be accomplished is to constantly monitor all of the process variables, with a printout of these variables with the necessary microprocessor control to shut down the operation if any of the variables drift outside of preset limits.

There are several microprocessor units in service today, to process various aircraft and industrial components. In these installations, the process variables of shot flow, air pressure (or wheel speed), nozzle oscillation and part rotation or translation are all constantly monitored with a computer printout of the settings and microprocessor control of the machine functions. Continuous shot classification is also an integral part of this new generation equipment.

SUMMARY

As shown in the various examples, the controlled shot peening process can be effectively used to improve the fatigue characteristics of many components common to the automotive industry. This process is used with increasing frequency in the automotive, as well as in other industries, which utilize highly stressed parts subject to cyclic loading. By using shot peening, the potential exists for using higher strength metals in cyclically loaded applications, thereby allowing the use of smaller, lighter weight parts.

The control aspect of the shot peening process is extremely important to optimize the results of the process and to assure repeatability of results.

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