INCREASING ENDURANCE LIMIT OF GEARS BY 20-50%

BY JOHN S. ECKERSLEY
METAL IMPROVEMENT COMPANY
41200 Coca Cola Drive
Belleville, MI 48111 USA
313/397-8400

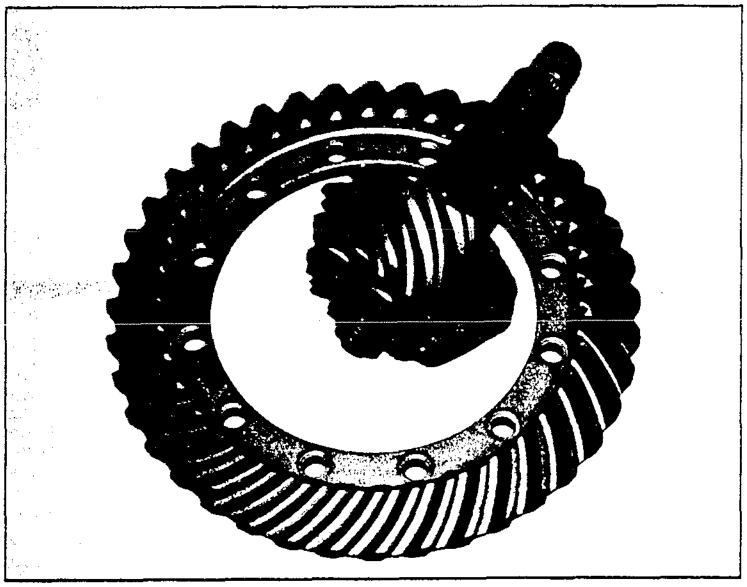
93053

ABSTRACT

Today's major trend in the gearing industry is to extract increasingly higher outputs from smaller and smaller components. The reliability of computer monitored shot peening methods has made the process useful beyond the traditional role of "fixing" fatigue failures. Shot peening is now included at the design level of helicopter and fixed wing aircraft gear trains, as well as automotive transmissions, so that these can meet the impositions of stronger/smaller criteria. Paper will present results of recent studies on the effects of hard vs regular shot, and the benefits of dual peening on both root bending and surface fatigue of carburized and carbonitrided gear teeth.

KEYWORDS

Gears, Shot Peening, Dual Peening, Carburizing, Carbonitriding, Fatigue, Pitting, Spalling, Intensity



Close-up of heavy duty ring and pinion set, shot peened at MIC-Detroit.

HOW TO INCREASE THE FATIGUE STRENGTH OF GEARS BY 40%

I would like you to imagine that you are an engineer who is faced with adapting an existing transmission design to a higher horsepower engine: you may soon discover that one or two of your gears, or a shaft, for instance, start to break at less than "infinite life", as the load/stress goes up.[1] What are your options? Not too many:

1. You can consider a larger gear. That certainly would reduce the load on each tooth but this is hardly an option. A larger gear would almost certainly mean a larger transmission which would no longer fit the design envelope but would also involve a very costly retooling.

2. You can increase the strength of the material, if you are not already at the limit. Mostly, transmission gears are of carburized steel and case hardened to 60 HRC minimum and, for practical purposes, that is about as strong as you can get. Aircraft quality gears, for helicopter and turbo-prop transmissions, for instance, and some marine gears, can be made stronger but are cost-prohibitive for most land-based applications. There is another problem, though: in many cases, steel becomes increasingly brittle or notch sensitive as hardness is increased. In other words, beyond a certain strength level, as the ultimate tensile strength goes up, the fatigue strength goes down. There is a rather simple way to overcome this phenomenon and we will address it later in this paper.

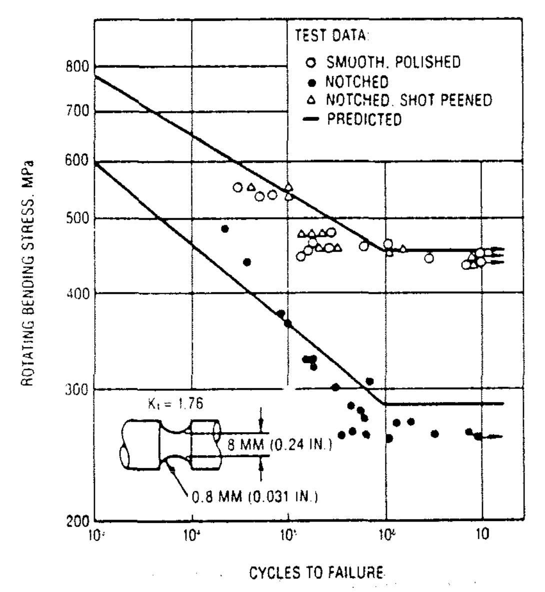


Fig 1: FATIGUE TESTS ON NOTCHED SHAFTS

3. You, the transmission designer, can change the surface stress pattern in the gears. This option takes some explanation but it may offer the ideal solution to the problem of "higher horsepower". Changing the stress pattern does not reduce the load but it can increase the fatigue strength by 20-30%, often more. It requires no change of material nor does it increase the size or weight of the gear. Best of all, it is very cost effective. (Figure 1)[2]

HOW TO PREVENT FATIGUE CRACKS

Let's think of a gear tooth as a cantilevered beam. When the tooth is engaged, the operating load causes a tensile stress or a stretching action of the steel in the root radius on the load side. On the opposite side, the root radius is being pushed together in a compressive stress. It is easy enough to understand that, after many load cycles, fatigue cracks can start only where the metal is being stretched the most in tension: fatigue cracks can never start where the metal is being pushed together in compression. The trick, then, is to find a way to pre-load the tension side of the root with a compressive stress that must be overcome by the applied load before any fatigue crack can start. This will raise the fatigue strength and allow an increase in load (stress) for the same life (cycles) or a longer life (more cycles) at the same load.

We have been using gears as our example but the same principle is true for springs, crankshafts, connecting rods, ball studs, jet engines, wing structures, highway bridges, crane booms - any metal component that experiences repeated service loads. The most practical and economical process to generate the high magnitude of residual compressive stresses in such a wide variety of parts and geometries is Controlled Shot Peening.[3]

WHY SHOT PEENING WORKS

Shot peening involves the bombardment of the metal part by millions of tiny (typically .023 inch or 0.5 mm diameter) steel spheres, each of which slightly indents the surface upon impact. Sometimes, the peening media may be glass or even ceramic beads. Shot peening is often called "impact prestressing" and under each indentation, there is formed a hemisphere of cold-worked metal that tries to push the indentation out again and restore the surface to its original shape. Because the surface has been yielded (in tension) past its plastic limit, the indentation remains and the cold-worked hemisphere develops a compressive self-stress (or residual stress) that is beneath the surface, to a depth of typically 0.020 inch or 0.50 mm. The value of the self-stress is just below the yield strength of the metal: if it were greater than yield, it would push the dimple out and if it were less than yield, the dimple would remain deeper: in short, an equilibrium is reached just below yield.[4]

This very high magnitude of compressive prestress must be overcome by the applied load before a fatigue crack can start at the surface. Since applied loads rarely exceed the yield strength, the endurance limit and/or life is greatly increased for that particular part. In our example, the transmission gears and shafts in question can be shot peened very economically and will now sustain the higher horsepower without any other changes in the transmission design. Actually, controlled shot peening is often included at the design stage to produce a lighter transmission in the first place, particularly for aerospace applications (Figure 2).[5]

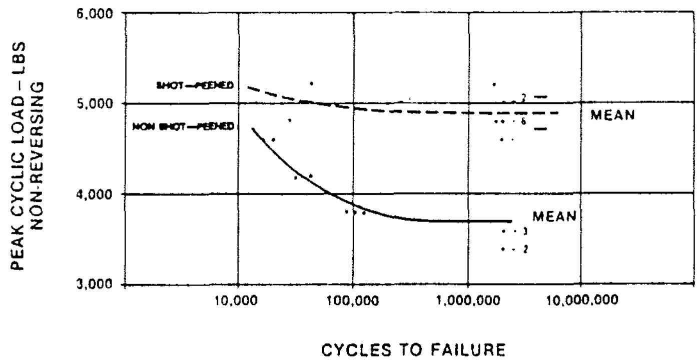


Fig 2: INCREASE IN FATIGUE RESISTANCE OF SPIRAL BEVEL GEAR

OVERCOMING DETRIMENTAL MANUFACTURING EFFECTS

The irony is that many of the most common manufacturing processes used to make metal parts, actually have the effect of dramatically lowering the fatigue strength -- a fact that is often not well understood by design engineers. Engineers tend to assume that if a part is dimensionally correct and the material is to specification, all is as it should be. Consider this situation: we recently shot peened test torsion bars for a space application. They were about 20 inches (500 mm) long by 0.5 inches (13 mm) thick and made of the best vacuum-melted steel. Unpeened, the bars tested out at around a million cycles and the stress analyst calculated that with shot peening, the bar should go for about 5 million cycles to failure. To his amazement (and our delight) the very first shot peened torsion bar ran for 366 million cycles, when they discontinued the testing! Had the stress analyst miscalculate? Not really: he simply was not aware that he had to factor in a rather critical item. He had based his calculations on a zero stress state for the unpeened torsion bars before any load was applied. In reality, the torsion bars had been ground to obtain the final shape and the grinding operation had introduced detrimental tensile stresses at the surface that approached the yield strength of the material (see Figure 3)[6]. When the torsion loads were applied, they added to the residual tensile stress from grinding, taking the resultant stress to well past yield. Under these conditions, fatigue cracks started very quickly and the failures at one million cycles were actually premature failures, not "base line" failures, upon which the stress analyst computed his calculations. When we shot peened the test torsion bars, the surface was yielded by the impact action and the high magnitude of detrimental tensile stresses from grinding were replaced by the beneficial compressive stresses from impact prestressing -- a difference of almost twice the yield strength! Not all shot peening results are this dramatic but it is an excellent reminder that residual stresses are not to be ignored.

Manufacturing processes detrimental to fatigue are not limited to grinding. On the list are through-hardening to very high hardness levels (as opposed to surface hardening, which is beneficial), abusive machining, hard plating, anodizing and flame coating, welding, even electro-discharge machining and electro-chemical milling. We will comment on through hardening, as it has application in gearing. Most metals, as you increase their hardness level, after a point become increasingly brittle or notch-sensitive. With steels, the fatigue strength typically begins to fall off as the hardness passes about 45 HRC (see Figure 4) -- the brittle metal simply cracks more easily. However, if the steel is shot peened, the fatigue strength increases proportionately to the hardness. Using the example of Figure 4, the SAE 4340 aircraft quality steel actually exhibits almost three times the fatigue strength, in the shot peened samples, at an ultimate tensile strength of 300 KSI. This principle is often employed on the gears, hammers and anvils of impact tools that are subject to very high shock loads and wear. It is also used for aircraft landing gears and propeller hubs where very high strengths are used so as to be able to reduce weight. Engineers have even used this combination of increased hardness followed by shot peening to improve the wear and the fatigue life of the drivers in industrial stapling and nailing machines.

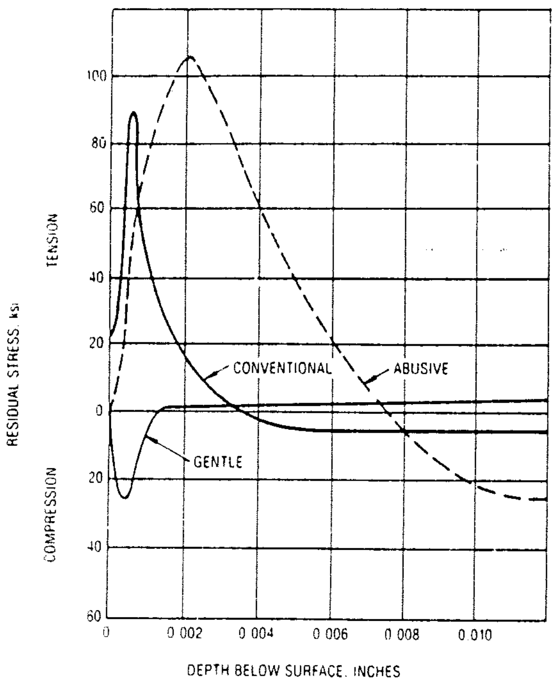


Fig 3: RESIDUAL STRESS IN 4340 STEEL (HRC50) AFTER SURFACE GRINDING

WHAT SHOT PEENING CAN DO FOR GEARS

By understanding the effects that can be produced by shot peening, a gear designer can derive benefits mainly from the following two advantages:

a). Improved bending fatigue strength of the gear tooth in the root fillet;

b). Increased surface fatigue resistance to retard pitch line pitting.

Additional benefits from peening of gears also include:

c). The very slight dimpling on the tooth flanks to retain lubricant and contribute to the reduction of noise and wear.

d). Some gear machining methods leave continuous parallel lines in the roots, that will become stress risers. Peening has been used before heat treating to blend out these machine marks, particularly on large gears. Since exposure to very high temperatures negates the residual stresses from peening, the gears are then repeened for fatigue after heat treating.

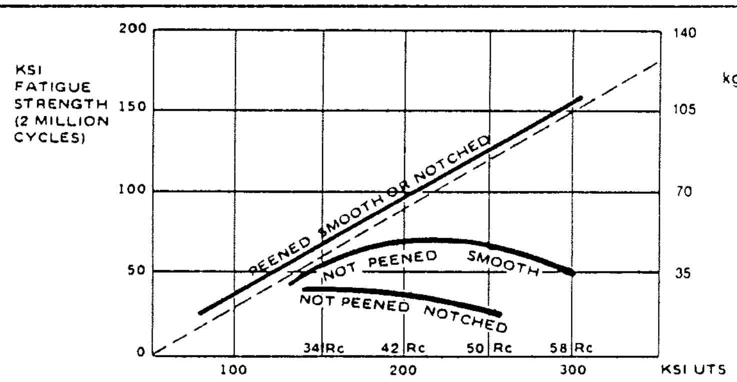


Fig 4: COMPARISON OF PEENED AND UNPEENED FATIGUE LIMITS FOR SMOOTH AND NOTCHED SPECIMENS AS A FUNCTION OF ULTIMATE TENSILE STRENGTH OF STEEL

RECENT DEVELOPMENTS IN SHOT PEENING OF GEARS

It makes sense and has been well known for many years that for maximum residual compressive stress, the shot hardness should at least equal the hardness of the part. It appears that this practice is gaining popularity, probably because designers are increasing the loads upon components and must squeeze out as much fatigue strength as possible. Figure 5 shows the residual stress distribution on an automotive transfer shaft peened on the hypoid pinion teeth with regular (45-52 HRC) and hard (55-65 HRC) shot. The teeth are SAE 8620 carburized and hardened to 60-64 HRC, and the hard shot is used in production (MI 230H at 18-22 A intensity and 200% coverage, verified by Peenscan®)[8]. It should be noted, however, that a helicopter manufacturer specifies regular hardness shot for peening of their very hard transmission gears: they are willing to forego the extra margin of residual stress gained from hard shot in favor of preserving the surface finish of their near-polished gear faces.

Recent testing, by the University of Munich, was performed on shot peened automotive transmission gears. Alloys were SAE 6120 and an European alloy designated 20 NiMoCrS63, carburized and hardened to 60 HRC minimum. Both sets of gears were peened with MI 170H shot at 10-12A and 200% coverage, verified by Peenscan®, and were processed at MIC's shot peening facility in Unna, Germany. Figure 6 indicates fatigue strength increase of 40 and 42%. Also from Europe comes the chart in Figure 7 that shows increased depth and magnitude of compression on a carburized surface as the result of increasing shot velocity. We would have preferred to see Almen intensities and coverage rather than just shot velocities but the chart shows very clearly the relationship of the residual stress obtained by carburizing only to that obtained by the addition of shot peening.[9]

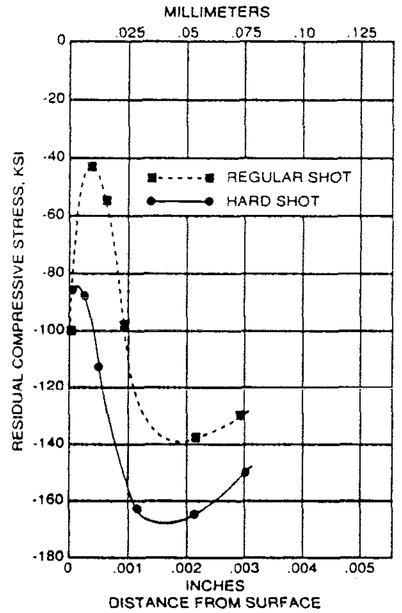


Fig 5: Carburized Hypoid Pinion Gears, shot peened with hard (55-62HRC) and Regular (45-52 HRC) shot.

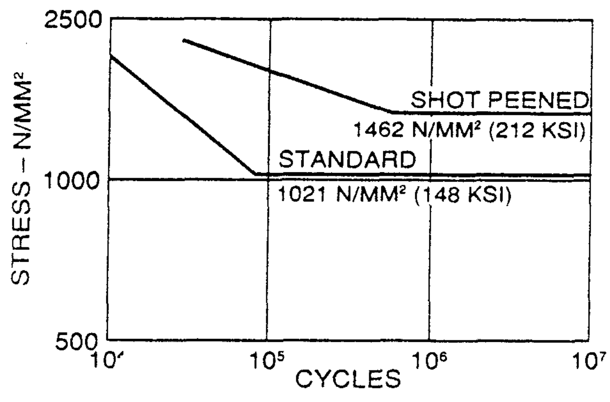


Fig 6: S/N CURVE FOR CARBURIZED 20N, MoCr 563 GEARS

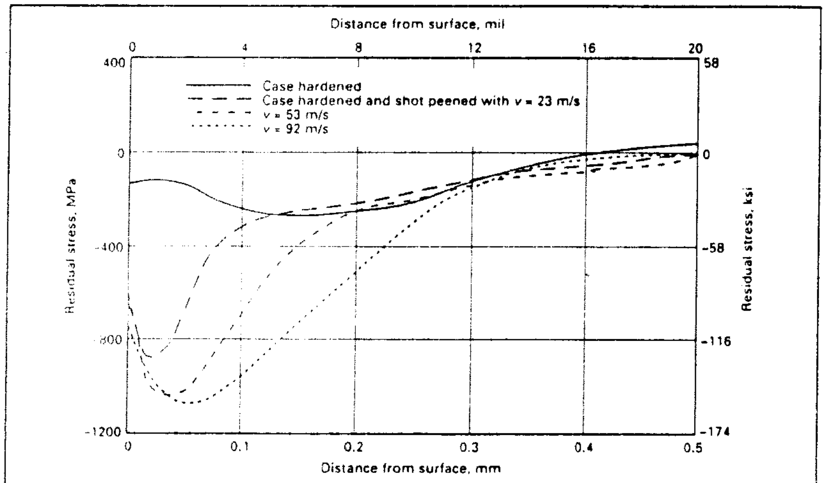


Fig 7: EFFECT OF SHOT PEENING AT DIFFERENT VELOCITIES ON COMPRESSIVE RESIDUAL STRESSES IN CARBURIZED 16MnCr5 STEEL.

DUAL INTENSITY SHOT PEENING

If you look again at Figure 7 you will notice that the maximum residual compressive stress is at a depth of between 0.0005 and 0.002 inch (0.013 and 0.05 mm). At the immediate surface, there is a reduction in the compressive stress. Assuming no detrimental products of transformation (oxidation) at the surface (more on this later), this decrease in stress at the surface can be restored by a secondary peening with smaller shot at a lower intensity. Figure 8 shows how the surface residual stress in carburized SCM 420 (Japan) steel is increased by dual peening: actually, from about 780 MPa to 1330 MPa.[10] Figure 9 shows that the fatigue properties of SCM 420 gears are improved by 50% from dual peening when compared to "as carburized". Dual peening involves peening the part with a shot size and intensity that would be normal for that part and then following up with a secondary peening using a much smaller shot size and correspondingly lower intensity.

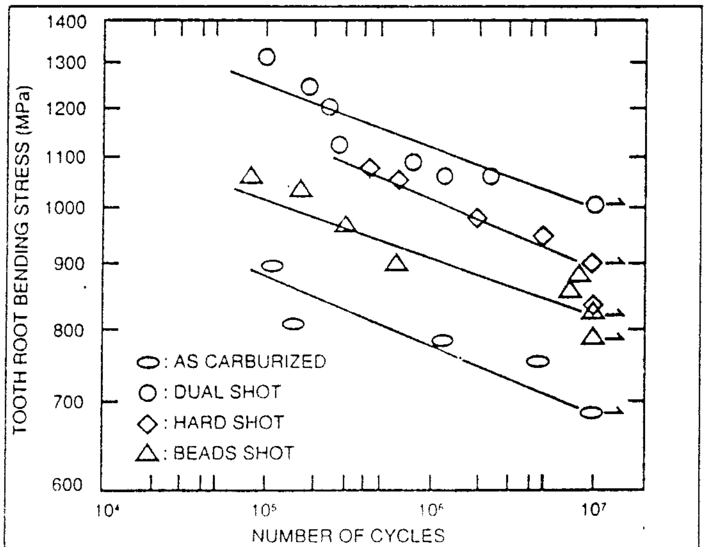


Fig 8: GEAR FATIGUE PROPERTIES OF SCM420

Dual peening obviously increases the cost of processing but can be well worth it, for instance, for racing car applications or aircraft turboprop gearing, where every last ounce of strength must be wrung out.

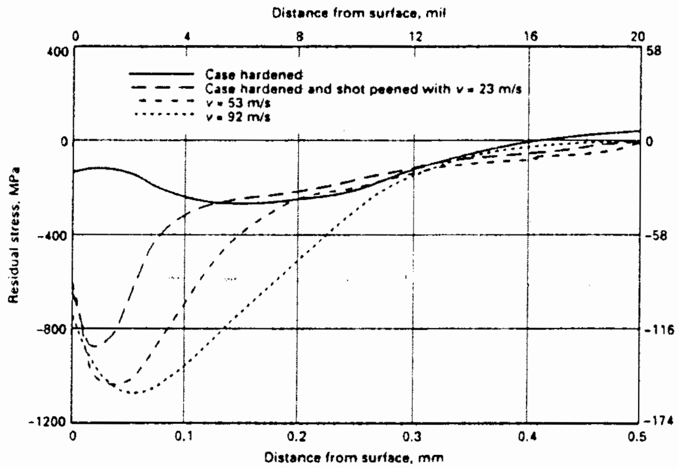


Fig 7: EFFECT OF SHOT PEENING AT DIFFERENT VELOCITIES ON COMPRESSIVE RESIDUAL STRESSES IN CARBURIZED 16MnCr5 STEEL.

DUAL INTENSITY SHOT PEENING

If you look again at Figure 7 you will notice that the maximum residual compressive stress is at a depth of between 0.0005 and 0.002 inch (0.013 and 0.05 mm). At the immediate surface, there is a reduction in the compressive stress. Assuming no detrimental products of transformation (oxidation) at the surface (more on this later), this decrease in stress at the surface can be restored by a secondary peening with smaller shot at a lower intensity. Figure 8 shows how the surface residual stress in carburized SCM 420 (Japan) steel is increased by dual peening: actually, from about 780 MPa to 1330 MPa.[10] Figure 9 shows that the fatigue properties of SCM 420 gears are improved by 50% from dual peening when compared to "as carburized". Dual peening involves peening the part with a shot size and intensity that would be normal for that part and then following up with a secondary peening using a much smaller shot size and correspondingly lower intensity.

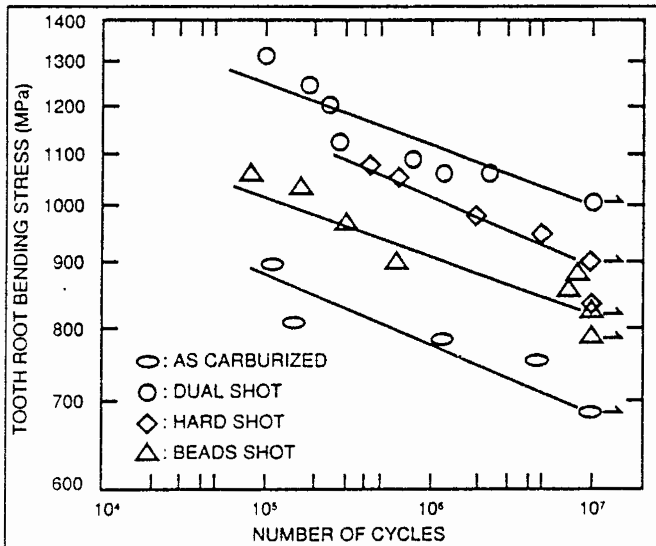


Fig 8: GEAR FATIGUE PROPERTIES OF SCM420

Dual peening obviously increases the cost of processing but can be well worth it, for instance, for racing car applications or aircraft turboprop gearing, where every last ounce of strength must be wrung out.

CARBONITRIDING AND HARD SHOT PEENING

From Japan comes a report of yet another approach to extracting the most from the least; the most fatigue strength from the least gear size.[11] Oddly, Miwa et al apparently initiated their project with the intent of reducing surface roughness caused by peening carburized gears with hard shot. They had observed the relatively softer immediate surface layer caused by products of transformation and often referred to as "zone of decarburization". Because it was softer, this thin surface layer produced a rougher tooth profile surface when it was peened. Certainly, this is a correct observation but what is surprising is that the researchers were apparently not concerned by the reduction in fatigue strength that is caused by a decarburized layer, however thin.[12] Miwa et al developed a multi-step carbonitriding process to permeate nitrogen into only the extremely shallow surface layer, thereby reducing oxidation and the undesirable products of transformation. They found that peening with hard shot (in this case 53-55 HRC) produced a much higher residual compressive stress (64% more than conventional shot peening) but they also found that they could produce a significant increase in surface hardness. In addition, they were able to maximize residual compressive stress and micro hardness from "hard shot peening" when they controlled the content of retained austenite that was transformed into martensite by the action of the peening. In terms of improvement in fatigue strength, their new carbonitriding process followed by hard shot peening, produced an increase of 1.3 times the fatigue strength of standard carburizing followed by peening with regular hardness (46-48 HRC) shot, (Figure 9). It would have been interesting if Miwa had compared their new carbonitriding plus hard shot peening with standard carburizing also followed by hard shot peening, especially with shot at a hardness of 55-62 HRC.

SHOT PEENING "ALLOWABLES"

From the foregoing, we have seen results of testing showing improvements in bending fatigue strength of carburized and shot peened gears as high as 42%, when compared to carburized only gears; even 50% from dual peening. This is a far greater effect than can be obtained by any other process, with only insignificant changes to gear geometry. At the same time, controlled shot peening is a very economical process that adds usually less than 5% to the cost of a finished gear or shaft. To take full advantage of the shot peening benefits, it is necessary to conduct fatigue tests for a given gear under at least simulated operating

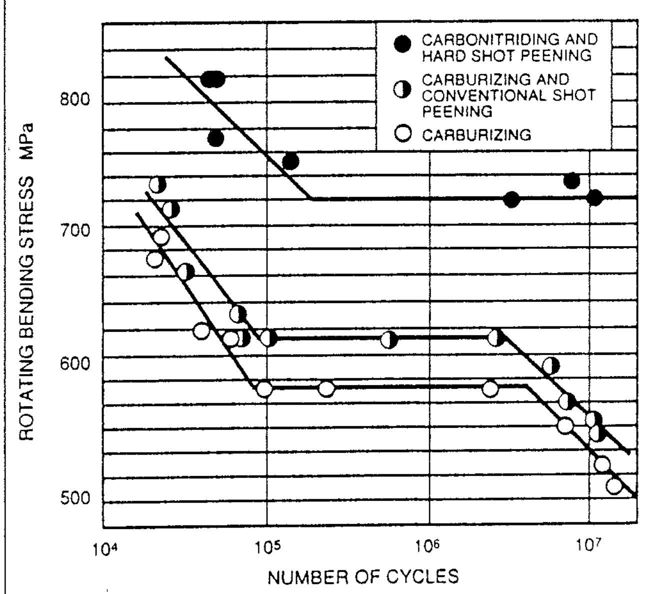


Fig 9: ROTATING BENDING FATIGUE STRENGTH OBTAINED BY CARONITRIDING AND HARD SHOT PEENING

conditions. However, not all gear applications warrant extensive testing and designers look for rules of thumb that they can apply to their gears, whether they are carburized, induction hardened, through hardened, not heat treated, forged, cast, wrought, cut from bar stock; alloy steel, low carbon and even powdered metal gears. (We have to exclude plastic gears!) Gears are, after springs, the most commonly peened component, from the finest pitch to segmented mining gears 40 feet (12 meters) in diameter where you can comfortably stand between the teeth. Also, shot peening is beneficial on spur gears, bevels, spiral bevels, hypoids, rings, pinions, internals, racks, even splines. Sorry, but we have never yet found shot peening to be useful on worm gears.

With all this variety, there are still some rules of thumb that apply. American Gear Manufactures Association Standard ANSI/AGMA 2004-B89 states: "Shot Peening... may improve the bending fatigue strength of a gear tooth as much as 25 percent" but warns that "shot peening should not be confused with grit and shot blasting, which are cleaning operations".

Lloyd's Register of Shipping, in a letter dated 3rd May 1990, informed Metal Improvement Company that "the following allowance will be considered with the new Gearing Rules where properly controlled shot peening process has been applied to gear teeth. "Surface stress -- no increase of the allowable Hertzian contact stresses". "Bending stress -- up to a 20% increase of the allowable bending stress at the tooth root".

Our files indicate that British Standard BS 436: Pat 3: 1986 recognized the value of shot peening on gear tooth bending by permitting a credited residual stress in compression of 500 MN/M^2 (72.5 KSI) in calculating permissible tooth root bending stresses. This is in addition to the credit for residual compressive stresses due to carburizing (in Quality A & B gears) of 400 MN/M^2 (58 KSI). Stated another way, for a typical mid-range carburized gear, a 15% increase in tooth bending is permitted due to controlled shot peening.

Germanischer Lloyd, in "Section 5-Gear, Couplings" of their "Rules for Classification and Construction of Seagoing Steel Ships" advises that "If the fatigue bending strength of the teeth is increased by a technique approved by the Society, e.g. by shot peening, then values higher than those shown in Table 5.1 -- by up to 20% for case-hardened tooth systems and by up to 10% for gears made of quenched and tempered steels -- may be allowed". Det Norske Veritas also allows 20%.

SHOT PEENING RETARDS SURFACE PITTING AND SPALLING

In 1982, work performed at NASA's Lewis Research Center, was published by Townsend and Zaretsky.[13] This comprehensive report showed that the pitting fatigue life of AISI 9310 (carburized) spur gears was lengthened by 50% when the gear faces were peened at "medium intensity" using MI 70R shot at 7-9A (0.18-0.23mm) with 100% coverage. In 1992 Dennis P. Townsend presented a follow-on paper at the Sixth International Power Transmission and Gearing Conference. The new work involved the same gears and material but a "high intensity" shot peening was used: MI 330H shot at 15-17A (0.38-0.43mm) with 200% coverage.[14] In both cases, Peenscan^R was used for coverage determination -- also note the use of hard shot in the second series of tests, as well as the additional coverage. In both groups, the gears were honed after shot peening to a 16 RMS surface finish. "The 10-percent surface fatigue (pitting) life of the high intensity shot peened gears was 2.15 times that of the gears that were shot peened to a medium intensity". This very considerable improvement was attributed to 57% higher residual stress at the peak, with greater depth of compression. We have taken the liberty of combining the curves from both papers and present them in Figure 10. It is interesting to note that the "high intensity" shot peening increased the pitting fatigue life by almost four times when compared to the unpeened test gears.

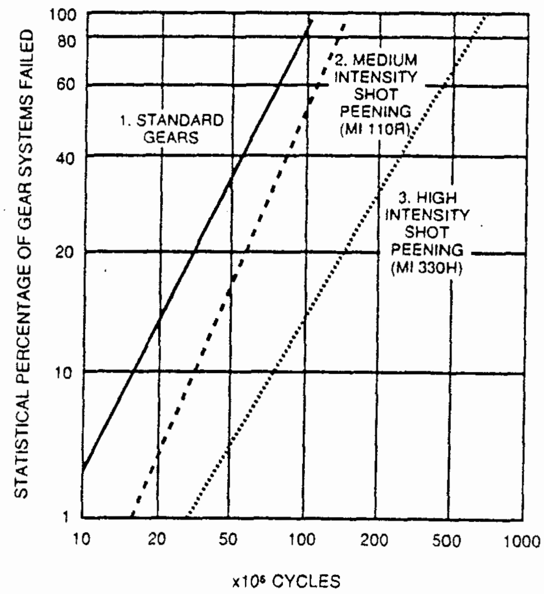


Fig 10: COMPARISON OF SURFACE (PITTING) FATIGUE LIFE OF CARBURIZED AND GROUND AISI 9310 SPUR GEARS: 1. STANDARD FINISHING; 2. MEDIUM INTENSITY SHOT PEENING; 3. HIGH INTENSITY SHOT PEENING

CONCLUSION

Do all gears require shot peening? Of course not, but the fatigue strength of just about all metal gears can be improved by shot peening: even "perfect" gears. There is a school of thought that claims that "perfectly" manufactured gears do not need shot peening. We couldn't agree more but "perfection" is a relative term; relative, in the case of a gear, to its application. A "perfect" gear quickly becomes less than perfect when it is necessary to increase the load beyond the original design criteria. For many applications, the "perfect" gear must be as small as possible to meet the demands of envelope, weight and fuel economy. A "perfect" gear may well be one that is sufficient to do the job for the design price but is far from the ultimate in terms of material, machining and processing. And then, there are always the end users, who invariably find ways to overstress "perfect" gears to levels never anticipated by the most carefully considered testing schedule.

In all these cases, and many others, intelligent use of controlled shot peening may well be the answer to meeting the demands of the application. Remember that even a modest 10% increase in fatigue strength can result in an increase in gear life by an order of magnitude or more.

REFERENCES

1. Daly, J. J., "Boosting Gear Life Through Shot Peening"; Machine Design, May 12, 1977.

2. Loewenthal, S. H, "Design of Power Transmission Shafting", NASA Report RP-1123.

3. "Shot Peening Applications"; 7th Edition, Metal Improvement Company, Inc.

4. Eckersley, J. S., "Shot Peening Process Controls Ensure Repeatable Results"; Shot Peening Theory and Applications, A. Niku-Lari, Ed.; I.I.T.T. International.

5. Daly, J. J., "A Concept for Using Controlled Shot Peening in Original Gear Design"; American Gear Manufactures Association, Technical Paper No. 87FTM13.

6. Koster, W. P., et al, "Surface Integrity of Machined Structural Components"; Technical Report AFML-TR-70-11, March 1970.

7. Horger, O. J., "Mechanical and Metallurgical Advantages of Shot Peening"; The Iron Age, March 29 and April 5, 1945.

8. O'Hara, P. "Dyescan Tracers as a Quality Control Tool for Coverage Determination in Controlled Shot Peening"; SAE Technical Paper Series 850708, February 1985.

9. Sholtes, B. and Macherauch, E., "Case-Hardened Steels: Microstructural and Residual Stress Effects"; D. E. Diesburg, Ed. TMS-AIME, 1984, pg. 141-151. Referenced by Kraus, G., "Microstructures and Properties of Carburized Steels"; Metals Handbook, Volume 4, Heat Treating, ASM.

10. Hatano, A., Namiki, "Applications of Hard Shot Peening to Automotive Transmission Gears"; Daido Steel Co., Ltd., Steel Res. Section.

11. Miwa, Y. et al, "Carbonitriding and Hard Shot Peening for High-Strength Gears"; SAE Technical Paper Series 880666.

12. "Material Characterization of Aermet 100"; WL/MLSE, Wright Patterson AFB, OH 45433-6533.

13. Townsend, D. P., and Zaretsky, E., "Effects of Shot Peening on Surface Fatigue Life of Carburized and Hardened AISI 9310 Spur Gears"; NASA Technical Paper 2047, 1982.

14. "Improvement in Surface Fatigue Life of Hardened Gears by High-Intensity Shot Peening"; NASA Technical Memorandum 105678, 1992.