Improved Fatigue Performance of Gears through Controlled Shot Peening

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Introduction

Controlled shot peening improves the fatigue performance of gear teeth. Today, there is no argument over that claim. Extensive data from programs of fatigue testing gear teeth conducted throughout the industrial world for the past forty years (1) demonstrate that shot peening can be recommended to :

- prolong gear life
- increase stress level
- avoid redesign of gears
- allow reduced size and weight
- reduce costs.

Shot peening has been used for many years to salvage marginal designs or to compensate for increased output requirements. However, the last ten years have seen a dramatic increase in the number of applications and the volume of production involved coupled with a growing tendency to integrate the fatigue performance improvements in the original design of gears.

Controlled shot peening improves fatigue resistance by introducing compressive self stresses or residual compressive stresses at and below metal surfaces.

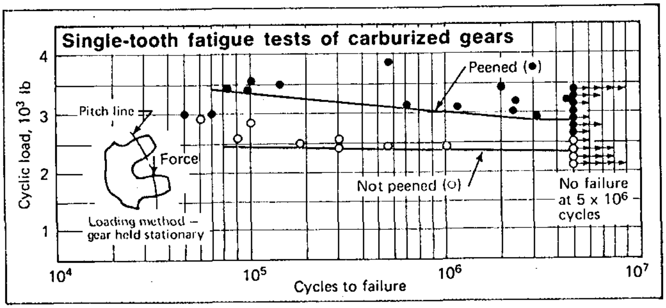
The vast majority of gear tooth failures are of the bending fatigue type (2). Bending loads on gear teeth usually cause the highest stresses to occur at root fillets or, in certain instances, at junctions of active profiles and roots. Unpeened gears also contain tensile self stresses introduced by the manufacturing processes (3). The highest concentration of these stresses is also in the root fillets. The combination of applied load and residual tensile stress may cause the gear to fail prematurely. Shot peening replaces the residual tensile stresses with residual compressive stresses. Because fatigue failures are associated with crack propagation phenomena occuring in the regions of maximum tensile stress, the applied tensile load must first overcome the residual compressive stress before fatigue is initiated.

But gears can also fail because of surface fatigue phenomena known as surface pitting, subsurface pitting and spalling leading to abrasive wear or to secondary bending fatigue failures. Although traditionnally, shot peening has not been considered as a means of extending the surface fatigue life of gears, recent test programs have shown that the compressive self stress generated by a carefully controlled shot peening operation can substantially reduce surface fatigue and pitting (4).

Tooth bending fatigue

Gears are prone to many problems. In operation, they can fail in deformation, fracture, or surface damage (2). In the majority of cases, tests have to be conducted to investigate the effect of shot peening on the tooth bending fatigue performance of specific gears. However, other types of gear failure tend to confuse the results when rotating tests are run at high loads or extended times. A quantitative evaluation of shot peening is difficult unless bending fatigue is isolated. The single tooth bending fatigue test has been developed for that purpose. The test principle is simple : each gear tooth is treated as a cantilever beam, and a load is applied to the outer portion of the tooth until it fails. One tooth is loaded at the pitch line with an alternating load to failure or to a minimum of 5 to 10 million cycles. The gear is then advanced two teeth and another tooth is tested, at a higher load if the previous tooth did not fail or at a lower load if it did.

In such a typical test, shot peening improved the endurance limit of a set of carburized gears by 30 % (5). FIG.1



Carburized planet gears (4.8 DP with 1.4-in. faces), from the same 4118 stock, showed increased load capacity when shot peened

Fig.1 - Ref.5

All the gears were forged from the same bar of 4118 steel, they were carburized, quenched and tempered to produce a .6 to .9 mm case. The test gears were then divided into two sets : one was shot peened while the other was not. Average endurance limit was 1370 daN for the peened gears and 1060 daN for the unpeened ones.

Controlled shot peening as a tool to combat tooth bending fatigue is now well recognized, well documented and used in production in the automotive and tractor industries, in the aerospace industry, the marine industry and a wide range of other mechanical industries. It is successfully applied to carburized, carbonitrided and through hardened gears.

For instance, the Lloyd's Register of shipping allows an increase in tooth loading up 20 % after controlled shot peening (6).

More dramatic improvements were illustrated by tests performed by the University of Munich (Prof. Winter) for Carl Hurth A.G. on carburized gears : the results showed a 54 % fatigue strength increase (7).

As regards shot peening of hardened gears, it should always be kept in mind that the shot peening compressive self stress is proportional to the UTS of the processed material (between 50 and 60 % of UTS) (8). Hence the harder the gear, the higher the selfstress available to offset service load stresses.FIG.2

Besides, as tooth hardness increases above 45 Rc, the fatigue strength levels off or even falls off because of increased notch sensitivity. Shot peening eliminates this problem (9) FIG.3. A new application of shot peening also deserves attention : austempered ductile iron has recently become a hot topic among gear material users. Shot peening has been proven to substantially raise tooth bending fatigue strength.FIG.4 In one reported case, bending fatigue increased from 30 to 50 daN/mm².

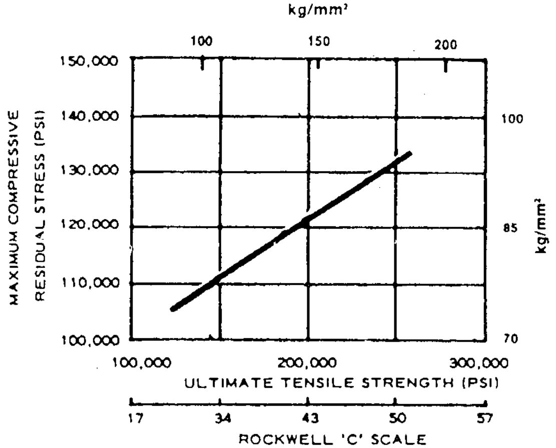
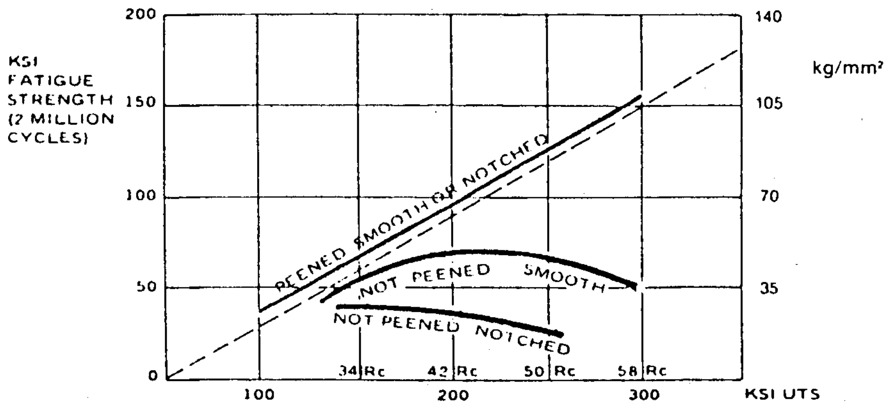


Fig.2 RESIDUAL STRESS PRODUCED BY SHOT-PEENING VS TENSILE STRENGTH OF STEEL



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

Fig.3 - Ref.9

TYPICAL RANGES OF EXPERIMENTALLY DETERMINED VALUES OF THE BENDING FATIGUE STRENGTH OF GEAR TEETH.

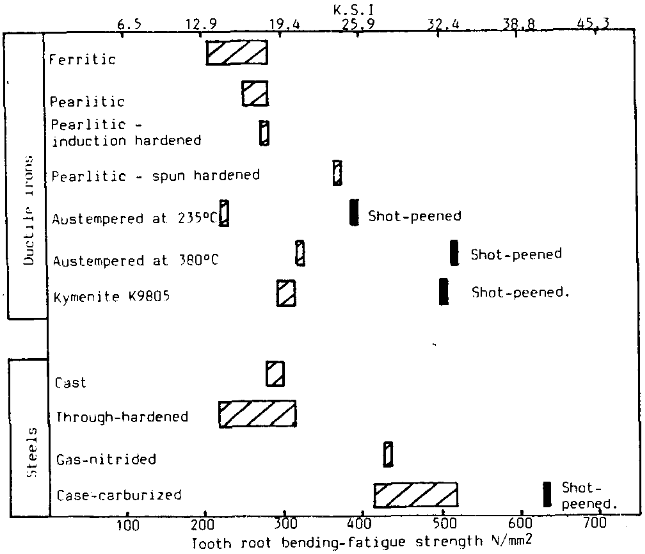


Fig.4

Surface fatigue

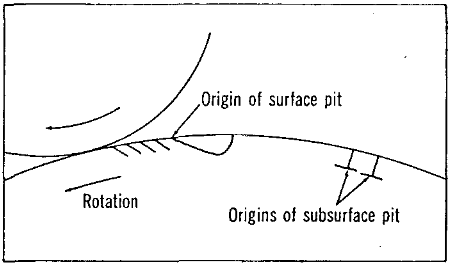
Surface contact fatigue is characterized by formation of cavities in the surface. The principal types are subsurface pitting, surface pitting and spalling. The mating surfaces of a pair of gear teeth are stressed by rolling under pressure across one another, with or without sliding. Each active gear flank is then submitted to repeated stresses where each cycle is characterised by a complex stress pattern travelling with the area of contact. Pure rolling causes maximum shear or Hertzian stresses below the surface.

These shear stresses in turn, possibly intensified locally by non metallic inclusions, are believed to be the cause of subsurface pitting (2).

In many parts, relative motion involves both rolling and sliding. For example, with spur gears, pure rolling occurs only at the pitch line. In certain other gears, such as hypoid pinions, sliding is even more pronounced. In such cases, the frictional force added to the normal force raises the maximum shear stress closer to the surface. With coefficients of friction of 0.1 or more, it is at the surface, where it may cause surface pitting. FIG.5

On the other hand, spalling is characterised by larger cavities. They commonly start at the case coil boundary of case hardened parts. The origin is believed to be comparable to that of subsurface pitting.

The residual compressive stress introduced by shot peening of gear teeth reduces the maximum shear stress.



Surface pits start when a surface point is loaded, and cracks form at a shallow angle, as shown at the left. Then, they turn toward the surface, surrounding a volume of metal which drops out, leaving a pit. See Fig. 8 and 9. Cracks from a subsurface origin grow parallel and perpendicular to surface, surrounding a volume of metal which drops out, leaving a pit. See Fig. 11.

Fig.5 - Ref.2

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15. Supplementary Notes

16. Abstract

Surface fatigue tests were conducted on two groups of AISI 9310 spur gears. Both groups were manufactured with standard ground tooth surfaces, with the second group subjected to an additional shot-peening process on the gear tooth flanks. The gear pitch diameter was 8.89 cm (3.5 in.). Test conditions were a gear temperature of 350 K (170° F), a maximum Hertz stress of 1.71×10^9 N/m^2 (248 000 psi), and a speed of 10 000 rpm. The shot-peened gears exhibited pitting fatigue lives 1.6 times the life of standard gears without shot peening. Residual stress measurements and analysis indicate that the longer fatigue life is the result of the higher compressive stress produced by the shot peening. The life for the shot-peened gear was calculated to be 1.5 times that for the plain gear by using the measured residual stress difference for the standard and shot-peened gears. The measured residual stress for the shot-peened gears was much higher than that for the standard gears.

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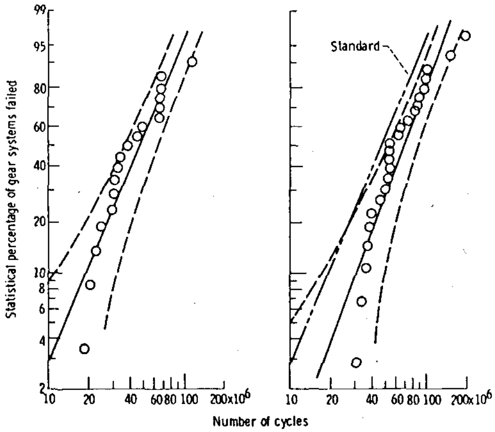
Fig.6 - Ref.4

Experience shows that careful selection of the shot peening parameters is very important to obtain optimum results in surface fatigue. This selection will be a function of mode of failure (surface or subsurface initiation) depth of maximum shear stress, material hardness, surface finish, percentage of residual austenite, etc. At any rate, the shot flow should be normal to the tooth flank for best results.

Townsend and Zarelski ran endurance tests to determine the effect of shot peening on the surface fatigue life of carburized and hardened AISI 9310 spur gears (4). They found that shot peened gears exhibited pitting fatigue lives 1.6 times the life of standard gears. FIG.6 - FIG.7

Similar tests recently conducted by a major automotive manufacturer in France showed even more dramatic improvements with fatigue lives systematically 2 or 3 times the lives of unpeened gears.



(a) Standard gears. (b) Shot-peened gears.

Fig.7 - Ref. 4

- Comparison of surface (pitting) fatigue lives of standard ground and shot-peened carburized and hardened CVM AISI 9310 steel spur gears. Speed, 10000 rpm; lubricant, synthetic paraffinic oil; gear temperature, 350 K (170° F); maximum Hertz stress, 1.7×10^9 N/m^2 (248 000 psi).

Additional benefits

Since shot peening produces small indentations on the surface of a gear tooth, these become tiny pockets or reservoirs. Lubricant accumulates in these dimples and promotes better lubrication. Scoring and operating temperatures are reduced.

Shot peening also eliminates continuous machine lines on gear tooth flanks and in tooth fillets at the tooth root. These lines can cause stress raisers shortening gear life. Although using hard shot is usually sufficient to solve this problem on heat treated hard gears sometimes, the best solution is to shot peen the gears in a "green state" and then follow with the heat-treating process (8). A secondary peening operation is required to reintroduce compressive stresses removed by the shot treatment.

Surface finish

Typically the dimpling effect associated with the shot peening process may increase the surface roughness of a 45 Rc gear tooth flank by .4 or .5 µm Ra.

This effect is a function of material hardness, Almen intensity, shot hardness, shot size, and coverage and may vary between 0 on carburized gears to a few µm Ra on soft materials peened at high intensities. Although many engineers who are not familiar with shot peening are concerned about what they feel is a deterioration of the surface, in fact, experience has shown that in more than 90 % of the cases, the shot peened "orange peel" skin does not impair gearing performance, unless the peening parameters are not properly selected. However, in those cases where the flank roughness produced by shot peening proves objectionable, the flanks can be masked before peening or they can be shaved, lapped or honed after peening. In any event, one should keep in mind that masking or post machining may increase the cost, that sharp lines of demarcation between peened and unpeened areas may be harmful and that material removal must be limited to no more than 10 % of the depth of compression and performed without generating heat. Grinding is not allowed and temperature control of the surperfinishing operation is critical.

Shot peening in gear design

Traditionally a process resorted to in cases of failures of existing parts, shot peening has gained recognition over the years to become a tool of the designer. Ideally, the gear designer needs the assurance that a given selection of shot peening parameters can be associated with a given stress increase, or life increase, or weight reduction (10).

Considerable progress has been acomplished in the last decade towards the understanding of residual stresses due to shot peening.

However, the relationship between compressive self stresses and fatigue performance is complex and only partially understood. It must take into account multiaxial criteria, stress distribution and gradient, influence of coverage and partial stress relaxation in service. Besides, the influence of shot peening is also related to workhardening, retained austenite and grain size change, as well as surface finish and geometrical effects (action on stress raisers, tool marks, etc).

The designer cannot rely on formulas to forecast the performance of shot peened gears.

Fatigue tests are necessary to quantify the improvements and select the best shot peening parameters.

Repeatability in production will then enable the design engineer to acquire confidence in the process, to identify specific peening parameters as giving the best results for given materials, manufacturing processes, types of gears, types of loading, etc and to develop reliable improvement factors applicable to other designs. Quality and repeatability of the controlled shot peening process are essential to ensure the dependability of this method.

The two case histories that follow briefly illustrate this new approach.

The transmission group of a major helicopter manufacturer in the U.K. has been using shot peening for about twenty years. The level of confidence in the process to-day is such that the use of shot peening improvement factors at the design stage of new products is now standard practice.

A major French automotive manufacturer, after conducting extensive lab and road tests of shot peened gears and progressively applying the process to more and more models over a period of about six years, has decided to incorporate controlled shot peening in the original design of a new gearbox with a weight reduction of about 40 % for the same life and torque.

Controls

Effective shot peening hinges on accurate controls aimed at ensuring repeatability.

They can be summarized as follows :

Media

Many types are available but cast steel shot is most commonly used on gears. Incoming media should be checked for size, hardness, chemistry, microstructure and shape. In operation, the media must be kept round and uniformly sized as sharp corners may produce harmful effects. The use of hard shot is recommended for application on hard gears except in specific cases of surface pitting.

Almen Intensity

An indication of the kinetic energy transfer in the peening process, the Almen intensity can be directly converted into depth of compression.
Although it is not sufficient alone to define a peening operation, it is the main variable ensuring repeatability as it integrates most relevant parameters (media velocity, mass and hardness, angle of impingement, etc).
The use of Almen test strip fixtures, which represent the geometry of the part, is required. Test strips will be located at critical areas, e.g. tooth root fillet, to control peening against bending fatigue, or tooth flank in the case of pitting.
Design engineers should be encouraged to specify the location of Almen strips on the engineering drawing.

Coverage

100 % minimum coverage is a requirement. Verification is performed using 10 power minimum magnification or an approved fluorescent tracer (such as Dyescan) (11) (12). Coverage verification is required on the first piece part of each lot only, provided microprocessor control is used to ensure repeatability.

Microprocessor control (13)

The microprocessor receives measurements each second for shot flow, air flow, air pressure, wheel speed, wheel motor amperage, nozzle(s) reciprocation speed, location and piece part movement, and prints out the average readings for each part or lot of parts processed in the machine cycle. High and low level limits for all of the above are preset. If any of the variables fall out of the preset range for longer than two seconds, the machinery aborts the cycle and prints out the cause. Processing data are stored on disc or cassette for retrieval at a later date.

Conclusion

All sizes and most types of gears can be peened to improve their fatigue strength.
Recent years have seen both a considerable expansion in the use of shot peening and significant advances in its technology, with improved controls, upgraded specifications and development of more sophisticated machinery.
The aircraft and automotive industry have taken advantage of the new controls and specifications in the original design of components.

The significant accomplishments of the last decade have had a major influence on the quality, the repeatability and reliability of controlled shot peening. Product quality is tantamount to customer satisfaction ; in the future this should promote further expansion in the variety and the quantities of gears being peened, increased use of controlled shot peening as a design tool and stepped up research and development activity.

References

(1) "Results of a Fifteen Year Program of Flexural Fatigue Testing of Gear Teeth"
John B. Seabrook and Darle W. Dudley, 1963, ASME Paper 63-WA-199
(2) "How Components Fail"
Donald J. Wulpi, 1966, ASME Metal Progress Book Shelf
(3) "Boosting Gear Life through Shot Peening"
James J. Daly, Machine Design, May 12, 1977
(4) "Effect of Shot Peening on Surface Fatigue Life of Carburized and Hardened AISI 9310 Spur Gears"
Dennis P. Townsend and Erwin V. Zaretsky, 1982, NASA Technical Paper 2047
(5) "Shot Peen Gears for Longer Life"
Doug Mc Cormick, July 1981 issue of Design Engineering
(6) "Lloyd's Register of Shipping"
Letter to Metal Improvement Company, June 6, 1975
(7) "Bericht 746 B. Ergänzung zu Bericht Nr. 746. Pulsatorvesuch an einsatzgehärteten Rädern mit unterschiedlicher Zahngrundbearbeitung"
Prof. Dr Ing H. Winter und Dr Ing H. Rettig, (FZG), Munich Technical University, June 9, 1971
(8) "Shot Peening and its Effect on Gearing"
Mark D. Lawerenz, 1984, SAE Paper # 84 1090
(9) "Improved Gear Life through Controlled Shot Peening"
N.K. Burrell, October 1985, AGMA Paper # 85 FTM 15
(10) "Controlled Shot peening used in the Original Design of Critical Parts"
Claude P. Diépart, April 1986, Fatigue Prevention and Design Conference, Amsterdam, Proceedings - Editor J.T. Barnby
(11) "A method for Improving Gear Life"
N.K. Burrell, Power Transmission Design, March 1987 issue
(12) "Shot Peening of metal Parts"
MIL-S-13165 B - Amendment 2, 25 June, 1979
(13) "Status of Controlled Shot Peening Technology in the United States"
JamesJ. Daly, September 1986, Impact Surface Treatment, Edited by S.A. Meguid