Adaptation of Shot Peen Parameters for Gear Geometry

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Abstract

Shot peening is a well established process for the surface enhancement of gearing. Gearing is a primary example of a high cycle fatigue application that can benefit from residual stress enhancement. Designing shot peening parameters to specific gear geometry based on material, heat treatment, and surface finish is a more precise way to achieve better performance outcomes. One of the best tools to assist in the optimal shot peening is x-ray diffraction (XRD) and its ability to measure small differences that can result in significant performance outcomes. XRD residual stress measurements are a direct measurement of elastic strain. The diffraction peak width is an indication of plastic strain and is also proportional to the hardness of steels. Together, the elastic and plastic strain information provides tremendous insight into the condition of a shot peened gear.

This paper will review a wide variety of gear geometry and their various heat treatments and surface finishes. The discussion will encompass how the shot peen parameters can be modified based on the physical characteristics of the gear and also the failure mode. X-ray diffraction results will be provided to supplement the discussion.

Keywords

Shot peening, x-ray diffraction, residual compressive stress, peak width, gears, case hardening

Introduction

Gear engineers are highly technical designers who consider many factors when creating a new gear design or upgrading an existing application. Some of the design aspects to be considered are: material selection, heat treatment, tooth geometry, surface finish, lubrication, and surface treatments. The purpose of this paper is to focus on the surface treatment of shot peening and its ability to improve bending and contact fatigue properties when implemented properly.

The shot peening process involves bombarding the tooth (root and/or flank) surfaces with round, spherical media called shot. The localized impact results in tensile yielding of the near surface region which then results in residual compressive stress. The maximum residual compressive stress occurs slightly beneath the surface. The stress versus depth profile varies depending on material, heat treatment and tooth profile of various gear applications.

This paper will present the adaptation of shot peening to a number of gear applications along with residual stress analysis of various heat treatments that are shot peened. Residual stress analysis is highly useful to the gear engineer as subtle differences in residual stress can result in large differences in the longevity of a gear. In addition, residual stress analysis can be used in conjunction with finite element stress analysis. Modeling software can predict stresses from applied loads. X-ray diffraction (XRD) shows the design engineer the actual residual stress levels in a component without applied loading. Both the residual stress and applied stress are factors when calculating the 'net' stress on a gear which is the actual stress experienced for failure analysis purposes.

This paper will review a range of gear designs and the adaptation of shot peening to further improve the gear performance. For most gear applications, tooth root bending fatigue strength increase of 15-30% is typical. Generally, case hardened gears experience greater improvements than through hardened gears as the residual compressive stress magnitude from shot peening is proportional to the material strength at the surface. This will be shown in the XRD results presented in the paper.

Discussion and Conclusions

When generating shot callout parameters, the author recommends a review of the following for shot size and intensity selection: tooth root radius, failure mode, and surface finish

Tooth Root Radius: In order to achieve 100% coverage of the area to be peened, it is important that the shot media be small enough to impact the area of interest. The most common rule is to start with a media diameter that is closest to one-half the geometry to be peened. Therefore, a 1.25 mm radius would be a 230 sized media (0.58 mm Ø). Usually you can go one media size larger or smaller and still produce effective shot peening results. This gives the designer (and shot peener) a reasonably wide selection of shot media: 170, 230, 280, and possibly 330 (or their cut wire equivalent sizes). Please note that the author is not aware of a metric shot size. Therefore, a 170 sized shot is 0.017” nominal diameter.

Failure Mode: Once the shot media diameter is selected, the engineers involved should be familiar with the effective peening intensity that can be achieved with a selected shot size. For example, a 230 sized media can effectively peen from 0.20-0.51 mm A. In general, a shot should not be used at either extreme such that the “sweet spot” for 230H shot would be anywhere from ~ 0.25-0.46 mm A depending on the peening equipment.

If the failure mode is tooth flank contact fatigue, the tooth flank surface finish is more critical than for a bending fatigue failure. Therefore, a 230H @ 0.25-0.36 mm A would be a likely intensity range as this will produce a better surface finish due to the lower shot velocity required. The authors strongly recommend a subsequent surface finish enhancement to further improve the surface finish and residual stress condition. The following are excellent choices for subsequent surface enhancement: glass beads, ceramic media, vibratory surface finishing.

If the failure mode is bending fatigue, the peened tooth flank surface finish is less critical than for a contact fatigue failure. Therefore, a 230H @ 0.33-0.43 mm A would be a likely intensity range as this will drive a slightly deeper residual compressive layer but produce a slightly rougher surface finish. Usually, secondary peening treatments are not recommended unless the application has extremely high bending fatigue loads. A dual peen treatment with smaller steel media would most likely be recommended to further enhance bending properties.

Surface Finish: Upon review of the drawing or actual gear, if the tooth flanks have very good surface finish, it is highly recommended to follow the same shot callout recommendation for a tooth contact fatigue failure. The good surface finish was generated from grinding (or another gear finishing process) and if peening roughens the surface finish, this can produce negative consequences. For example, if the gear has a ground tooth flank, a rougher surface finish produced by shot peening would improve bending fatigue properties, but could worsen contact fatigue properties. Proper implementation of secondary treatments (glass beading, ceramic, or vibratory superfinishing) will allow up-rating in tooth flank contact fatigue (also called tooth durability) from the non-peened (as ground) condition.

In some applications, gears that have the tooth flanks ground can be shot peened prior to grinding. During the grinding operation, the tooth flanks are ground but the tooth roots are left alone. This preserves the shot peening in the tooth roots but removes the residual compressive stress on the tooth flanks. The author would recommend peening closer to the higher end of the effective intensity range for a given shot size as surface finish concerns from peening are eliminated.

Shot peening has the potential to change a failure mode. For example, a gear that was limited by bending fatigue will be more durable in bending fatigue once shot peened. The next failure mode could potentially be tooth flank contact fatigue. A potential way to accomplish the next up-rating of the gear could be to add tooth flank grinding and shot peening followed by secondary processing (glass beads, ceramic, vibratory superfinishing).

A number of aerospace gear applications are shot peened with regular hardness media which is 45-52 HRc. Many aerospace gears are carburized and ground thus producing a very hard, durable surface along with a very nice surface finish. If the surface of the gear is 58-62 HRc and it is shot peened with shot media that is 45-52 HRc, the shot media tends to produce minimal surface roughness increase. The tradeoff for the good surface finish is that the residual compressive stress when using regular hardness media is significantly less than when using fully hardened shot media (55-62 HRc).

When shot peening carburized gears, the maximum compressive stress will likely be about half that when using 45-52 HRc media. One can expect 1300-1450 Mpa with 55-62 HRc media and 700-800 MPa when using 45-52 HRc shot media.

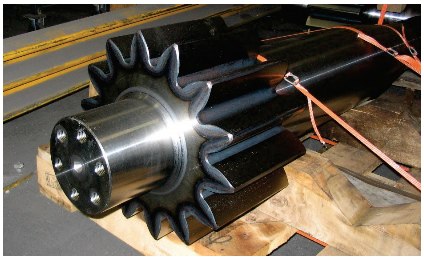
There may be significantly more benefit to the gear engineer by using a fully hardened shot media (55-62 HRc) and performing a secondary surface enhancement operation (glass, ceramic, or vibratory superfinishing) since this allows the gear application to be up-rated in both bending and contact fatigue properties.

The paper will discuss the adaptation of shot peening to the following types of gearing:
- Through hardened with and without tooth flank grinding
- Induction hardened with and without tooth flank grinding
- Carburized with and without tooth flank grinding

Photographs

First Row Photographs #1, #2, #3
Second Row Photographs #4, #5, #6






Through Hardened

Photographs #1 and #2 depict large gears used in mining applications. The pinion shaft shows a through hardened gear steel with the tooth flanks ground. The large bull gear shows tooth flanks that are not ground.

In both situations, the gears have the tooth roots shot peened with overspray allowed on the tooth flanks. Allowing some overspray on the tooth flanks prevents the labor intensive process of masking and unmasking of individual tooth flanks. Generally, a larger steel shot is used at an above average intensity. An example would be 460H shot @ 0.46-0.56 mm A. Using this large shot, the above average intensity can be easily achieved such that the shot velocity is not very high. The produces a better surface finish than if the shot is used at high velocity, especially if the gear is 30-35 HRc.

Induction Hardened

Induction hardening is a case hardening heat treatment where localized surface contours are hardened. Photograph #3 shows the tooth flanks and roots as blackened from the induction hardening. The induction hardening process hardens the surface from 45-60 HRc depending on the alloy chemistry. By case hardening the surface, the ductile properties of the core part of the gear are retained. In addition, residual compressive stress is imparted as part of the phase transformation of the metal during case hardening. Similar to all metals, the residual compressive stress from shot peening is proportional to the hardness/tensile strength of the surface of the material being peened.

Photograph #3 shows a tooth flank surface that has been ground. The tooth profile is large enough to shot peen the tooth roots and have minimal overspray on the tooth flank surfaces. It is generally important to maintain a better post shot peen surface finish on the ground tooth flank surfaces, however direct masking of tooth flanks is very labor intensive.

Carburized

Carburizing is the most common type of heat treatment performed on shot peened gears. This section will present a number of variations of adapting shot peening to carburized gears.

Carburized (No grinding): (No photo) This is a gear that is carburized but not subsequently ground. The high surface hardness/strength will result large amounts of residual compressive stress and considerable improvement in bending fatigue properties. The surface finish on the tooth flanks is not as critical as ground gears.

Carburized, Shot Peened, then Ground: This is the least expensive way to shot peen a ground gear. Since the gear is peened after carburizing, there are no finish machined surfaces. This eliminates the need to oil for corrosion protection (and subsequent removing of oil) and masking/demasking critical surfaces before/after peening. There is also less cost and risk of quality control associated with masking. Following shot peening, the gear will be finish machined and the tooth flanks will be ground (but not the tooth roots). Photograph #4 is a pinion gear that is ground after shot peening.

Carburized, Ground, Shot Peened With Glass/Ceramic Processing: This is a more expensive way to shot peen a gear that produces better results with improved properties of the gear in both bending and contact fatigue. Oiling of the gear is required after grinding for corrosion protection. Removing the oil and masking the machined surfaces is required prior to shot peening.

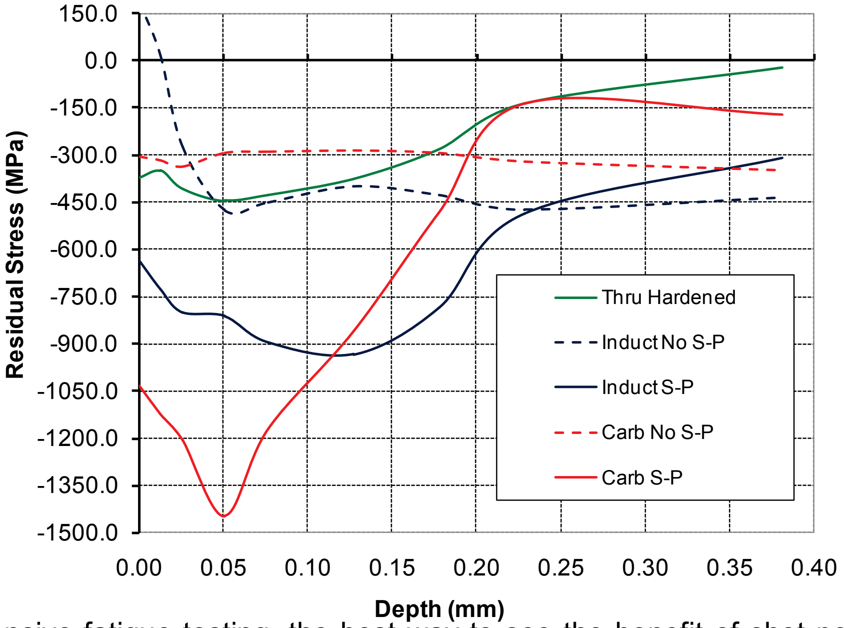
Shot peening on the finish ground tooth flanks should be done at lower intensity to minimize surface roughness of the tooth flanks. Photograph #5 shows a gear that is (steel-glass) dual peened. The steel peen and subsequent glass bead peen stages are shown. Glass beads are lighter and harder than steel media. During glass bead peening, the steel peened surface finish is improved along with the residual stress properties at the outer surface.

Carburized, Ground, Shot Peened With Vibratory Superfinishing: This processing method also involves processing carburized gears after grinding (Photograph #6). Following grinding, the gear is usually peened with a steel media and subsequently vibratory superfinished. When done properly, the surface finish after vibe finishing is better than the ground surface finish.

Once again, the steel peening should not be performed at high intensity because the rougher the surface finish after steel peening, the more vibratory finishing is required to achieve the mirror-like surface finish depicted in the photograph. If too much time is required in the vibratory finishing machine, there is a risk that the tooth flank profile can be modified by removing more material near the tip of the tooth flank than the base of the flank.

Residual Stress Evaluation

Figure 1. Residual Stress From Different Gear Steels (Unpeened & Peened)



Without expensive fatigue testing, the best way to see the benefit of shot peening residual stress is through the use of residual stress measurement techniques such as x-ray diffraction. The previous graph shows x-ray diffraction results on the following type of gear heat treatment:

- Through hardening (green curve)
- Induction hardening (two blue curves)
- Carburizing (two red curves).

The benefits of XRD is shown as differences in surface compressive stress, maximum compressive stress and depth of compressive stress are clearly shown. The summary of each gear heat treatment is described below.

Through Hardened

The green curve represents the results of a through hardened gear steel shot peened using 460H sized media at 0.46-0.56 mm A intensity. The gear steel that was measured was 4340 steel, quench and tempered to 25-30 HRc (855-980 MPa TS). The maximum compressive stress was 450 MPa (at 0.05 mm depth) and the total depth of the residual compressive layer was 0.40 mm if the curve were extended. The maximum compressive stress should be 50-55% of the tensile strength (TS). All of the results were within expected ranges.

Induction Hardened

The two blue curves were generated with 4330 material, induction hardened to 45-55 HRc (1450-1970 MPa TS). Prior to shot peening, the blue dashed line shows a material that is in residual tension at the surface and about 415-480 MPa residual compression sub-surface. It is not known why the surface was in residual tension. If there were an unusual failure, the XRD measurement of residual tensile stress would show this a potential root cause.

However, the 415-480 MPa of residual compression is a result of the induction hardening heat treatment prior to shot peening. Once the surface was shot peened (460H @ 0.46-0.56 mm A), the magnitude of residual compressive stress increases to almost 965 MPa (at 0.13 mm deep). The depth of the residual compressive layer would be about 0.30 mm if the positively sloping part of the curve were extended. The maximum compressive stress should be 55-60% of the tensile strength. All of the results were within expectation.

Carburized

The two red curves were generated with 8620 material, carburized to 58-62 HRc (2172-2490 MPa TS). The red dashed curve is the residual compressive stress from the carburizing heat treatment. Once the surface was shot peened (460H @ 0.46-0.56 mm A), the magnitude of residual compressive stress increases to about 1450 ksi (at 0.05 mm deep). The depth of the residual compressive layer would be about 0.23 mm if the positively sloping part of the curve were extended. The maximum compressive stress should be 60% of the tensile strength. All of the results were within expectation.

As stated previously, the magnitude of the residual compressive stress from shot peening is proportional to the hardness/strength of the surface being peened. As the surface gets progressively harder, the magnitude of compressive stress increases. The higher the magnitude, the better the surface is able to resist the initiation of fatigue cracking thus producing a stronger gear in bending fatigue. This is why gears with case hardened surfaces are expected to perform very well once shot peened. There was inadequate time and resources to evaluate the glass-ceramic peening or vibratory superfinishing which enhance contact fatigue properties.