SHOT PEENING
OF
STEEL GEARS

By

K.K. MODI
& CHIRAG MODI

SURFACE FINISHING EQUIPMENT CO.
E-100, MIA, PHASE II, BASNI
JODHPUR –M 342 005
Email: info@sfecindia.com
www.sfecindia.net

Tel: 0291-2740128 Mobile: 098290-22624

CONTACT 89/02 PART 1

1. TITLE : SHOT PEENING OF STEEL GEARS

2. SUMMARY

Guidance for designers is given on the use of shot peening to enhance the fatigue properties of steel gears. The document covers three main areas :

a) Shot Peening Equipment and Procedures. This is intended to specify a quality standard for shot peening contractors and to give general information for designers (Section 5).

b) How to specify Shot Peening on Engineering Drawings. For use by designers in conjunction with (a). (Section 6).

c) Estimation of the Improvement in Bending Fatigue Attributable to Shot Peening of Carburised Gears. Provides guidance on the benefits of Shot Peening in the context of carburized spur and helical gear teeths: an approximate calculation method (Section 7).

3. INTRODUCTION

Shot peening is a process in which superficial compressive residual stresses are introduced to a component by means of bombardment with spherical steel particles (shot). With careful definition, control and inspection this can give very substantial increases in high cycle fatigue performance. These improvements can be used to overcome the effects of surface defects (eg. Decarburization, grinding abuse) or more significantly, to increase fatigue performance above that obtained by conventional processing. The purpose of the present document is to define the necessary quality standard and to provide guidance to great designers on the definition of peening requirements and on the benefits to be obtained.

Much of the document is written in the form of a specification and is based on aircraft industry practice. It is appreciated that some users may wish to relax some of the recommended requirements in the light of their own experience. However contract and inspection is essential if reliable benefits are to be obtained from shot peening and users are cautioned against compromising the quality standard.

Compliance with the recommendations of the document should ensure good results. An approximate method for calculating the expected improvement in tooth bending fatigue is included. Compressive residual stresses induced in the tooth root by shot peening act to suppress fatigue initiation; this often results in the controlling region of the structure being elsewhere then at the tooth root surface, usually either just below the peened layer or at even greater depth. The calculation method given locate3s the fatigue-critical depth and provides an estimate of the improvement in endurance limit. In general the benefit declines with tooth thickness but improvements of 20-30% are common.

4. SCOPE AND APPLICATION

4.1 The present data item covers the use of shot peening in the manufacture of gears for power transmissions. It may be applied to any steel gear. However the calculation method given in Section 7 is applicable only to carburized gears, where the reference, un-peened residual stresses can be reasonably estimated.

4.2 Other than that data explicitly concerned with gears, the methods described in Sections 5 and 6 can also be applied to other steel mechanical components where fatigue limits structural strength. It should not however be applied to rolling elements bearings (nor to integral journals on gears or shafts).

4.3 The calculation method given in Section 7 is approximate and intended for comparative purposes only.

5. SHOT PEENING EQUIPMENT AND PROCEDURES

5.1 MACHINE

5.1.1 The machine used for shot peening must be mechanized and be capable of reproducing consistently, the requirements of a given peening procedure. It shall provide a suitable means of propelling the shot in an even flow by controlled air pressure or controlled centrifugal force.

5.1.2 Provision shall be made to mechanically move the work through the shot stream or move the shot stress through the work in either translation, or rotation or both as required.

5.1.3 The machine must also be capable of continuously removing broken or defective shot and dust during the peening operation. Broken shot shall be removed at such a rate that not less than 80% by weight of full sized shot is present in the machine at all times.

5.2 PEENING MEDIA

5.2.1 Shot Type

5.2.1.1 Unless otherwise specified by the controlling authority cast steel shot in accordance with MIL-S-851 (see reference 6), meeting the size and shape requirements of Table 1 and Figure 1 respectively shall be used. Where shot is of British manufacture it may be classified to meet the size and shape requirements of Table 2 and Figure 1 respectively.

5.2.2 Shot shall be supplied hardened and tempered as follows :

1. Regular shot 45-55 HRC (450-600 HV)
2. Hard shot 57-63 HRC (630-770 HV)

5.2.2.3 For parts where material strength exceeds 1380 N/mm or surface hardness exceeds 43 HRC Hard shot in the range (57-63 HRC) shall be used unless specified otherwise by the controlling authority.

5.2.3 Shot shall be dispatched from the manufacturer in a moisture free condition in sealed water proof packaging. Each delivery shall be accompanied by certificates stating that procurement specification (BGA….) requirements are satisfied and include the result5s of the following tests :

1. Chemical Analysis for each batch.
2. Hardness Testing.
3. Sieve Analysis.
4. Shape Analysis.

5.2.4 To ensure that new shot meets the requirements of paragraph 5.2.1 and 5.2.2, a 100 gram sample shall be taken from each sack for sieve and shape analysis. Hardness testing shall be carried out on a 10 gram sample and this test may best be achieved by mounting the shot in thermo-setting plastic and using a Vickers, or Vickers micro hardness tester employing a 5 kilogram load.

5.2.5 New shot shall be conditioned by cycling for not less than 10 minutes while directing the shot at a case hardened steel surface.

5.2.6 Shot Maintenance

5.2.6.1 Shot shall be kept in a clean condition free from dirt, rust, dust, grit, oil, greased and moisture.

5.2.6.2 Analysis of the shot for size and shape in accordance with the requirements of Table 3 and Figure 1 shall be carried out on each charge of shot after every 8 hours of continuous use.

5.2.6.3 A record shall be maintained of the total number of hour4s accumulated by every charge of steel shot and the results recorded.

5.3 ALMEN TEST SPECIMENS

5.3.1 Control test specimens used to measure intensity shall be of the Amen A type as shown in Figure 2 and manufactured from commercial spring steel SAE 1070 or EN42 uniformly hardened and tempered to 44-50 HRC.

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5.4 ALMEN TEST GAUGE

5.4.1 The Almen No. 2 Gauge in accordance with the requirements of Figure 3 shall be used to measure peening intensity and the flatness of Almen test strips.

5.5 HOLDING FIXTURES

5.5.1 Fixtures used to support the Almen test specimens shall be manufactured in accordance with Figure 4.

5.6 MASKING

5.6.1 Suitable masks and baffles shall be provided to direct the shot where desired and to prevent peening of areas not requiring peening. It is recommended that where heavy gauge steel is used for masking, it shall be case hardened to prevent wear and where thin gauge material is used, it shall be faced with rubber to prevent distortion. Where it is impractical to mask or otherwise protect areas which do not require to be peened, material affected by shot peening indentation may be removed by a subsequent machining operation provided that sufficient stock has been left on the part to permit such material to be removed and still comply with the dimensional requirements of the Drawing or Technique Sheet.

Unless otherwise specified by the drawing the variation in boundaries of areas to be peened shall be -0 to +3.2 mm (-0 to +0.125").

5.7 PEENING PARAMETERS

5.7.1 <u>Intensity</u>

5.7.1.1 The intensity of peening is a function of the energy transfer capability of the sho9t at the point of impact with a surface and is controlled by the deflection (arc height) of an Almen test specimen as described in Para 5.3.

Intensity is controlled by the followi8ng factors :

1. Size, hardness and mass of shot.
2. Air pressure or impelled speed.
3. Distance of nozzle/s or impeller/s from work pressure.
4. Nozzle/s orifice diameter/s.
5. Number of nozzles ore impellers used.
6. Duration of peening.
7. Angles of impingement.

These effects are integrated by shot peening to give an intensity on an Almen test piece and, therefore, to ensure reproducibility, the Drawing or Process Sheet need only nominate "Shot peen to intensity Oxy Almen A2 using 2 dia. Shot. For example, the instructions "Shot peen to intensity 0.25 mm (.010"). A2" means, peen with the specified shot size to obtain an arc height of 0.25 mm (.0910") on an Almen "A" test specimen, the arc height being measured on an Almen No. 2 gauge.

5.7.1.2 Peening intensities shall be expressed by a range i.e. 0.2-0.3 mm (.008-.012") A2.. However, where existing drawings call only a single intensity i.e. 0.2 mm (.008") A2., the variation in intensity shall be -0 to +0.1 m (-0 to+0.004") A2 unless otherwise required by the design authority.

5.7.1.3 For the purpose of this specification intensities have been based on the use of Almen A test strips. See Figure 2.

It should be noted, however, that others test strips exist being designated 'N' and 'C' strips. These are identical to Almen "A" strips apart from thickness which are as follows :

N Strip : 0.787 +/- 0.025 mm (.031 = .001").
C Strip : 2.362 +/- 0.025 mm (.093 + .001").

The 'N' strip is generally used to monitor intensitie3s less than 0.15 mm (.006") A2. This is usually associated with glass bead peening.

The 'C' strip was used for very high pe3ening intensities greater than 0.6 mm (.024" A2. Such intensities are no longer used because such overpeening introduces micro cracking at the extreme surfaces of the peened component.

5.7.2 Recommended Intensities

Recommended peening intensities are given in Table 4.

5.7.3 Coverage

Where p[eening is required all surfaces shall be peened to complete (100%) coverage. This is achieved when by visual examination using x110 magnification the dimples in the surface just overlap. Where 200% coverage is required this is obtained by peening for a time twice the length of that to pro produce 100% coverage on the component.

5.7.4 Saturation

It is possible but very undesirable to obtain a given Almen arc height by extremely short time high pressure peening, as shown in Curve 1 of Figure 5. This may well reduce rather than increase fatigue life. Correct shot peening is obtained when the factors referred to in Para 5.7.1.1 are adjusted such that the desired Almen intensity is achieved when the Arc height/Exposure time relationship becomes virtually parallel with the X Axis, i.e. the curve flatters out as indicated in Curve 2 of Figure 5.

The surface is now considered saturated, i.e. induced stresses have reached a max. value for the given intensity. Saturation time is defined as the min. duration of exposure, necessary to achieve the desired Almen arc height that when doubled, does not further increase the arc height by more than 10%.

5.8 PROCEDURE

5.8.1 Process Sheets

5.8.1.1 Before components can be processed a procedure (process sheet) has to be established to ensure that the correct intensity and coverage can be achieved consistently over the desired areas of a component.

5.8.1.2 This procedure will establish the machine settings by using Almen test specimens mounted on test strip holders. The quantity of test specimen holders required will be dependent on the complexity, shape and size of the component to be processed. However, at least one holder shall be provided for each critical position on a component i.e. radii, tooth roots, bore etc. Almen test pieces representing tooth root radil should be positioned at 30 Deg. To the vertical to represent the tangent point. See Figure 7.

5.8.1.3 When possible the Almen test specimen holders should be bolted or welded to a scrap component or if this is not possible a fabricated dummy component should be used.

5.8.1.4 The test specimen holder/s should then be fitted into the machine and the various translations and rotations set up to ensure complete peening of the component will be achieved.

5.8.1.5 Almen test strips in accordance with paragraph 5.3 shall then be peened in order to pr4oduce a saturation curve as shown in Fig. 5 for each test specimen position. If the results fall outside the intensity range required b the drawing then the exercise shall be repeated making suitable adjustments to air pressure/wheel speed etc. until the correct results are obtained.

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5.8.1.6 After an Almen test piece has been peened and removed from its holder it shall not be used again.

5.8.1.7 Now that the saturation curves have been produced to obtain the required intensity the first component shall be processed in order to determine that uniform coverage is achieved and also to establish the process time to achieve the selected coverage requirement i.e. 100% or 200%. Very careful inspection using x10 magnification is required or a combination of x10 visual magnification and visual examination using an approved tracer liquid system.

5.8.1.8 A process sheet shall be produced for each part number processed, showing all parameter selections, machine settings and Almen test piece positions as used in the above procedure. The procedure shall also include drawing requirements including specification, intensity, shot size, coverage and areas to be peened and masked. It shall also contain the inspection requirements and any other information required to ensure compete reproducibility of the process.

5.8.1.9 The peening procedure shall be agreed between the peening contractor and the controlling authority before production components are processed. Once agreed the procedure shall be sealed and not changed unless agreed with the controlling authority.

5.8.2 Verification of Peening Procedure

5.8.2.1 A component or if not available, a test specimen of the same material, same heat treatment, and same surface conditions shall be shot peene3d prior to approval and issue of the Technique Sheets.The thickness of the test specimen shall be similar to the thickness of the section of the peened component. The test specimen shall be metallographically prepared and examined for possible micro cracks. If micro cracks are not revealed by this examination, the established conditions shall be frozen for production peening. However, if micro cracks are observed further peening conditions shall be established.

5.8.2.2 Peening conditions for a new component may be based on previous experience, where the material specification and section thickness is considered similar to that of components for which tests at Para 5.8.2.1 were carried out.

5.8.2.3 Alternatively in para 5.8.2.1 a shot peening procedure may be approved on the basis of satisfactory justification or substantiation testing.

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5.9 PREPARATION OF PARTS TO BE PEENED

5.9.1 Unless otherwise specified, parts shall be within dimensional and surface finish requirements before peening. All machining and required polishing of areas to be shot peened shall be completed, all fillets shall be properly formed, all barrs shall be removed, all forming and straightening operations completed and all sharp edges shall have a 0.75 mm (.030") min. radius.

5.9.2 All heat treatment for specification, physical and mechanical properties shall be completed before peening.

5.9.3 Where magnetic or penetrate flow detection is required, parts shall be subjected to such inspection before peening.

5.9.4 Those areas to be peened shall be free of any surface coating and contamination such as plating, paint, grease corrosion, heat treatment scale etc. If such features exist inform the controlling authority.

5.9.5 All areas not to be peened shall be properly masked in accordance with paragraph 5.6.1.

5.10 PRODUCTION PEENING PROCEDURE AND CONTROL.

5.10.1 <u>Verification of peening intensity and coverage requirements</u>

5.10.1.1 Although the peening parameters for each part number are given in the relevant process sheet it is necessary to verify that the specified intensity and coverage is obtained on each part and that shot peening remains consistent from batch to batch. This shall be controlled in the following manner :

1. Set up the peening machine in accordance with relevant process sheet as developed in accordance with Paragraph 5.8.1.

2. Fit the Almen strip(s) into the holding fixtures and tighten the four screws.

3. Operate the cabinet to peen the Almen strip (s) for, say 20 seconds, 2 reversals and/or 2 traverses, whichever is applicable. Stop the machine, remove the Almen strip (s) and examine the uniform coverage. The surfaces requiring peening have a similar percentage of converge, not necessarily complete visual coverage).

4. If the coverage is not uniform check the position of the nozzles/impellers, possible blockage of nozzles and movement of Almen str4ips. Then repeat 2) and 3) above. If uniform coverage cannot be achieved contact the controlling authority.

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5. Place new Almen strip (s) in the holder (s) and peen for the time given by the process sheet to achieve single saturation. Time 2t of Figure 5.

6. Place new Almen strip(s) in the holder(s) and peen for the time given by the Process Sheet to achieve double saturation. Time 2t of Figure 5.

7. The arc height measurements obtained from 5) and 6) above shall be within +/-0.05 mm (.002") A2of the intensities given in the process sheet at the relevant exposure times. It should be noted, however, that the intensity achieved must also be within the drawing requirements. The test strips shall also exhibit compete and uniform coverage.

8. If the results are not within the required tolerances, the tests shall be repeated until satisfactory results are achieved or if this is not possible the controlling authority hall be informed.

5.10.2 Preparation

5.10.2.1 Parts shall then be degreased to the controlling authority requirements examined for damage and those features given in Paragraph 5.9.4.

5.10.2.2 Components shall then be masked to the requirement of the relevant process sheet and Paragraph 5.6.

5.10.3 Peening

The first component shall be mounted in the machine and peened in accordance with the relevant process sheet. Further components shall not be peened until it has been confirmed that coverage satisfies the drawing and process sheet requirements.

5.10.4 Control of Peening Intensity

5.10.4.1 The arc height measurements at single and double saturation times shall be checked.

1. Prior to starting and at the end of each batch of more than 5 components.

2. At the beginning only of each batch of less than 5 components. Providing peening time does not exceed 8 hours.

3. After any replacement of shot.

4. After any change to the machine settings.
5. After any other event that may effect shot peening control.

5.10.4.2 These verifications shall be witnessed by a qualified inspector.

5.10.4.3 If the intensity verification does not satisfy the requirements of paragraphs 10.2, the operation shall be stopped immediately and the non compliance procedure as given in paragraph 5.10.7 shall be implemented.

5.10.4.4 All Almen test specimens used for the intensity verifications in accordance with paragraph 5.10.4.1 shall be uniquely identified and be stored in accordance with the controlling authority requirements.

5.10.5 Control of Peening Coverage (Initial and Patrol Inspection)

5.10.5.1 A qualified inspector shall check the first and last component plus every teeth component (for batches greater than ten) for full coverage as specified in paragraph 5.7.2.1.

5.10.5.2 The inspector shall also inspect for conformance with regard to correct masking and areas to be peened and scatter peened as required by the drawing/process sheet.

5.10.5.3 If any components exhibit unsatisfactory coverage or any other non conforming features the operation shall be stopped immediately and the non compliance procedures given in paragraph 5.10.7 shall be implemented.

5.10.6 Control of Shot

5.10.6.1 The shot shall be maintained in accordance with paragraph 5.2.6.

5.10.6.2 Any charge of shot failing to meet the size and/or shape requirements of paragraph 5.2.6 shall be removed from the machine. It shall then be reclassified to meet the requirement of paragraph 5.2.6 or rejected and replaced with new shot meeting the requirements of paragraph 5.2.1.1.

5.10.7 Non Compliance

5.10.7.1 Whenever it is shown that operating conditions do not satisfy the requirements of paras 10.4 to 10.6 peening operations shall be stopped immediately and shall not recommence until the problems have been resolved.

5.10.7.2 All parts shot peene3d between the last satisfactory inspection and the first unsatisfactory inspection shall be reje3cted and quarantined until inspection has been carried out.

5.10.7.3 Where components have been rejected and found to be unsatisfactory because of incomplete coverage they may be re-peened once in accordance with the relevant process sheet requirements and then re-inspected. The fact that parts have been re-peened shall be highlighted by the inspection documents.

5.10.7.4 Components rejected for other reasons shall remain in quarantine until the problem has been discussed with the controlling authority. They shall then be rejected, re-peened, etc. In accordance with the controlli8ng authorities requirements.

5.11 POST PEENING TREATMENTS

5.11.1 After shot peening and the removal of protecting masks and tape all components shall be properly cleaned to remove all shot from the parts. This shall be carried out in accordance with the requirements of the controlling authority.

5.11.2 Shot peened steel components corrode very readily and should be protected from corrosion in accordance with the requirements of the controlling authority.

5.11.3 Temperatures of stresses to which the parts are subjected in subsequent processing shall not be high enough to reduce the compressive residual stresses introduced by shot peening or to adversely affect the physical properties of the material.

Unless otherwise specified by the controlling authority post peening processing temperatures shall not exceed the following :-

Carburised parts	140 Deg. C (limited by tempering Temperature)
Nitrided flame hardened and other steel parts.	200 Deg. C or 20 Deg. C below Temperature.

5.11.4 It is permissible to improve surface finish after peening by polishing honing, lapping,vapour blasting and grinding provided that the material removed by the process does not extend to a depth greater than 20% of the depth parameter indicated by figure 8(b) and the temperature limitations of para5.11.3 are not exceeded.

Note: Parts that are ground may require acid etch inspection and de-embitterment if required by the controlling authority.

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5.11.5 Unless otherwise approved by the controlling authority, hardness testing, vibro etching, engraving or stamping of parts or any other such process that will cause local stress raisers is prohibited.

5.11.6 Unless otherwise approved by the controlling authority straightening and distortion correction of peened parts is prohibited.

5.12 FINAL INSPECTION

5.12.1 After removing protecting masks and steel shot as per paragraph 5.11.1 all parts shall be inspected in accordance with drawing and process sheet requirements using times ten magnification, an approved tracer liquid or a combination of both.

5.12.2 The inspector should also ensure that all short has been removed from the component, paying particular attention to bores and cavities.

5.12.3 The inspector should note any damage or other inconsistencies.

5.12.4 Rejected parts should note any damage or other inconsistencies.

5.12.5 After inspection components shall be protected and packaged in accordance with the requirements of the controlling authority.

5.13 QUALITY CONTROL

5.13.1 <u>Records</u>

5.13.1.1 A permanent record in the form of an approved process sheet (See paragraph 5.8) shall be maintained for each part number processed.

5.13.1.2 A permanent record shall also be maintained for each batch of parts processe3d. This record shall include:

1. Date of processing.
2. Part number and description.
3. Quantity of parts.
4. Job card batch number or Release Note identity.
5. Serial Number of parts, if applicable.
6. Identification of peenikng machine.
7. Shot type and size.
8. Intensity specified and obtained.
9. Process sheet identity which contains all peening parameters.
10. Deviation and/or non compliance action.
11. Release note identity.

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5.13.1.3 These records shall be he3ld on file for a minimum period defined by the controlling authority.

5.13.2 Instrumentation and Gauge Control

5.13.2.1 These shall be checked and calibrated in accordance with the requirements of the controlling authority.

5.13.3 Approval

5.13.3.1 Shot peening shall only be performed using equipment and material approved by the controlling authority.

5.13.3.2 Process sheets as defined in paragraph 5.8 must have the approval of the controlling authority before components can be processed.

6. SPECIFYING SHOT PEENING ON ENGINEERING DRAWINGS

6.1 Drawing requirements

6.1.1 When specifying shot peening requirements on a drawing the following parameters should be included.

1. Process specification.
2. Areas to be shot peened.
3. Areas that must not be shot peened (masked)
4. Areas where peening is optional.
5. Areas where scatter peening is permissible
6. Areas where fade out of shot peening is necessary.
7. Size and type of shot required.
8. Peening intensity.
9. \Coverage requirements.
10. Inspection method.
11. Location of Almen test pieces for intensi8ty verification. However, this may be agreed between the shot peening organization and the controlling authority when compiling the process sheet for each individual part.

6.1.2 The drawing notes should be worded and detailed in a similar manner to the example shown in Figure 6.

Example

"Shot peen the areas indicated thus xxxx in accordance with Process Specification BGA…….. to an intensity of 0.20 to 0.30 mm A2 using S170 Hard (57 to 63 HRC) shot. Component coverage 200% minimum. Inspection of gear teeth by x10 magnification and tracer liquid. Process sheet 0001 refers.

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6.2 Additional Information

6.2.1 Intensity

6.2.1.1 The intensity of peening should be chosen either from the recommendations given within the shot peening specification or alternatives which have been proven by fatigue/justification testing to give acceptable gear life.

6.2.1.2 The intensity range should normally be over a 0.1 mm (.004”) A2 range. However, if it is necessary to restrict it further for surface finish requirements etc. a range of 0.05 (.002”) A2 is achievable.

6.2.2 Shot

6.2.2.1 The size of the shot to be used is important and the following factors should always be considered.

1. Shot must be of sufficient mass to achieve the desired intensity.
2. Where radii are to be shot peened the shot size selected must be no greater than one half of the fillet radius.
3. For slots and other apertures through which the shot must pass to peen shielded critical areas, the nominal shot size shall not be greater than one quarter of the diameter or width of such apertures.
4. Shot size can also influence surface finish. For a given intensity larger shot will produce a finer surface finish.

6.2.2.2 Shot hardness is also an important factor as it can be influence both the depth and magnitude of residual stress. It is generally recommended that5 to obvtain optimum benefit from shot peening the hardness of the shot should be at least as hard as the surface being processed. Therefore, where component material strength is 1380 MPa or greater or of equivalent surface hardness (43 HRC) peening should be carried out using hard shot (57-63 HRC).

6.2.2.3 Hard shot will however, increase surface roughness when compared with the effect of regular shot at the same intensity. This fact should be taken into consideration when surface finish is an important feature. It may therefore be necessary to improve the surface finish of the gear tooth flanks by either a buffing or Abral polishing. Masking of great tooth flanks is an alternative but is not practical for small gears. Suggested peening and masking practice for carburized gears is given in Table 4A.

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6.2.3 Inspection

6.2.3.1 Inspection is a very important part of shot peening as it only requires the smallest area of inadequate coverage to cause premature fatigue failure.

6.2.3.2 For uncomplicated parts, inspection to ensure the component has been completely covered, can be achieved by the use of a times ten power glass and good lighting. However, for more complicated parts with bores recesses or very small root radii etc. it would be prudent to use an approved tracer liquid system in combination with the visual times ten power examination. The choosen method of inspection should be called up on the drawing.

7. ESTIMATION OF THE IMPROVEMENT IN BENDING FATIGUE (ATTRIBUTABLE TO SHOT PEENING OF CARBURISED GEARS).

7.1 INTRODUCTION

In this section a method is given to enable the benefit due to shot peening to be estimated. The method is based on a comparison with an ide3ally carburized surface i.e. with no decarburization, intergranular oxidation or other surface defects.

The essential features of the method are :

1. Residual stresses are estimated using an empirical formula and coefficients related to the peening parameters.
2. The distribution of applied stresses with depth is estimated.
3. A fatigue life model is used to find the weakest depth in the structure (where fatigue is expected to originate) and to estimate the effective endurance limit in terms of the peak applied root stresses.

A further simplified method is given in Section 7.7 and may be used directyly for initial estimation of carburized gears.

7.2 RESIDUAL STRESS

Many residual stress distributions in (correctly) carburized components fit the general form :

$$S_r = -K_1 \operatorname{sech}^2 \left(\frac{x-x_1}{x_1}\right) + K_2 \operatorname{sech}^2 \left(\frac{x-x_2}{x_3}\right) + K_3 \quad (1)$$

(See note 1)

Where coefficients K1, K2 relate to the residual case compression and case core interface tension respectively. Here, x is the depth below the surface and x1, x2, x3 are depth parameters. For correct carburizing :

$$K_1 = 350 \text{ MPa}$$

$$K_2 = K_1/5$$

$$\text{and} \quad \frac{x_1}{2.5} = x_2 = 4x_3 = \text{case depth}$$

K3 is determined by the equilibrium condition:

$$\int_0^D S_r dx = 0$$

Where D is the depth of the neutral axis in bending which in the context of sput and helical gear teeth we interpret as the normal distance from the 30 degree tangent point to the tooth centre: thus,

$$D = \frac{h}{\cos 30°}$$

Where 2h is the chordal rooth (root) thickness (Figure 7).

Shot peening introduces an additional compressive stress:

$$S_r' = S_r - K_4 \operatorname{Sech}^2 \frac{(x-x_4)}{x_5} + K_5 - K_3 \qquad (3)$$

Here, K4 is the compression due to peening which cn be estimated from Figure 8(a) and

$x_5 = 1.5\, x_4$ can be found from Figure 8 (b).

Again K_5 is found from

$$\int S_r' dx = 0$$

7.3 APPLIED STRESS DISTRIBUTION

This will usually consist at a linear distribution of alternating tension due to teeth bending, factored by a near surface stress concentration.

$$S_A\ (x) = (S_A)\ \max\ \frac{(h-x)}{h}\ K_T\ (x)$$

The form of K (x) varies with tooth root details; if the stress distribution is known in detail it should be used. Otherwise the following is relevant to a full fillet form.

$$K_T\ (x) = 1 + 0.7\ (1 - x/0.2h) \qquad x \leq 0.2h$$

$$K_T\ (x) = 1 \qquad x \geq 0.2h$$

(See note 2)

7.4 DAMAGE FACTOR

Shot peening in addition to causing beneficial compressive residual stress can give rise to surface plastic damage and even micro cracks. In order to account for the detrimental effect of this, a further stress concentration factor is introduced for the peened layer:

$$K_{TSP} = 1 + K_{SP}\ \mathrm{sech}^2\ \left(\frac{x}{2x_4}\right)$$

For correctly peened gears K_{SP} has a very small value but over peening increases K_{SP} (as well as adversely affecting the residual stresses). For good practice K_{SP} – 0.02.

(See note 3 and Figure 9)

7.5 FATIGUE MODEL

For simplicity, the Landgref equation is used:

$$S_A = (S_f - S_M - S_r)\,(kN)^b$$

where S_A = applied alternating stress
S_M = applied mean stress
S_r = residual stress
k = constant
N = fatigue reversals to failure
b = exponent = −1/3 (See note 4)

We determine k using the Goodman law (for $S_r = 0$) :

$$S_A = 2S_u/3,\ N = 3.10^6 \text{ if } S_M = 0 \text{ (reverse bending)}$$

$$S_A = S_u/2,\ N = 3.10^6 \text{ if } S_M = S_A/2 \text{ (pulsating load)}$$

Recalling that all stresses vary with depth, x, we can now write, for the endurance stress under pulsating load (i.e. maximum applied stress to give failure in 3.10^6 cycles):

$$S_E(x) = \left(\frac{1}{2}\right)\left(\frac{K_T(0)}{K_T(x)}\right)\left(\frac{h}{h-x}\right)\left(S_f(x) - S_r(x)\right) \qquad (6)$$

The minimum value of this and its associated value of depth x_{crit} give the endurance stress and depth of the predicted fatigue origin respectively.

It remains to calculate the fatigue strength parameters $S_f(x)$. An approximation used here is :

$$S_f(x) = 290.6\,(H(x))^{1/4} \text{ MPa} \qquad H \leqslant 400$$
$$S_f(x) = 3.25\,H(x) \text{ MPa} \qquad H \geqslant 400 \qquad (7)$$

where H is the (Vickers) hardness.

Finally, if the hardness distribution H (x) is not known, a good approximation is (8)

$$H(x) = H(0) + (H(0) - H(h))\,\mathrm{sech}^2\left(\frac{x}{Cx_2}\right)$$

where H(o) and H(h) are surface and core hardnesses respectively and C is a parameter which will need to be adjusted according to the local definition of case depth. For H (o) = 720 and H(h) – 400, C – 0.94 gives a case core transitio9n hardness of 520 HV.

7.6 EXAMPLES

Figures 10 gives the predicted endurance limits and origin positions for a gear of surface hardness 720, core hardness 350 HV for a range of case depths. Peening parameters correspond to an intensity of 0.35 mm A with normal hardness shot at 200% coverage. Note the distinct ranges of origin position and the general decline in benefit with tooth thickness – a result of the fixed depth of the beneficial residual stresses.

7.7 SIMPLIFIED METHOD

For normal industrial practice for carburized steel gears we may make the simplifying approximation:

$h = m_n$
$x_2 = 0.16\ m_n$
$K_4 = 1230$ MPa (hard shot, see table 4)
$x_5 = 0.03$ mm (0.25 mm A2, see table 4)
$H(0) = 720;\ H(h) = 350$

The percentage increase an endurance limit attributable to shot peening under these circumstances is shown in figure 12, which may be used directly for carburized steels treated in the recommended manner. Note that the reference (non-peened) condition refers to optimum carburized components whose residual stress distribution is given by equation (1). The curve given in figure 12 SHOULD NOT be extrapolated to higher or lower values of module because of the presence of sharp discontinuities.

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