SURFACE TREATMENT AND RESIDUAL STRESS EFFECTS ON THE FATIGUE STRENGTH OF CARBURISED GEARS

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This paper presents results from an investigation into the effects of different surface peening and blasting processes on the bending fatigue strength of pulsator tested case carburised gears. A variety of intensities of treatment have been examined, ranging from light alumina vapour blasting through to heavy peening with glass beads. In each case, the effect of the treatment on the residual stress depth profile in the material has been assessed. The changes in fatigue strength observed show a strong relationship with the measured change in the residual stress profile induced from the peening or blasting process. The site of fatigue crack initiation has also been characterised and was found to be dependant on the residual stress profile in the surface layers of the material. The change from surface to sub-surface crack initiation identified after some treatments partly helps to explain the large increases in fatigue strength observed.

INTRODUCTION

The failure of carburised gears normally occurs through a process of fatigue and is usually attributed to a combination of the material properties along with gear design and mechanical misalignment. Improving the fatigue strength of gears is therefore of great importance in attaining increased load carrying capacities and in improving component reliability. Since most bending fatigue failures are initiated at or near to the surface (1), one of the most promising methods of improving fatigue strength is through the use of different treatments to modify the surface properties of the material.

If the root bending fatigue strength of carburised gears is considered, there are several possibilities for surface modifications, such as root grinding, change of heat treatment technique, alteration of alloy composition, chemical etching etc., all of which may be beneficial in improving the bending fatigue strength. In each case, the aim is to remove or suppress the existing site of crack initiation. With normal gas carburising processes, this initiation site is normally associated with the internally oxidised surface layer (see Figure 1a)

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which forms during the heat treatment schedule. There is some debate over exactly what causes the crack to initiate (e.g. oxide on the grain boundaries (2), phosphorous segregation (3), non-martensitic layer (4)), but there is agreement that this modified surface layer can indeed result in reduced fatigue strengths.

Several of the possibilities being considered or currently used for improving bending fatigue strength in gears involve additional costly processes and in many cases, are therefore less likely to be an attractive solution. The processes mentioned above all rely on removing or preventing the formation of the thin oxidised surface layer. Levels of residual stress are, however, also known to have an effect on bending fatigue strength. The introduction of high compressive residual stress levels into the surface layers is, therefore, an alternative possible method for suppression of fatigue crack initiation (5).

The most common method of modifying residual stress levels is through the use of controlled shot peening or blasting techniques. In the gearing industry, a variety of processes of this type are currently used after heat treatment. However, this is primarily as a 'cleaning' process (6) rather than for benefits to strength. The work presented here investigates the strengthening effect of a range of different surface treatments currently employed as post-heat treatment methods for cleaning gears.

EXPERIMENTAL METHODS

Test gears, as specified in Table 1, were manufactured from a 20MnCr5 grade of steel produced by British Steel Engineering Steels using secondary steelmaking techniques (7) resulting in an oxygen content of less than 10ppm (i.e. very low oxide inclusion content in the steel). The gears were then gas carburised by David Brown Heatech to give a case depth of approximately 1.2mm. This heat treatment process resulted in a layer of internal oxidation of approximately 20μm (see Figure 1).

TABLE 1 - Test Gear Specifications

Module, mm	8.0
DIN quality	5
Number of teeth	20
Face width, mm	25
Base circle dia., mm	150.35
Pitch circle dia., mm	160
Tip dia., mm	175.75
Root dia., mm	137.36

The gears were then given a range of different surface treatments representative of those currently used in practice by gear manufacturers. The processes investigated were wet and dry alumina vapour blasting, shot blasting, grit blasting, shot peening and glass bead peening which covered a wide range from light to heavy intensity processes. The conditions used in each process were consistent and controlled to give a clean gear. However, in addition to cleaning the gear, the main effect of each processes was to alter the levels of residual stress present in the material. Surface roughness changes were also measured using optical profilometry, but although some slight differences were observed, the effect was considered to be insignificant in terms of the bending fatigue test results.

Residual stress levels in the gears were characterised using the well established technique of X-ray diffraction (8) on an AST X2001 X-ray residual stress analyser. This technique uses the internal atomic plane spacing to act, in effect, as a set of microscopic strain gauges. Changes in the plane spacing, due to residual stress, can be determined from the position of a diffracted X-ray beam and then the residual stress can be calculated from stress theory. A 1mm collimated Cr Kα X-ray source with a beam penetration depth of ≈10μm was used to carry out the measurements. The sampling volume was therefore equivalent to a disc of material 1mm in diameter and 10μm thick. Chemical etching and electropolishing techniques were used to gradually remove material without disrupting the residual stresses present in order to allow depth profiles through the surface layers to be obtained.

The fatigue strength of the gears after the different treatments was characterised using pulsator testing on an Instron 1603 resonance fatigue test machine (≈160Hz) fitted with a 10 tonne load cell. The test arrangement is shown in Figure 2. The teeth were loaded on the base tangent line with a flat, self-aligning anvil (≈1mm from the tooth tip) and tested using the staircase method. After failure, fracture surfaces were examined and initiation sites determined using a Camscan S4 scanning electron microscope fitted with an energy dispersive X-ray analyser.

RESULTS AND DISCUSSION

The results of the residual stress characterisation are shown in Figure 3. The results show a large variation in the maximum compressive residual stress between the different processes. The fine alumina blasting had very little effect on the residual stress levels, whereas, the glass bead peening gave the largest effect with a maximum residual compressive stress of ≈1GPa. The effect of shot peening as an additional process on top of the initial cleaning processes was also investigated (see Figure 4). This led to an increase in the maximum compressive stress for the less intense processes, but had very little additional benefit for the shot peened and glass bead peened gears.

The results of the fatigue testing are also indicated in Figures 3 and 4. To give an easy comparison between the strength improvements, all the results are normalised to 100 for an untreated (as-carburised) gear. Figure 5 clearly shows that there is a trend for the fatigue strength to increase with increasing maximum compressive stress introduced from the surface treatment process. The highest compressive stress actually resulted in a 62% increase in fatigue strength. By comparison, other tests carried out after the removal of the layer of grain boundary oxidation through chemical etching techniques, without any blasting or peening, gave a strength increase of 34%.

As identified in Figure 1b, examination of the fracture surfaces showed that, for all the gears except those given a glass bead peening process, the initiation site was from a surface location (i.e. from within the internally oxidised layer). However, Figure 6, shows that, for the glass bead peened sample, the initiation site was found to be sub-surface (i.e. the weakness of the internal oxidation was suppressed). Closer examination of the nucleation site indicated that failure was nucleated from a MnS inclusion. This implies that further increases in strength will require a reduction in the levels and size of inclusions in the steel.

These results show that, if the residual stress can be increased to give a high enough compressive stress, a substantial increase in the bending fatigue strength can be obtained. The largest increases in strength can partly explained by the high compressive stress level, but also by the fact that the compressive stress can suppress the internally oxidised boundaries as a site for crack initiation, resulting in sub-surface nucleation from inclusions. The work highlights the benefit of a post heat treatment cleaning process and shows that, if chosen carefully and carried out in a controlled manner, large benefits to strength and reliability can be obtained.

CONCLUSIONS AND FUTURE WORK

The main conclusions are therefore that large increases in fatigue strength can be obtained, through the careful control of the condition of the surface layers of material in a carburised gear. Effective peening has been shown to be effective in suppressing the detrimental effects of internal surface oxidation and it has been shown that, in the absence of surface oxidation and oxide inclusions, larger MnS inclusions will act as initiation sites for fatigue (i.e. the next weakest link).

The importance of understanding the influence of a process on the level of residual stress has been clearly shown. At present, post heat treatment peening and blasting is mainly regarded as a process of cleaning (e.g. removal of oil, stop off paint and oxide scale) and therefore, the results should be of value to gear manufacturers in showing that the method of 'cleaning' can actually be used to great benefit in terms of improving the life and reliability of a component.

The current investigation has examined relatively simple processes, as might be used in cleaning. Further investigations are ongoing and are examining more advanced peening methods to determine if even greater improvements in strength can be obtained. Modelling will also be used to help understand the process of residual stress development and the effect of residual stresses on crack initiation and growth.

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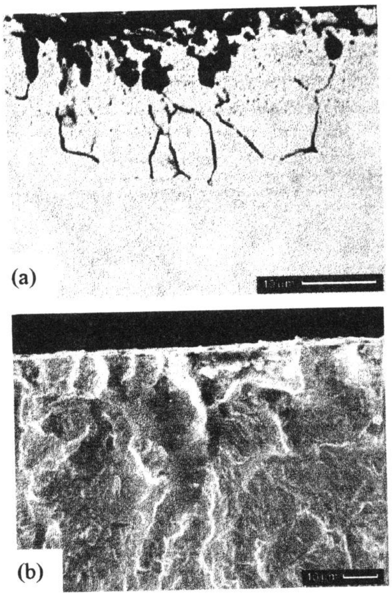

Figure 1 (a) Section with internal oxidation.
(b) Surface initiated fracture.

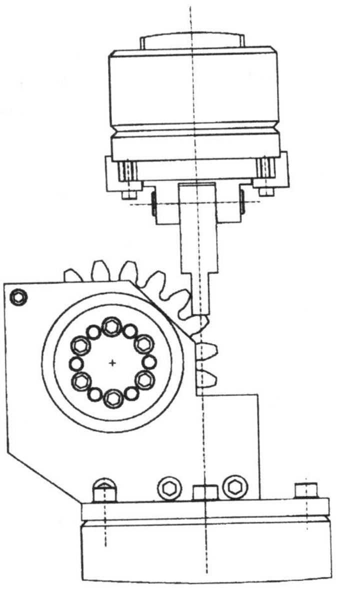

Figure 2 Gear pulsator test method.

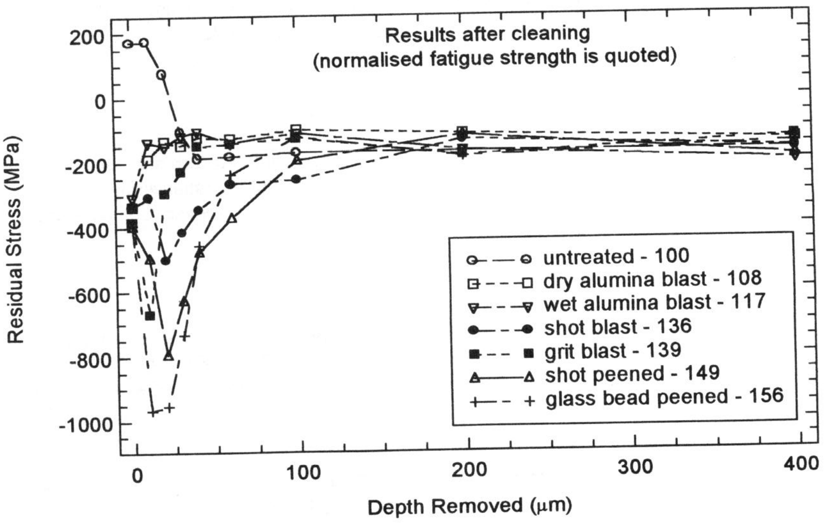

Figure 3 Residual stress profiles and fatigue strengths after different surface treatments.

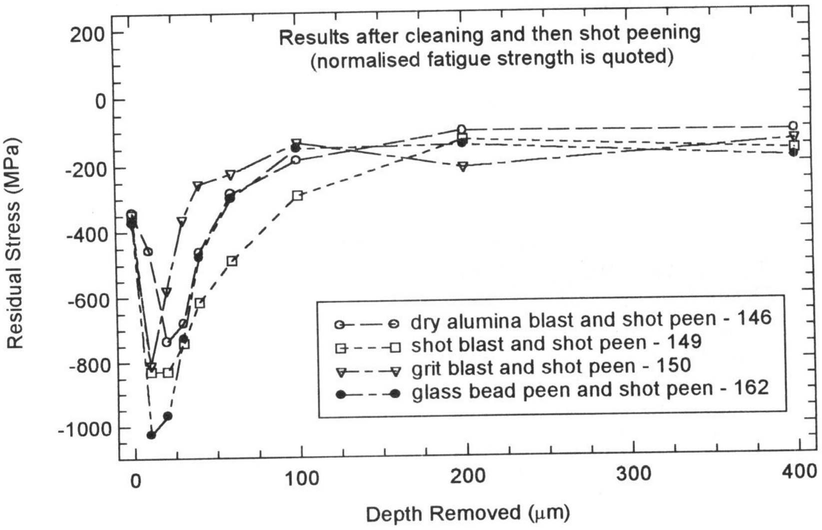

Figure 4 Residual stress and fatigue strength after an additional shot peening treatment.

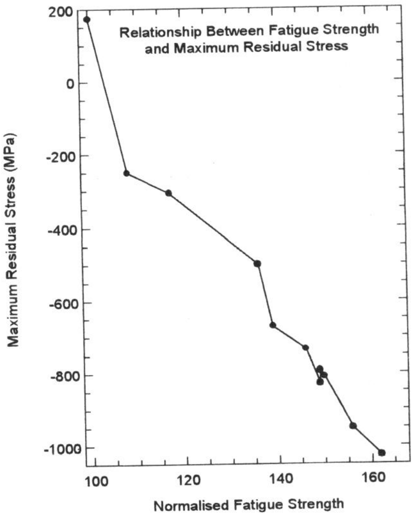

Figure 5 Relationship between residual Stress and fatigue strength.

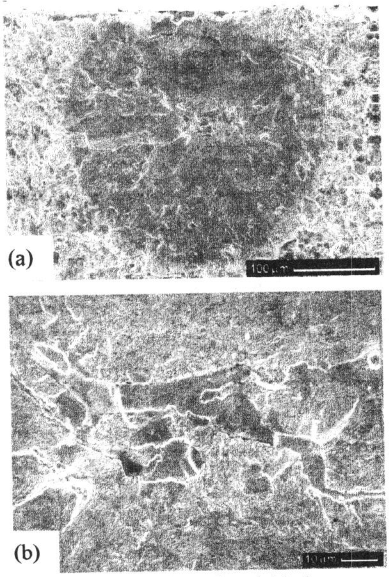

Figure 6 (a) Sub-surface initiation.
(b) Nucleation from MnS.