Diagnosis of Gear Wear by Experimental and Theoretical Approach

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Abstract:

When the teeth surfaces of a gear are subjected to excessive stress conditions, surface failure may occur. This can cause plastic deformation or removal of the contacting tooth surfaces, in some cases, surface fatigue cracks occur in plastically deformed regions under excessive contact stress, and these can also be caused by scuffing or wear failure. Most of the conventional failure criteria are stress based. As such, the stress analysis of a gear pinion is important for failure analysis. Further the residual stress present in a gear pinion arise during operation under higher loads and in many cases residual stress measurements of pinion can play an important role in prognosting service life of pinion. X-Ray diffraction residual stress analysis method can be used to measure residual stress of gear pinion in situations where failure results from overloading, stress corrosion, fatigue, stress concentration etc, hence stress analysis provides an abundant information in the characterization of gear wear failures. This paper also looks into the various wear particles produced under different load conditions as a result of varying stresses developed on the gear surface. Energy Dispersive Spectrum technique is also used for wear particle analysis of both morphological and compositional properties which are very much useful for the study of too small particles of the order of 5 microns or less. This work utilizes this method also for the study and analysis of wear debris particles . Tooth surface defects such as such as pitting, mild wear and scoring were observed. Residual stress measurement using XRD of pinion was undergone to characterize the changes after 12 million revolutions; a significant change is observed in XRD stress pattern, In addition spur gear geometry of FZG gearbox is modeled in ANSYS 8.0 to validate with experimental results.

1. Introduction

The aim of using gears is mainly to transmit power or rotary motion between shafts and to maintain the intended angular velocity ratio, together with smooth motion transfer at high efficiency. When gears operate at their maximum load, very high contact pressure occurs at their mesh interface, there by triggering operating stresses. The contact occurs along a line or point, or depending on the elastic constraints of the materials concerned, along a very small circular or elliptical area. As a result of such small contact areas, the shear (Hertzian) stress which develops at and near the surface is consequently very high. The maximum shear stress occurs at some distance below the surface.

When the contacting stress is repetitive, as in the case on the active flanks of gear tooth, the cyclic compressive stresses induced cause differing elastic and plastic behavior in the near- surface material. Depending on the microstructure and grain orientation of the material in this region, internal stress concentrations are formed, which can ultimately lead to crack initiation.

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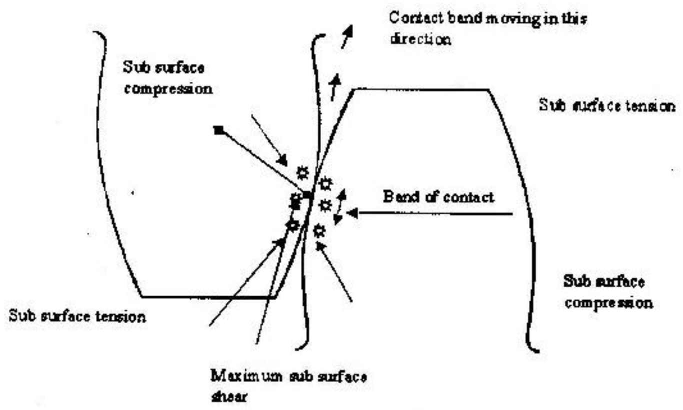

Fig.1 Stresses in the region of tooth contact

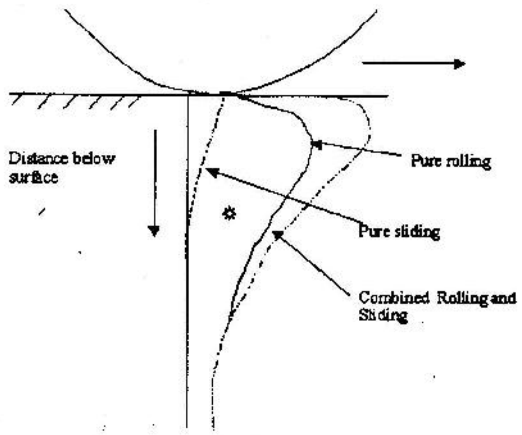

Fig.2 Stress distribution in contacting surfaces

Fig.1 shows the distribution of forces at the region of tooth contact in spur gears [9]. The band of contact is actually moving in the upward when the gear turns as shown in the figure. Maximum subsurface shear occurs at an area just close to mating point. Subsurface tension occurs at the tooth tip away from the contact point and subsurface compression is at the tooth fillet region away from the meshing point.Due to rolling and sliding motion between the surfaces, stresses are induced and the stress distribution is as shown in the Fig.2. When the subsurface shear stress exceeds the endurance limit of the material , a fatigue crack initiates and propagates parallel to the surfaces, isolating and removing a piece of surface material to form a pit.

1.1 Residual Stress Measurement using X-ray Diffraction

Any manufacturing process that changes the shape of the solid or where severe temperature gradient is developed during the process causes residual stresses.By their varying nature, processes that change the shape of a solid cause non-uniform plastic deformation in the solid, which leads to residual stresses.

A concern in the measurement of residual stresses in gears is addressed by XRD measurement since the area or volume over which the stresses are resolved is of the order of 1mm which may explain high stress gradients in wearing gear.

1.2 Wear Particle Analysis

Gear teeth contacts have been considered as one of the most complicated interactions in tribology. Under increased power and higher speeds, gear wear and fatigue failures, such as pitting ,scoring, spalling and tooth breakage are of major concern. Wear particle analysis allows non-interruptive diagnostic determination of lubricant condition by determining the amount of wear and the lubrication products. Energy dispersive spectrum technique (EDS) is a familiar elemental analysis attachment to a scanning electron microscope (SEM) where electrons are used as primary energy source to excite the X-ray spectra. SEM-EDS methods have been used for wear particle analysis of both morphological and compositional properties and are particularly useful where the study of very small particles (approximately five microns or less) is necessary as in the present study.

2. Experimental Setup

The equipment used for testing gears is a standard FZG back-to-back gear box .It consists of four gears (two pinions with 25 teeth and the other two gears with 54 teeth) and a three-phase induction motor. The readings were taken at the critical load bearing section of the gear pinion at different angular positions around the fillet region of the gear tooth. The residual stress values on the gear surface were measured after lapse of different million load cycles and also at different depths by removing metal by means of electro polishing.

The work piece, namely the gear pinion was used as the anode and a metallic sheet was used as the cathode. The electrolyte used in this work was a combination of 840 ml ethanol (absolute),4 ml distilled water ,125 ml glycerol and 31 ml $HClO_4$ (70%).The current applied was DC of 20 V and the current was 75 m A . The experiment was repeated by keeping the current, voltage and the time constant for to get the same depth of material in different stages.

3. Results and Discussion

3.1. Residual stress measurement by XRD method

Figure 3 shows the residual stress values measured using the XRD method at different depths from the gear tooth surface,the profile is found to be comparable to the data reported in literature book (Reference paper)

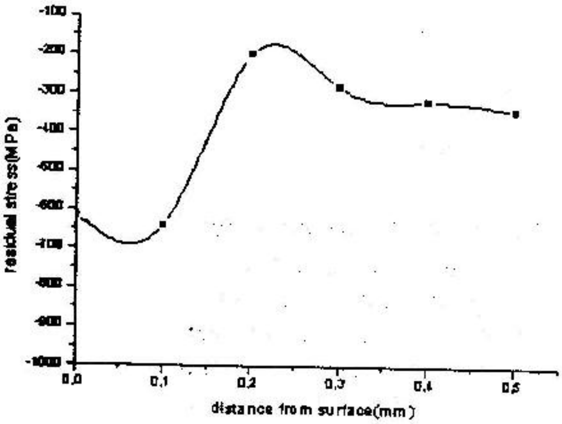

Fig 3. Distance from surface versus residual stress

From the chart (fig 3) one can see that the residual stress at all depths is of compressive nature (since all the values are negative). Moreover it is evident that the compressive stress increases gradually to a depth of about 0.07 mm (extrapolated data by curve fit) from the pinion tooth surface and thereafter decreases rapidly. The value reaches a minimum around 0.24 mm depth and after that increases slowly. Hence one can conclude that the residual compressive stress concentration is maximum around a depth of 0.07 mm very close to the pinion surface.

The relation between number of load cycles (in million) and the surface residual stress (MPa) is plotted as shown in fig 4. This was accomplished by removing the gear pinion from the FZG gearbox after different millions of revolutions and measuring the corresponding residual stresses by XRD method.

This graph makes it clear that the surface residual stress of the gear pinion decreases continuously from initial condition. When the pinion undergoes load cycles, the stress will be relieved and hence the stress moves to less compressive values as the number of fatigue cycles increases.This trend is also comparable to data in literature (Reference paper).

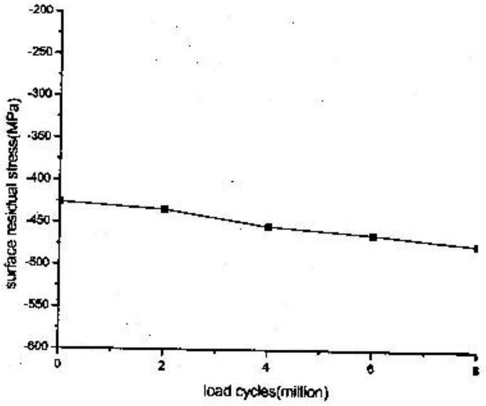

Fig.4 Load cycles versus surface residual stress

3.2 Energy Dispersive Spectrum (EDS)

The wear debris is first extracted from its fluid carrier and the sample is made by filtration on Teflon filter paper.The sample is then usually coated with a thin layer of a conductive element such as carbon to improve the overall conductivity. Figure 5 shows the EDS of ferrous wear debris collected from the gear box at the end of one million revolutions.The X-axis of the plot represents the energy of the wear particles ,while the Y-axis indicates the intensity of counts the scattered X-ray due to wear particle elements. From the plot it is evident that there is a significant amount of rise in the peaks of Fe, Mo, Si and P metal compositions, revealing that metal to metal contact has increasingly occurred as a result of film thickness failure .Other elements such as Ca and Zn ,which are detected by energy dispersive spectrum are from filter paper material and chemical composition (including oil additives).

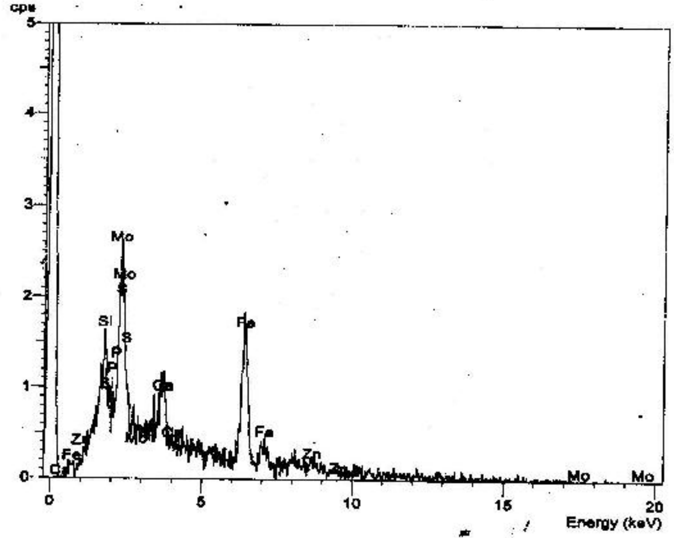

Fig 5 . EDS spectrum after 4 million revolution

3.3 Stress related wear particle analysis

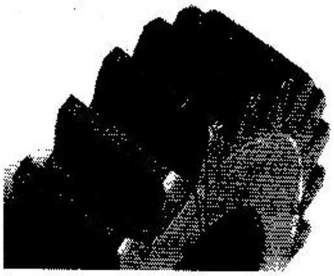

Fig 6 Worn surfaces after 8 million revolutions

Figure 6 shows a typical worn out surface of gear after 8 million revolutions .The worn surface exhibits fatigue failure mode such as pitting, scuffing and scoring. This is the most common problem observed at the pitch line where rolling occurs. Pits form in the pitch line area either initially or continuously in eventual damage. The formation of large number of pits may result in stepping pitch line.

Fig 7. Sliding wear particle (x 3000)

Fig 8. Chunk particle (x 2200)

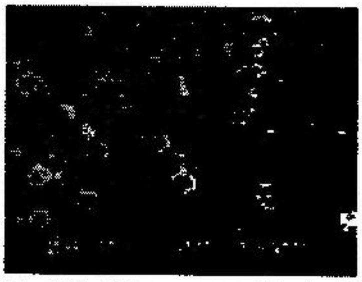

Fig 9. Rubbing wear particle (x 500)

In the sliding portion of the gear scuffing or scoring may occur, resulting in sliding wear particles with striated surfaces as shown in fig.7 which represents SEM picture of sliding wear particle. These defects trigger from cracking under repeated stresses and at excessive stress amplitudes. Further these defects can be increased significantly by increasing the average tensile stress of the loading cycle.

These failure conditions due to excessive operating stresses can be identified by wear particles generated from the gearbox. Fig .8 shows a few (using SEM) chunk particles resulting from tensile stresses on gear surfaces. The fatigue particles deepen into the gear tooth prior to pitting. Once initiated, scuffing usually affects the surface of the gear resulting in a large volume of wear debris. Since there is a large variation in both sliding and rolling velocities at the wear contacts, corresponding variations in the characteristics of the particles are generated. The ratio of large to small particles in a scuffing situation is low. The ratio of large to small particles depends on how far the surface stress limit is exceeded. The higher the stress level, the higher the ratio becomes. If the stress level rises slowly a significant increase in the quantity of rubbing wear prior to the development of any large severe wear particles may be noticeable. Rubbing wear particles are shown in the figure 9.

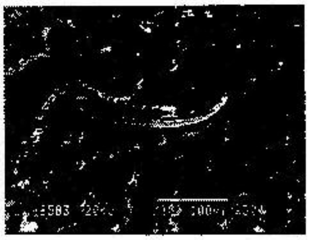

Fig 10 Cutting wear particles

Fig 11 Spherical wear particle

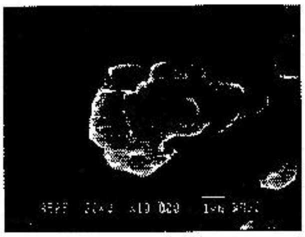

Fig 12 Laminar wear particle

Cutting wear particles are generated by the penetration or cutting of material bodies ; these particles are found at the end of 5 million revolutions .Teflon filter paper of size 0.2 μm is used to filter the debris,which are usually long strips as displayed in fig10.The presence of individual cutting wear particles is not significant,but frequent presence of several hundreds of cutting particles indicates severe cutting wear process being underway.

Fig 11 shows a spherical wear particle caused by fatigue or contamination found at 7 million revolutions.Their formation as a wear phenomenon is generally associated with rolling elements. Spheres formed by wear mechanisms are generally less than 5 μm in diameter ,with very smooth surfaces. Laminar particles observed at 8 million revolutions are shown in fig 12.These particles are formed by the passage of a wear particle through a rolling contact ,probably as a result of the crack between the secondary martensite layer and tempered martensite layer generated from rolling fatigue and combined rolling and sliding .

3.4 Modeling of gear stresses using ANSYS 8.0

The stress acting on the spur gear is modeled using ANSYS and the various graphs are plotted.

3.4.1 Variation of stress at different load conditions

The variation of contact stresses at the gear tooth contact area at different load conditions at no load, 100 N, 200 N, 300 N has been studied.The maximum stress is found to act at the contact point itself. The stress value is found to decrease continuously from this contact point towards the inside gear depths, the stress value shows increasing trend as the load increases which are typical for the chosen gears.

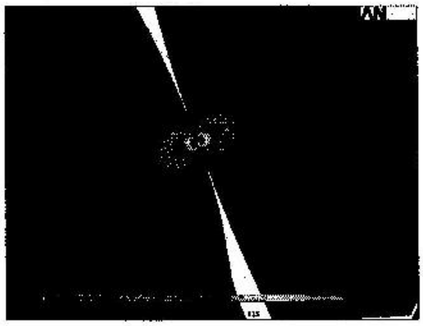

Fig 13 Variation of stress at 200 N load condition

These values of stresses are found to be matching with calculated values also.

Table .1

Load applied, F (N) F=Wt / cos Ø	Contact width ,b (mm) $b=\left\{\frac{2F\left[\left(1-\nu_1^2\right)/E_1\right]+\left[\left(1-\nu_1^2\right)/E_1\right]}{\pi l\left[\ (1/d_1)+(1/d_2)\ \right]}\right\}^{\frac{1}{2}}$ $C_p\left[\frac{W_t}{d_pLI}\right]^{\frac{1}{2}}$	Force acting ,F (N) F=W$_t$/ cosϕ	Contact Stress (N/m^2) Calculated $\sigma_c =$ $C_p\left[\frac{W_t}{d_pLI}\right]^{\frac{1}{2}}$	Contact Stress (N/m^2) From ANSYS
No load	0.056	602.28	139.7	128.8
100	0.111	1252.8	242.12	235.64
200	0.113	2409.2	339.69	321.67
300	0.134	3395.9	419.21	394.26

4. Conclusion

This work mainly concentrated on the analysis of different stresses acting on the gear pinion and the study of wear debris particles. The loading was by means of Torque adjustment coupling used in the FZG gearbox. The residual stress measured at different depths from the tooth surface as well as the stress measured at various load conditions are found out. The wear particles obtained from the gear box test rig after different load conditions were analysed in the Scanning Electron Microscope and found that different types of particles like sliding wear particles, chunk particles and rubbing wear particles are produced increasing concentration, correlating with pictures of surface wear of gear tooth.Wear debris analysis predicts wear and its impending mechanism. Energy dispersive spectra provide spectra of chemical compositions of wear particles . The contact stress acting on the gears is modeled in ANSYS 8.0 and compared with calculated values.

5. Acknowledgement

Author as a QIP scholar acknowledges sponsorship support given by College of Engineering ,Trivandrum, Kerala in helping to bring out this publication.

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