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SURFACE CONTACT FATIGUE FAILURES IN GEARS

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Abstract—Surface contact fatigue is the most common cause of gear failure. It results in damage to contacting surfaces which can significantly reduce the load-carrying capacity of components, and may ultimately lead to complete failure of a gear. Three types of contact fatigue damage are discussed, and a number of actual examples are presented to illustrate this failure mode in practice. © 1997 Elsevier Science Ltd.

1. INTRODUCTION

The most common mode of gear failure encountered in practice is that of surface contact fatigue. This mode of failure leads to crack initiation at or near the contact surface, and may subsequently lead to damage varying in extent from microscopic pitting to severe spalling. The metal removed from the surface in such cases enters the machine system, and can, in turn, cause abrasive wear and failure of other components. Furthermore, the pits formed on the damaged surface lead to the formation of stress concentrations, and serve as initiation sites for other modes of gear failure, e.g. tooth bending fatigue [1]. In this paper, various types of contact fatigue damage are reviewed and illustrated using practical examples. The causes and ways of preventing damage in each case are also discussed briefly.

2. MECHANISM OF CONTACT FATIGUE

Whenever two curved (usually convex) surfaces are in contact under load, the contact occurs along a line or point, or, depending on the elastic constants of the materials concerned, along a very small circular or elliptical area. As a result of such small contact areas, the shear (Hertzian) stresses which develop at and near the surface are consequently very high. The maximum shear stress occurs at some distance below the surface [2], as illustrated in Fig. 1.

When the contacting stresses are repetitive, as is the case on the active flanks of gear teeth, the cyclic compressive stresses induced cause differing elastic and plastic behaviour 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. In practice, crack initiation usually occurs at inclusions in the stressed near-surface material, the most deleterious being those inclusions which are hard, brittle and angular in shape.

Damage due to contact fatigue in gear teeth usually occurs in one of three areas, viz along the pitch-line, in the addendum (i.e. above the pitch-line), and in the dedendum (i.e. below the pitch line) [3]. Along the pitch-line, only pure rolling stresses exist (Fig. 1), while away from the pitch-line, both rolling and sliding stresses are experienced.* In the subsequent sections of this paper, surface damage under both pure rolling and rolling–sliding conditions, as well as a more advanced and severe mode of surface damage called spalling, is discussed.

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*Pure rolling stresses along the pitch-line occur only in spur, bevel and helical gears, and not in worm, spiral bevel or hypoid gears [4].

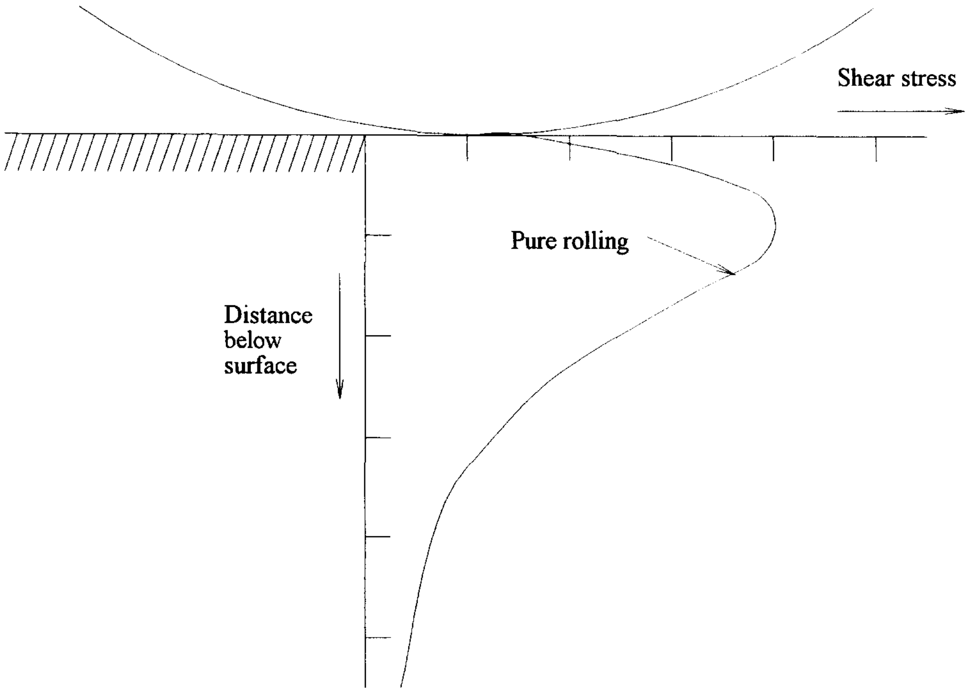

Fig. 1. Stress distribution at and near two contacting surfaces under pure rolling.

3. ROLLING CONTACT FATIGUE

The stress distribution resulting from pure rolling conditions prevalent at the pitch-line is shown in Fig. 1. The maximum shear stress occurs at some distance, usually 0.18–0.3 mm [3], below the surface, and just ahead of the contact point. Cracks initiate at the point of maximum stress, and propagate essentially parallel to the surface. Continued rolling may cause the cracks to deviate up towards the contact surface, resulting in the removal of metal from the surface. The pits formed in this manner initially have sides perpendicular to the contact surface, as illustrated schematically in Fig. 2. Continued operation of the pitted surface, however, may cause a breakdown in the pit shape.

Pitting under pure rolling can occur even under proper lubrication conditions, since oil, as an incompressible fluid, will merely transmit the contact loads [5]. The pits formed are generally very small and seldom give more than a "frosted" appearance to the damaged surface. In some cases, the pits may not progress beyond their point of origin, and may even be self-healing [3, 5]. There are two unique characteristics of rolling contact fatigue pits which can be used to distinguish this type of damage from other forms of pitting.

Firstly, the formation of rolling contact fatigue pits occurs with no surface plastic deformation. This is contrary to pitting under sliding–rolling conditions, as shown in Section 4. Secondly, in components with a case-hardened layer consisting of martensite with little or no retained austenite,

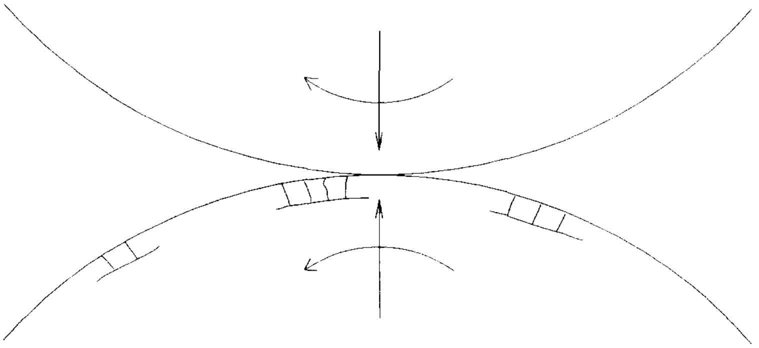

Fig. 2. Location and orientation of subsurface cracks under pure rolling conditions.

rolling contact fatigue leads to the formation of a microstructural feature referred to as "butterfly wings" [3]. These are formed when plastic deformation is constrained by the surrounding material, and is more common when shear stresses are extremely high.

4. SLIDING–ROLLING CONTACT FATIGUE

Pure rolling conditions prevail when the surface velocities of two contacting curved bodies are the same. However, if these velocities are different, an element of sliding is introduced which significantly alters the stress distribution in the surface and near-surface material. Depending on the relative velocities of the contacting bodies, rolling and sliding may occur in the same direction*—*positive sliding*—or in opposite directions—*negative sliding*. The effect of the latter is that the surface material is rolled in one direction, and pushed (sliding) in another, therefore resulting in higher stresses than those encountered in positive sliding [4]. The modified stress distribution in the surface and near-surface material resulting from combined rolling and sliding is shown in Fig. 3. The position of maximum shear stress is moved closer to the contacting interface, and crack initiation therefore occurs at the surface.

Gear teeth have complex combinations of sliding and rolling, which vary along the profile of each tooth, as illustrated in Fig. 4. In the addendum, the direction of rolling and sliding is the same, and positive sliding conditions therefore prevail. In the dedendum, however, the direction of rolling is opposite to that of sliding, and negative sliding conditions exist. Contact fatigue is therefore more likely to initiate in the dedendum, and pitting in this region is usually very severe, and often acts as a precursor to tooth bending fatigue [1].

In practice, it is common that contact fatigue damage will first occur in the dedendum of the smaller gear (which is usually the driving gear) of a gear set [4, 5]. This is explained by the fact that the smaller gear will undergo more revolutions, and therefore each tooth will experience a larger number of stress cycles. In order to prevent premature failure in such cases, it is common to make the smaller, driving gear harder than the other gears in the gear set.

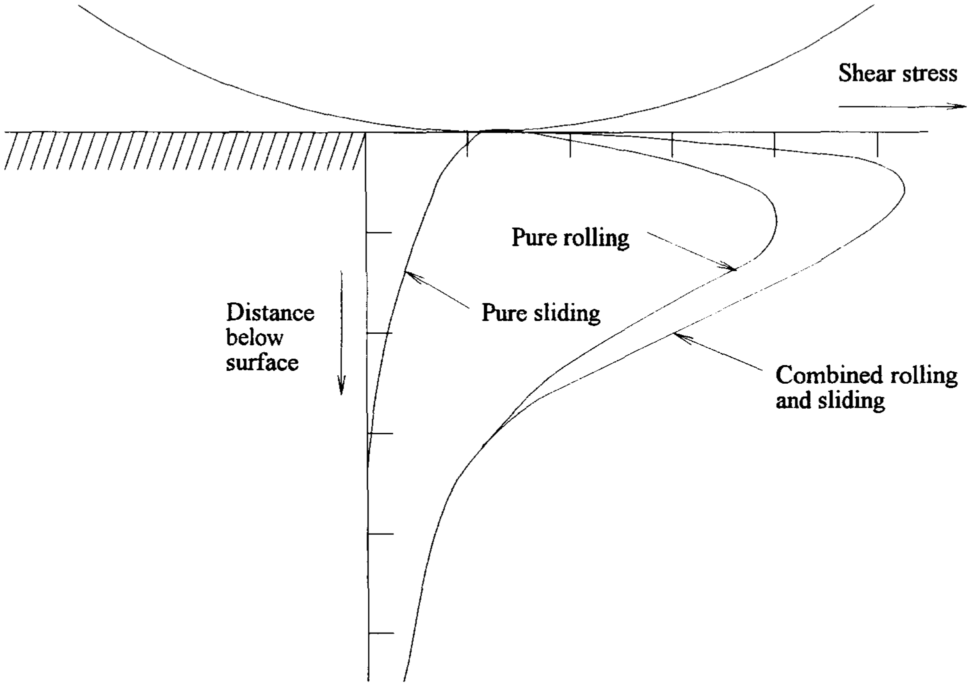

Fig. 3. Stress distribution at and near two contacting surfaces under sliding–rolling conditions.

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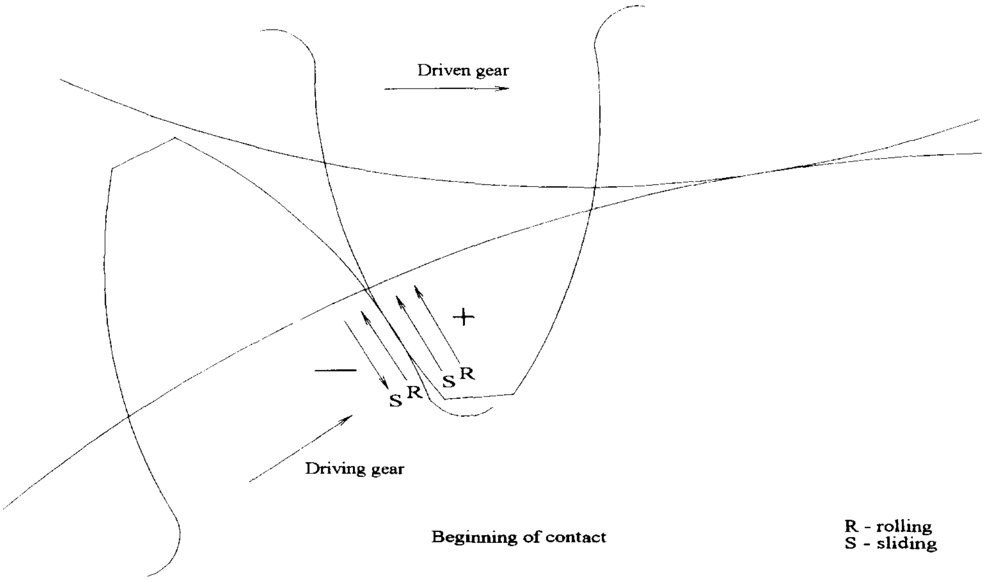
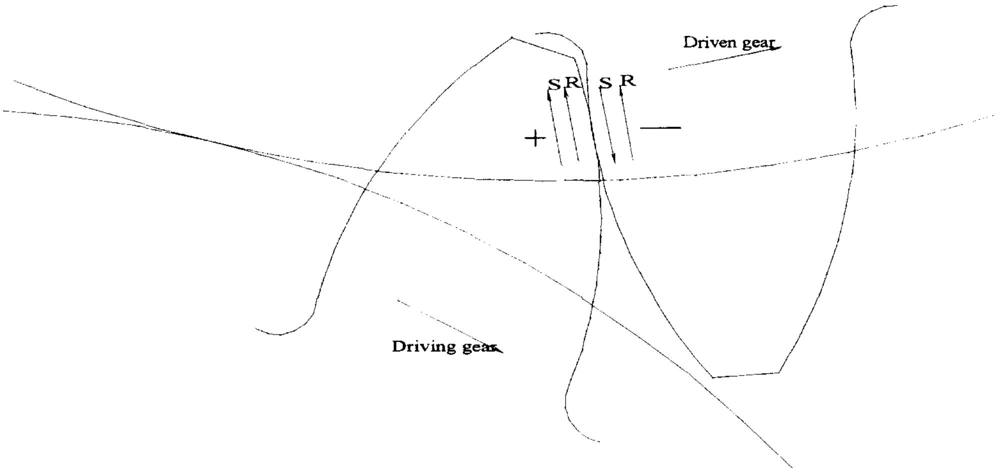
*The direction of rolling is the direction in which the point of contact between two bodies moves, and is always opposite to the direction of rotation.



Beginning of contact



End of contact

Fig. 4. Combination of sliding and rolling in gear teeth.

Another region in which contact fatigue damage is frequently encountered is at the lowest point of single tooth contact, i.e. the point at which contact is made with the tip of the matching tooth [3]. Since the contact area in this case is very small, high stresses are generated, even under normal loads. Moreover, the lowest point of single tooth contact is always in the dedendum of the matching tooth, and sliding speeds, both in approach and recess, are at a maximum. The negative sliding conditions in these regions, together with the high stresses and high sliding speeds, lead to rapid initiation of damage. Figure 5 shows the driving gear of a 1.5 ton lever hoist in which severe pitting in the dedendum has occurred at the point of single tooth contact [6]. The extent of damage observed occurred after only 500 cycles under test conditions.

Unlike contact fatigue damage under pure rolling conditions, the sliding–rolling action causes plastic deformation of the surface material, and this can usually be detected using metallographic analysis. The extent of plastic deformation, and hence of contact fatigue damage, can be reduced

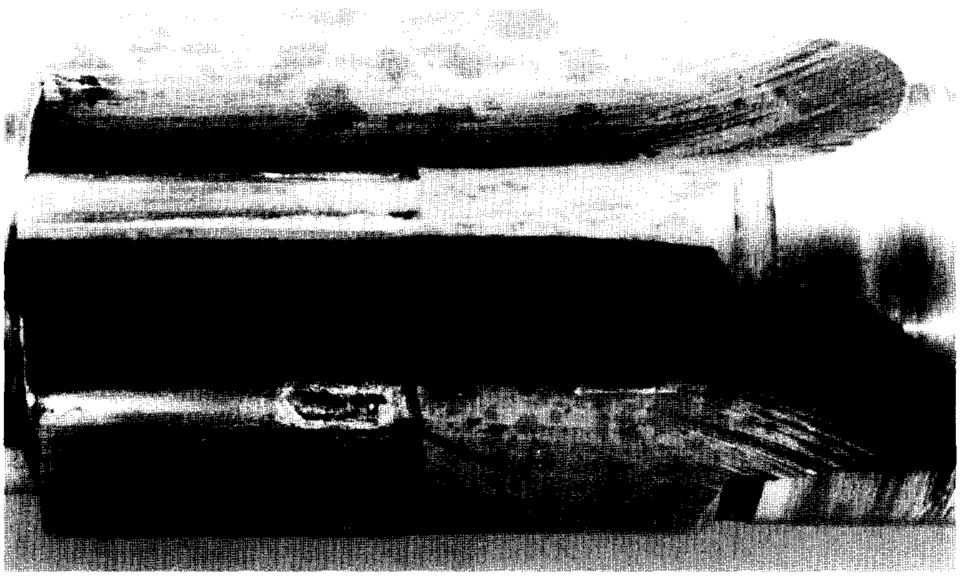


Fig. 5. Severe pitting in the dedendum of the driving gear of a lever hoist. Pitting initiated at the lowest point of single tooth contact.

effectively by ensuring that correct lubrication conditions are maintained. Furthermore, it has been shown that sliding–rolling damage can be minimized by achieving a surface hardness on the matching bodies greater than HRC 60 [4]. Retained austenite, at levels of 10–20%, in the case-hardened layer also minimizes the extent of contact fatigue since this microstructural constituent deforms plastically to form larger contact areas, and hence lower contact stresses. However, austenite reduces the fatigue strength of the material, and can therefore introduce other deleterious effects.

5. SPALLING

Spalling is defined by the *ASM Metals Reference Book* [7] as "the cracking and flaking of particles out of a surface". It refers to the formation of large and deep pits on contacting surfaces, which significantly reduce the load-carrying capacity of components. The pits themselves act as stress concentrations which may lead to other modes of failure, while the material lost from the surface can cause damage elsewhere in the component. Two mechanisms of spalling have been identified [5].

Firstly, spalling may occur as a continuation of pitting resulting from rolling or sliding–rolling contact fatigue. In some instances, the cracks initiated by these mechanisms will propagate into the material, and ultimately result in the loss of large pieces of metal from the contact surface. An example of this is given in Fig. 6, which shows severe spalling which occurred as a result of rolling contact fatigue pitting along the pitch-line of a helical gear. In some cases, pitting will start at one point, and progress outwards and upwards along the tooth profile to form what is known as the "cyclone" effect [3]. This is clearly shown in Fig. 7 for the case of a small helical gear from an automatic gearbox [8].

In the second mechanism of spalling, also known as "case crushing" or "sub-case fatigue" [4], fatigue cracks initiate at the metallurgical notch formed between the hardened case and core. Since this interface is usually very deep, the depth and size of the pits formed are significantly larger than those encountered in rolling or sliding–rolling contact fatigue. Figure 8 shows a spur gear in which large, deep pits have formed along the entire active flank as a result of sub-case fatigue [9]. The mechanism of crack initiation is the same as in the other modes of contact fatigue. Since this type of spalling is essentially due to the disparity in the mechanical properties of the case and core,

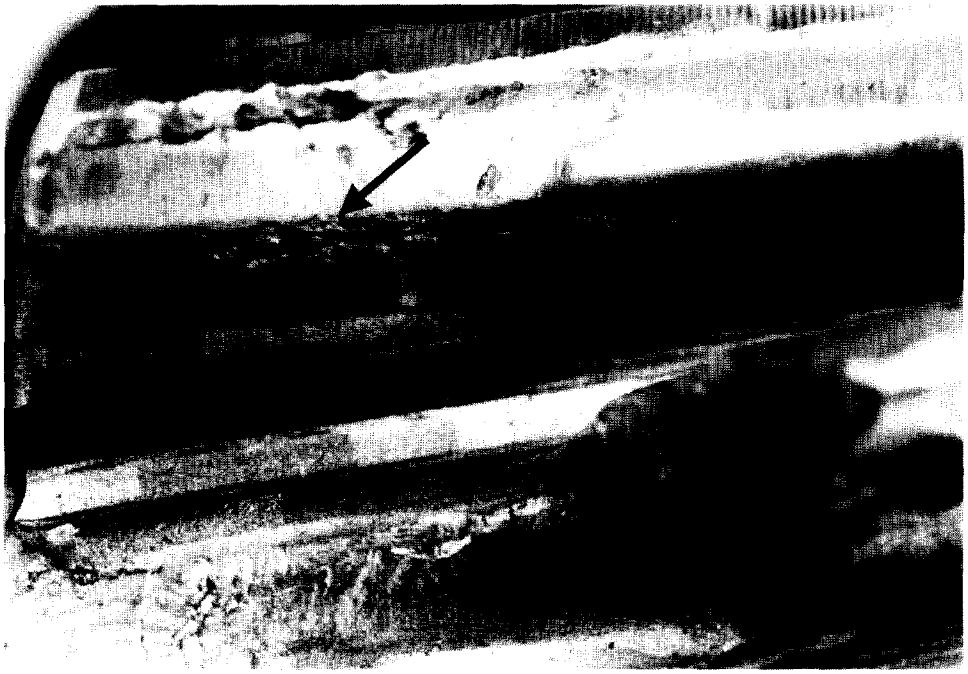


Fig. 6. Severe spalling along the pitch-line of a helical gear resulting from rolling contact fatigue.

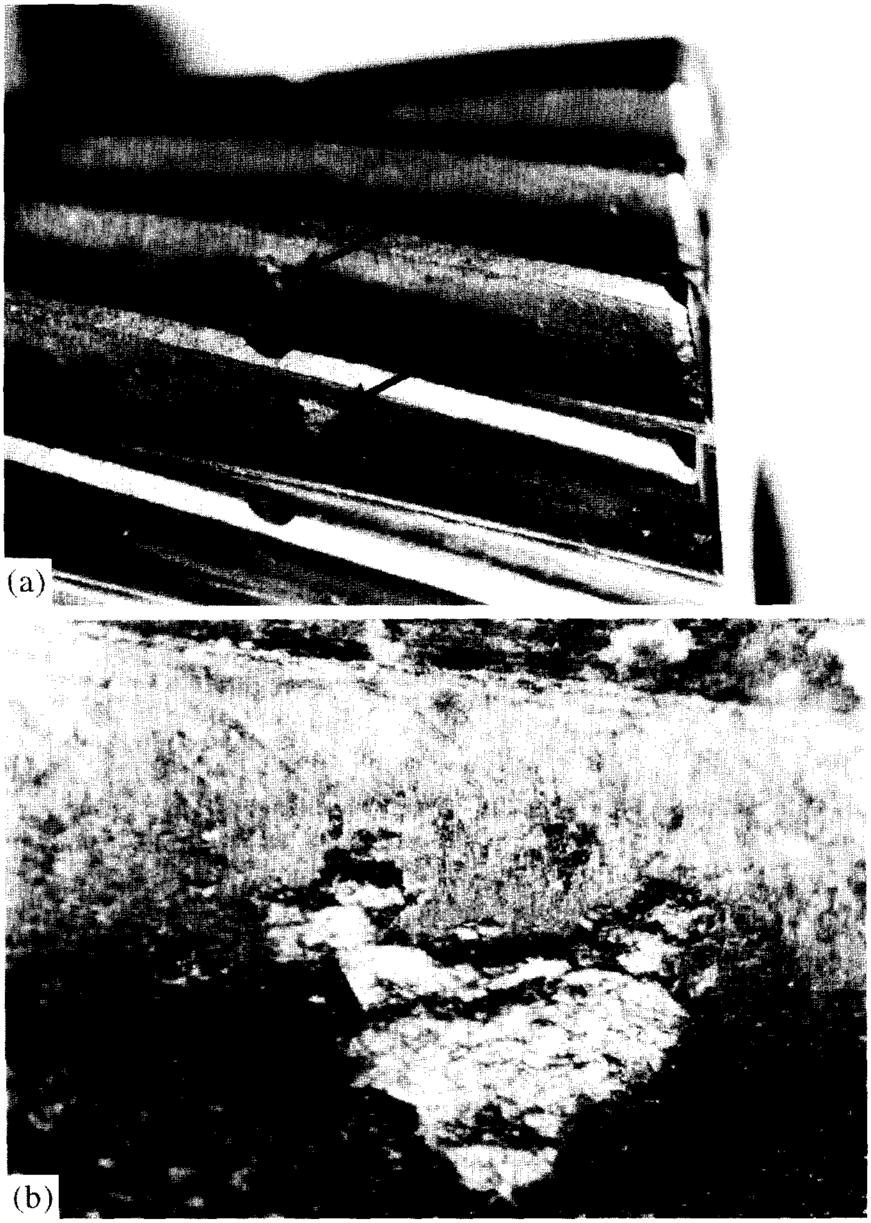


Fig. 7. (a) Active flank of a helical gear showing the "cyclone" effect, and (b) high-magnification photograph of the same area showing how pitting has extended upwards and outwards.

Fig. 8. Sub-case fatigue or spalling on the active flank of a spur gear.

increasing the hardness (or strength) of the core through material selection or heat treatment can effectively reduce the incidence of spalling. Alternatively, by increasing the depth of the case, the core–case interface can be moved to a position of lower stress.

6. SUMMARY

Surface contact fatigue is the most common cause of gear failures. Three forms of surface contact fatigue damage have been identified, depending on the stress distribution at and near the surface. From the preceding sections, the characteristics of each type of failure can be summarized as follows:

(a) Rolling contact fatigue occurs along the pitch-line of gear teeth and leads to the formation of microscopic pits.
(b) Sliding–rolling contact fatigue occurs away from the pitch-line, but predominantly in the dedenda of gear teeth, where negative sliding conditions prevail. This form of damage leads to the formation of surface pits which may act as initiation sites for other modes of failure.
(c) Spalling refers to the formation of large, deep pits on contacting surfaces, and is either a continuation of rolling or rolling–sliding contact fatigue damage, or may be due to cracking at the case–core interface.

A number of real, practical examples of gear failures have been used to illustrate the various types of contact fatigue damage.

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REFERENCES

1. Fernandes, P. J. L., *Engineering Failure Analysis*, 1996, **3**(3), 219–225.
2. Shigley, J. E., *Mechanical Engineering Design*, 1st metric edn. McGraw-Hill, Singapore, 1986, pp. 78–80.
3. Alban, L. E., *Systematic Analysis of Gear Failures*. American Society for Metals, Metals Park, OH, 1985, pp. 94–106.
4. Wulpi, D. J., *Understanding How Components Fail*. American Society for Metals, Metals Park, OH, 1985, pp. 183–204.
5. ASM Metals Handbook, *Failure of Gears*, Vol. 10, *Failure Analysis and Prevention*, 8th edn. American Society for Metals, Metals Park, OH, 1975, pp. 507–524.
6. McDuling, C., *Test Report*. Advanced Engineering and Testing Services, CSIR, 1996.
7. *ASM Metals Reference Book*, 2nd edn. American Society for Metals, Metals Park, OH, 1983, p. 67.
8. Heyes, A., *Failure Analysis Report*. Advanced Engineering and Testing Services, CSIR, 1996.
9. James, A., *Failure Analysis Report*. Advanced Engineering and Testing Services, CSIR, 1994.