THE INTERFERENCE MICROSCOPE - HIGH ACCURACY IN ENGINEERING MEASUREMENT

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SUMMARY

The principles and method of interference microscopy for the inspection of metal surfaces are briefly reviewed. It is shown how the interference phenomenon may be used for the formation of a contour map of the surface under examination, and how this map can be quantitatively interpreted. Examples of the application of the technique to the assessment of surface profiles of engineering parts are included and the range of applicability (from 10^{-2} *-* $2.5 \cdot 10^{-5}$ *mm) is emphasized. Examples include the assessment of the roundness of ball bearings, the measurement of the thickness of thin films, the degree of surface roughness associated with fine machining operations, and the assessment of the deformation around the tip of a growing fatigue crack. Comments on the advantages and disadvantages of the technique are listed.*

1. INTRODUCTION

Interference microscopy can provide a relatively low-cost method of making highly accurate measurements of surface profiles having a step height in the general range from 10^{-2} - 2. 10^{-5} mm. Although very costly instruments are on the market, measurements can be made using rather simple low-cost accessories to the metallurgical microscope. The technique may be applied to any surface that has a reasonably good reflectivity and which can also be examined by a microscope. Even critical surfaces of large units can be examined by the use of plastic replicas, a technique that is also applicable to inaccessible surfaces such as bores.

Although the principles of light interference have been known for many years, it is only relatively recently that interference microscopy has been developed as a science in its own right, principally by Tolansky [1], [2], [3], and this in turn has led to the development of a number of commercial instruments.

Because the technique has an upper limit of applicability - it cannot easily cope with step heights above 0.01 mm - it can be regarded as complimentary to other means of measuring surface roughness, providing a convenient means of extending to superfine finishes the range obtainable by say, the LVDT (linear variable differential transformer) type of probe. It is particularly suitable when very fine surface irregularities must be assessed quantitatively.

Using a refinement of the technique under particularly favourable circumstances, Tolansky [3] has reported observing step heights of only two atomic diameters. Fortunately this type of measurement is outside the bounds of engineering requirements, but step heights of say 50 times this can be determined quite straightforwardly.

The method is attractive because it involves no contact with the surface under examination and is therefore non-destructive. The technique can be used for biological samples in transmission as well as opaque samples in reflection. The present discussion is limited to the latter case.

2. HISTORICAL AND PRINCIPLES

Interference microscopy depends on the effects produced when light waves combine. The phenomenon of interference was reported by Robert Hooke in 1665 when he described the appearance of coloured rings (Newton's rings) formed when a convex lens lies on a flat reflecting surface, but it was only at the start of the nineteenth century that Thomas Young satisfactorily explained the effect through the wave theory of the propagation of light.

Young showed that when light from a single source passes through two closely-spaced parallel slits and falls on a screen, the image produced has a single bright band at the centre with alternately dark and light bands on either side, Figure 1.

Young argued on the basis of the wave theory of light propagation that the light coming from the two slits was 'coherent', that is, the crests and troughs of the light wave from one slit corresponded with the crests and troughs of the wave coming from the other slit. Then, where the crests or troughs reached the same point on the screen at the same time, they produced a bright band (constructive interference or reinforcement). Similarly, when the light from one slit had to travel a little further than the light from the other slit, a trough corresponded with a crest and the two waves cancelled each other out giving a dark band (destructive interference). In this case the path difference for the two waves was half a wavelength. When the path difference reached one full wavelength, a bright line was formed and so on.

Since the time of Young's experiment the principle of interference of waves has been used for a remarkable range of measurements requiring both high sensitivity and accuracy, both of which are inherent in the method. These applications include:

(i) The attempt to measure the 'aether drift' by Michelson and Morley in 1887. (The result of this experiment formed one of the starting points for the theory of relativity).

(ii) The measurement of the diameter of stars.

(iii) Evaluation of gas flow around aerodynamic models.

(iv) Standardization of the length of the meter.

(v) Assessment of the nature of surface contours.

Details of some of these experiments as well as others are given by Tolansky, [1].

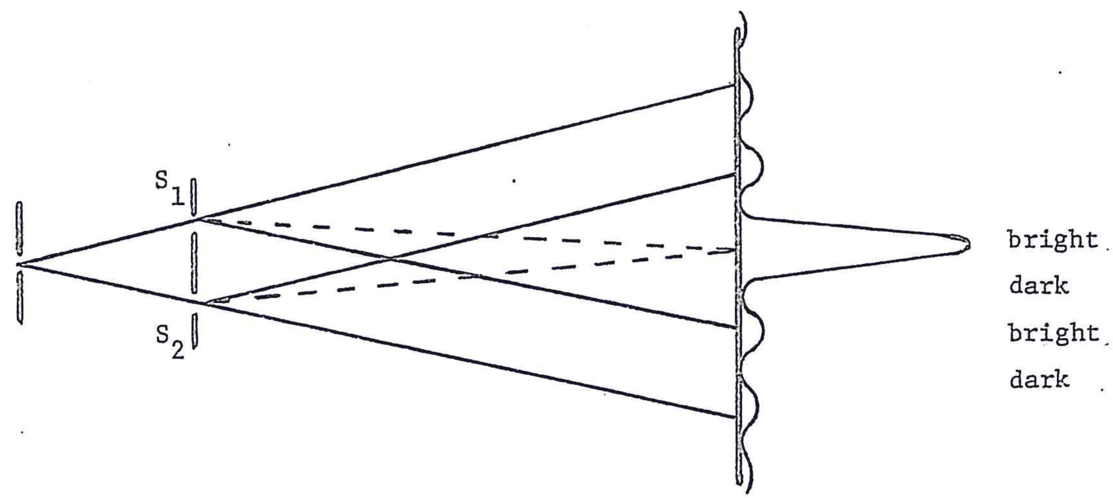


FIGURE 1: YOUNG'S EXPERIMENT DEMONSTRATING THE INTERFERENCE OF COHERENT LIGHT WAVES FROM TWO SLIT SOURCES S_1 AND S_2. IMAGE INTENSITY IS SHOWN SCHEMATICALLY AT RIGHT

3. EXPERIMENTAL ARRANGEMENTS

The arrangement due to Michelson shows the interferometer in its simplest form, Figure 2. It consists of a light source S in front of which is a beam splitter B, usually a half-silvered mirror which allows part of the light to pass through directly and part to be reflected. Similar mirrors are commonly used in the illuminating systems of metallurgical microscopes. The two beams pass back along the same paths by reflection at optically flat mirrors M_1 and M_2 placed at right angles to the beams. The beams recombine at the half-silvered mirror and interference fringes are produced at this point. The fringes are observed from H. Since the fringes are produced by the interaction of two beams, this arrangement is called a two beam interferometer.

In order to adjust the relative path lengths to M_1 and M_2 one of the mirrors is mounted on a carefully machined slide, and the angle of both mirrors can be adjusted by three screws.

If a reflecting specimen whose surface profile is to be examined is substituted for one of the mirrors, the height differences of the surface will lead to a fringe pattern caused by the differences in optical path length. Within the sensitivity of the method, this fringe pattern contains all the information about the contours of the surface.

For the examination of metal surfaces the two beam system designed by Linnik (1933) is particularly useful. Examination of metal specimens often requires high magnification (500x - 1000x) which in turn means that the objective lens of the microscope must be very close to the specimen surface (often less than 1 mm). The Linnik system, Figure 3, uses a beam splitter and a pair of very closely optically matched microscope objectives, one facing an optically flat mirror, the other the surface under examination. In this way, interference fringes can be obtained even at the highest magnification of the microscope when using oil immersion, providing that the objective lenses are optically matched. It is this requirement that makes microscopes built according to the Linnik system particularly expensive. Control of path length, and hence the orientation and spread of the fringes seen in the microscope is achieved by tilting and rotating the glass blocks G_1 and G_2 behind the objective lenses. This is equivalent to adjustment of the position of the mirrors.

Other interference attachments are available for mounting on standard metallurgical microscopes, but only some of these, that due to Watson, incorporate the ability to adjust fringe spacing and orientation, a most important property for surface contour examination.

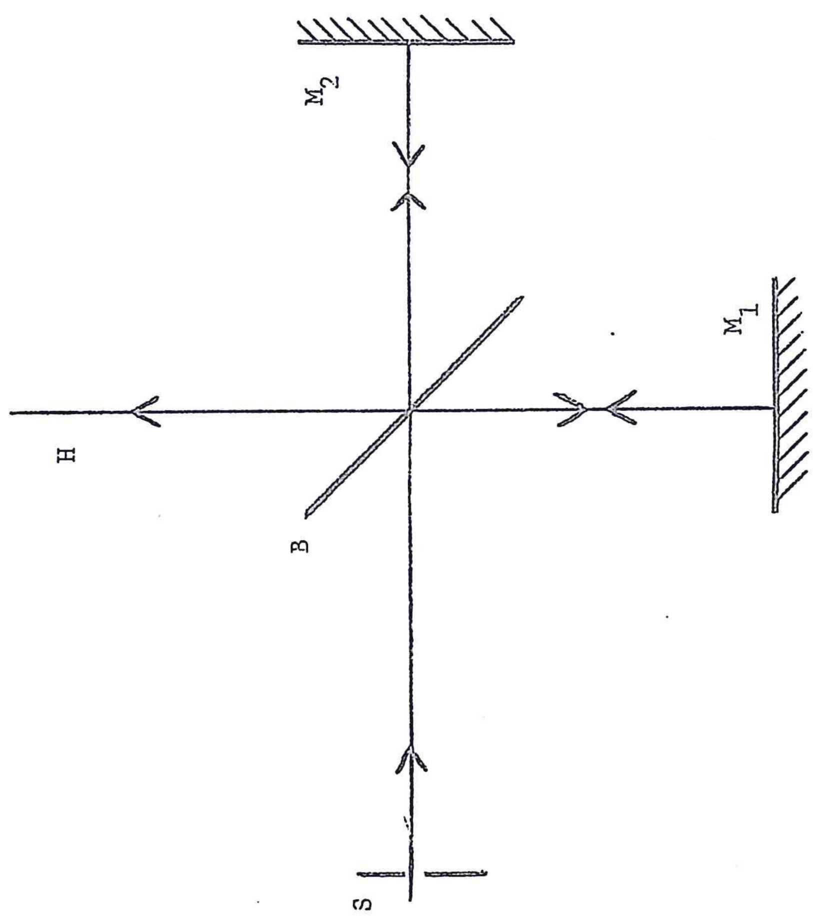


FIGURE 2: MICHELSON'S TWO BEAM INTERFEROMETER. LIGHT SOURCE S, BEAM SPLITTER B, ADJUSTABLE MIRRORS M_1 AND M_2 AND OBSERVER AT H

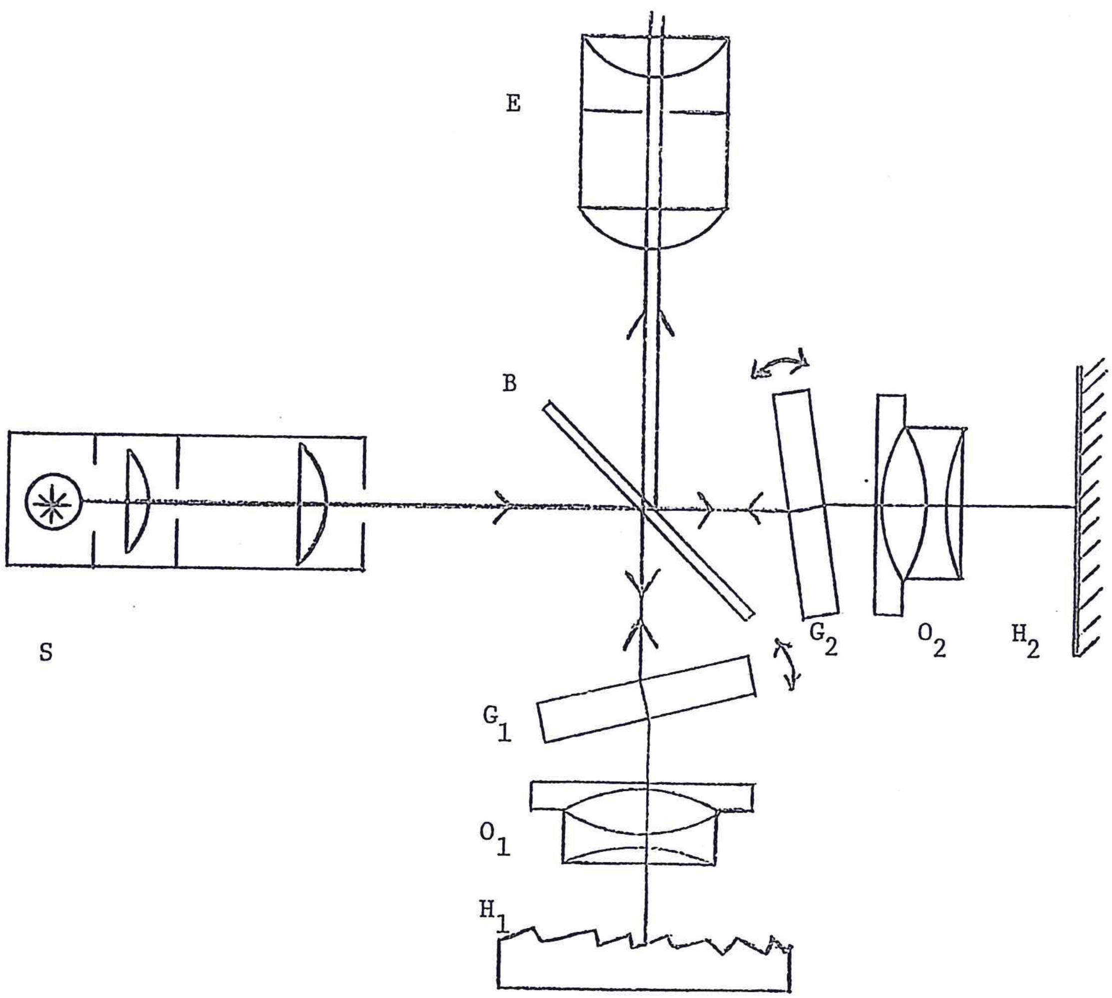


FIGURE 3: TWO BEAM INTERFERENCE MICROSCOPE, LINNIK SYSTEM. LIGHT SOURCE S, BEAM SPLITTER B, FRINGE ADJUSTMENT BLOCKS G_1 AND G_2, OPTICALLY MATCHED OBJECTIVES O_1 AND O_2, SPECIMEN M_1, REFERENCE MIRROR M_2, MICROSCOPE EYEPIECE E, (4).

The system is shown in Figure 4. The essential features of the Michelson interferometer can be recognised, the light source S, the beam splitter B, the adjustable mirror M_1 and the specimen acting as the second mirror M_2.

Because the whole unit is positioned between the objective lens of the microscope and the specimen, the working distance of the objective must be long, and the use of the Watson interferometer is limited to lenses with relatively low magnification, up to 20x for an objective. The Watson instrument offers the opportunity for measurement of surfaces using the interference technique at low cost. On the other hand relatively low light intensities and the inherent low magnification of the system are limiting factors.

4. LIGHT SOURCES

Interference microscopes can be used with either white or monochromatic light produced from a filter or a monochromatic light source. The wavelength range of visible light is approximately 4000A ($4 . 10^{-7}$ m) blue to 7000A ($7 . 10^{-7}$ m) red. The use of a monochromatic filter allows a narrow wavelength band to pass, though with some loss of intensity. A wavelength in the green range at about 5400A is often chosen.

When monochromatic light is used to produce fringes, the whole field of view will be covered uniformly with alternating black and light bands, each line corresponding with a contour line on the sample surface where the light path difference is 1, 2, 3 ... n wavelengths. In the two beam interferometer the dark and light bands will be of equal width.

If white light is used, a band of coloured fringes is produced with a dark central fringe, and the sharpness of the fringe edges is lost. Despite this lack of sharpness coloured fringes are very useful. If the surface contains a vertical step, fringe continuity is lost across the step, and when using monochromatic light the magnitude of the displacement of the fringes is impossible to assess. The amount of the displacement can be determined using white light since the position of the central dark fringe on either side of the step can be distinguished.

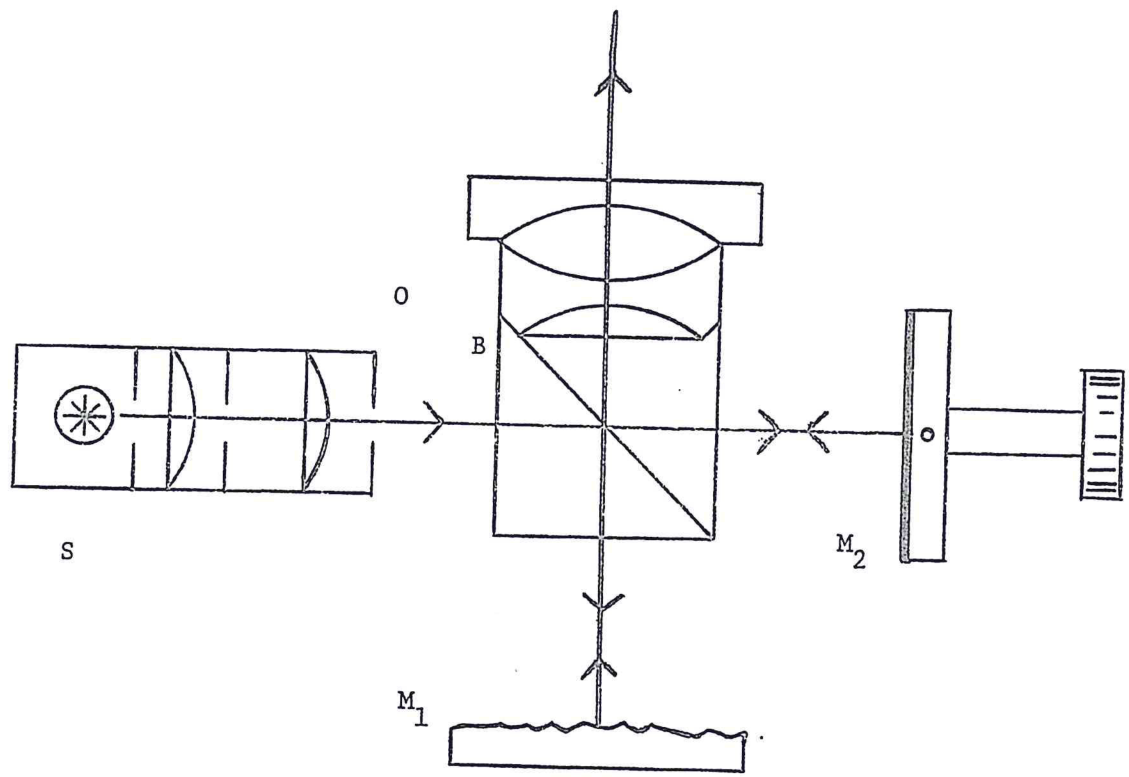


FIGURE 4: WATSON TWO BEAM INTERFERENCE ATTACHMENT HAS ITS OWN LIGHT SOURCE S AND REFERENCE MIRROR M_2. THE SPECIMEN IS M_1 AND THE MICROSCOPE OBJECTIVE O, (4)

5. MULTIPLE BEAM INTERFERENCE

Using the two beam technique the width of light and dark fringes is equal and the variation of light intensity across the fringes is as $\cos^2$, Figure 5a. Using the technique called multiple beam interferometry, Tolansky [1] has shown that very narrow fringes can be produced, and for this case the intensity across the fringes varies as shown in Figure 5b. Because of their narrowness and the rapid variation in light intensity at their edge, these fringes are inherently much more sensitive as a means of determining small surface height differences. The origin of the variation in fringe intensity and factors affecting it is discussed by Tolansky [1].

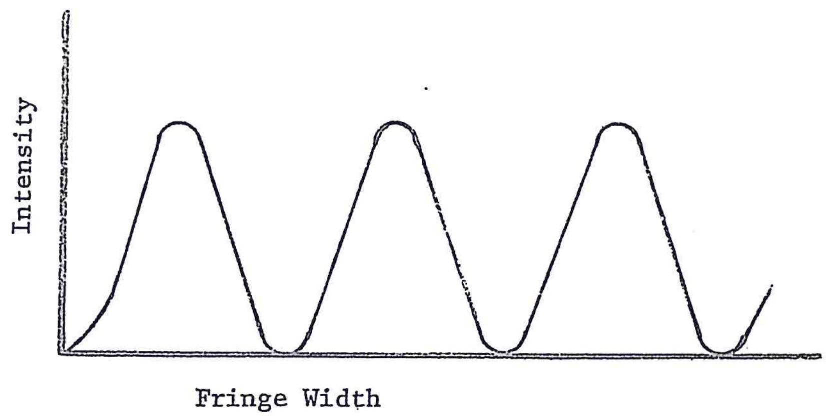
Briefly, multiple beam interferometry requires the establishment of an 'optical wedge' formed by the specimen surface and a half-silvered optical flat in close contact with, but at a small angle to, the specimen surface. In microscopy the optical flat must be introduced between the objective lens and the specimen, and therefore has the disadvantage that surface magnifications are relatively low. Further, the experimental conditions for the formation of fringes are a good deal more difficult to achieve than for the two beam technique, and may include the evaporation of a reflecting (silver) film onto the surface to be examined in order to increase its reflectivity [4]. Nevertheless, Tolansky has shown that step heights in the order of tens of atomic spacings can be determined easily by multiple beam interferometry, and claims the resolution of steps only 5A high in very favourable circumstances, [3].

6. READING THE FRINGE PATTERN

A surface profile and some possible fringe patterns formed by monochromatic light are shown schematically in Figure 6. In practice fringes are more irregular than shown and reveal fine detail particularly at the edges where the light intensity changes rapidly. Some fringe orientations are more helpful than others in revealing the details of profiles, Figure 6b and 6c, although each pattern is produced by the same contour variations. Note also the inherently greater sensitivity of multiple beam fringes resulting from their extreme narrowness.

Since the distance between fringes on a surface as well as their orientation can be varied by adjusting the microscope, no useful information is given by such observations. It is the displacement of a fringe relative to itself that is of interest. Although the fringe pattern on a surface may change it will, in principle, always contain information on the surface contours. Fringes are displaced in one sense for an increase in surface height and in the opposite sense for

A)



B)

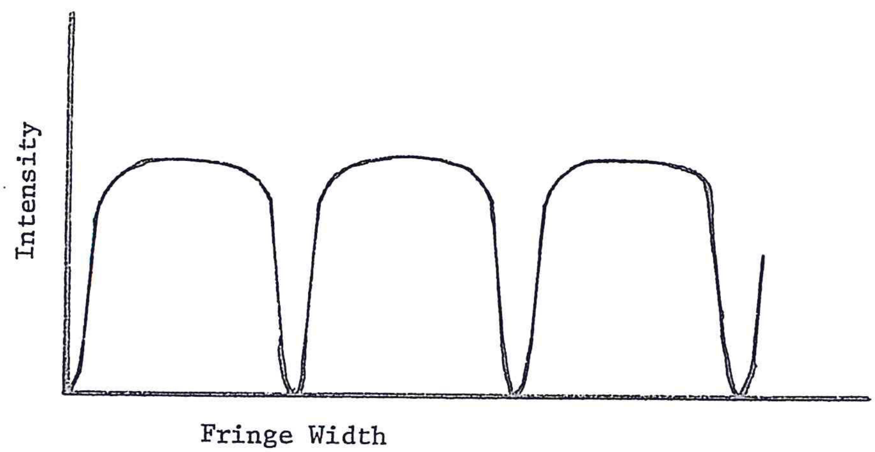
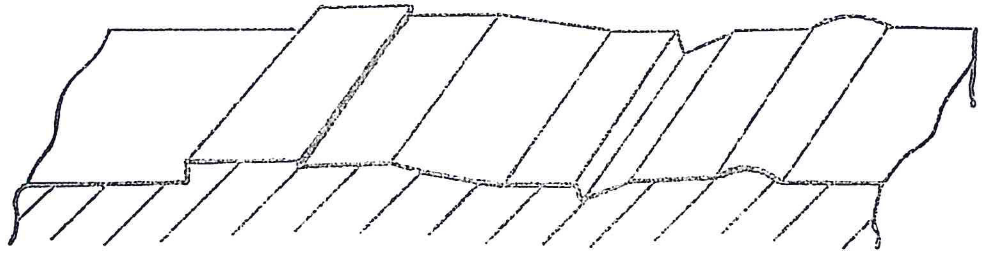


FIGURE 5: VARIATION OF LIGHT INTENSITY ACROSS FRINGES FOR

A) TWO BEAM CASE

B) MULTIPLE BEAM CASE

A)



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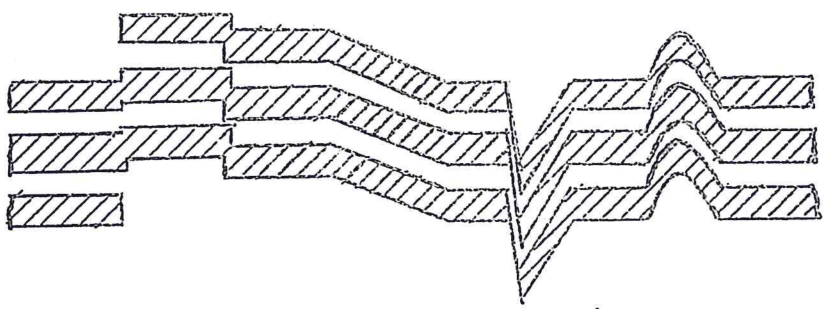

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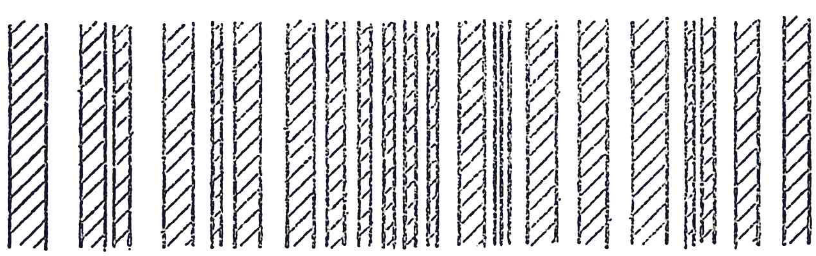

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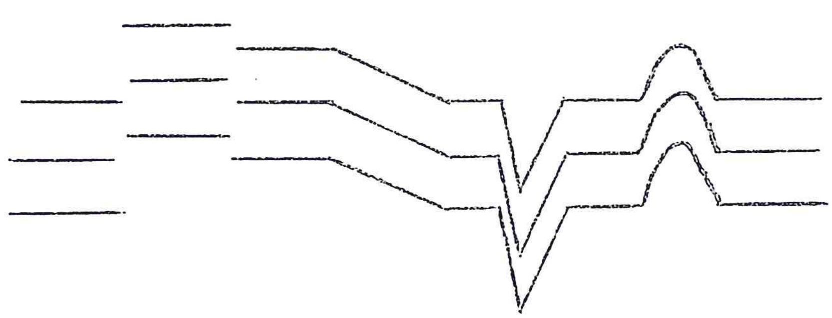

FIGURE 6: SCHEMATIC OF SURFACE PROFILE A) AND POSSIBLE ASSOCIATED FRINGE PATTERNS:

B) TWO BEAM CASE, FRINGE NORMAL TO FEATURES
C) TWO BEAM CASE, FRINGES PARALLEL WITH FEATURES
D) MULTIPLE BEAM CASE, FRINGES NORMAL TO FEATURES

a decrease in height. When examining a fringe pattern it is necessary to determine the sense of the fringe displacement. The nature of the surface may be such that the sense of the displacement is unequivocal, for example, when viewing etch pits or the steps produced by a plated film. Alternatively the microscope may be brought slightly in and out of focus and the direction of displacement of the whole fringe pattern then reveals the sense of the displacement.

In order to interpret the fringe pattern quantitatively it is necessary to measure fringe displacement. This is best done photographically since a permanent record of conditions is obtained. Measurements can be made at the microscope if a measuring eyepiece is available. Interference will occur, changing a bright fringe to a dark fringe when the optical path difference changes by half the wavelength λ of the light used. Since the optical path is measured from the beam splitter to the specimen and back again, a height difference of $\lambda/4$ on the specimen surface will change a dark fringe to a light fringe. Thus successive dark fringes correspond with successive contours of spacing $\lambda/2$.

Specifically, Figure 7 represents the fringe pattern across an ideal sloping step. If the wavelength of the light used is 5400A, the step height t is given by

$$t = h\,\lambda/d = 50.9 \times 0.00054/20.7 = 0.00133 \text{ mm}$$

where d is the displacement for one wavelength on the fringe pattern (every second dark or light fringe) and h the displacement of one fringe at the point of measurement.

If the magnification of the region is known, say 100x in this case, the angle of the step can easily be calculated:

$$\text{Step angle} = \tan^{-1} h\,\lambda/d\,w = \tan^{-1} (0.00133/0.32) = 0.24^\circ$$

where w is the actual width of the step in mm. It will be noticed that the fringe pattern greatly exaggerates surface irregularities. At one and the same time this gives the technique its great sensitivity but also limits the size of surface asperities that can be evaluated.

7. ENGINEERING APPLICATIONS

Interference microscopy is applicable to any situation in which the height of surface features is to be assessed, or in which the degree of regularity of form of a surface is required. Four examples will be briefly considered.

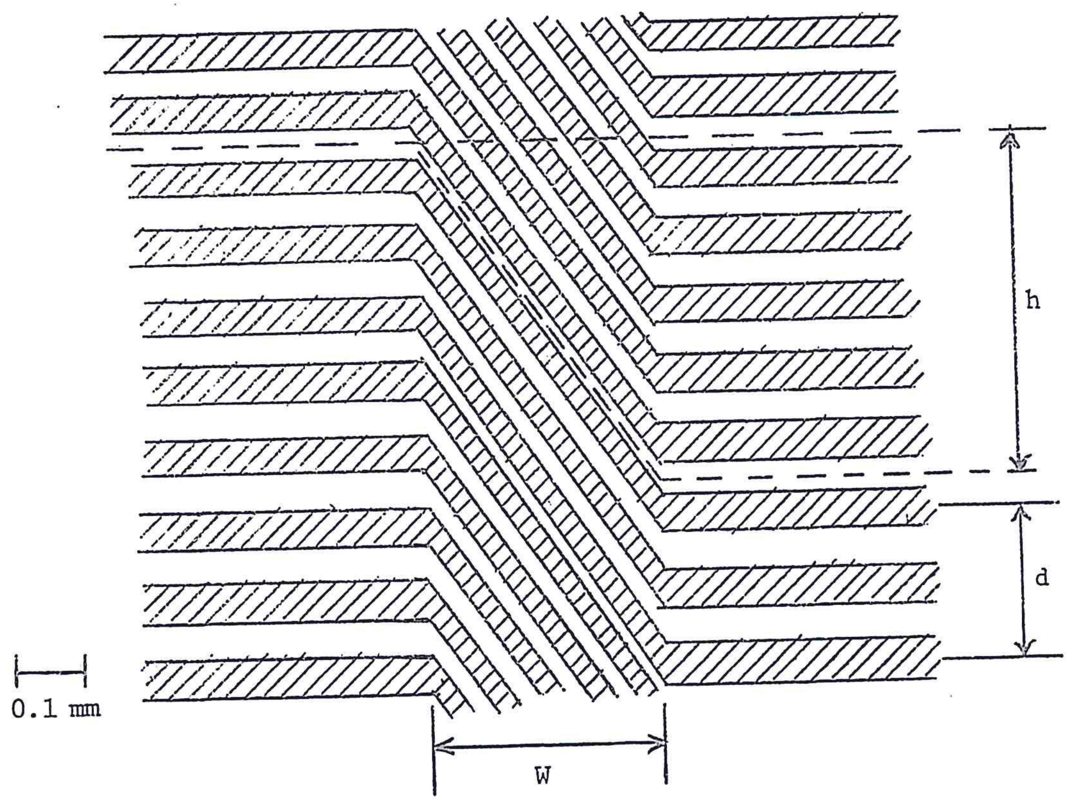

FIGURE 7: IDEALISED TWO BEAM INTERFERENCE PATTERN ACROSS A SLOPING STEP

7.1 The Roundness of Ball Bearings

The degree of roundness of ball bearings may be assessed by arranging the fringe pattern so that it forms as concentric circles centred on the field of view. Any variation of the fringes from a circular shape will indicate lack of roundness. The degree of this out-of-round can be assessed by comparison of the determined profile with an ideal. This is best done photographically. Such a case is shown in Figure 8. Where the inter-fringe spacing is not constant, as here, an appropriate value would have to be determined by measurement and interpolation.

7.2 Film Thickness

This case is essentially that of the assessment of the step height on a surface. In obtaining a sample for measurement care should be taken to obtain a sharp step so that the 'level' of the top and the bottom of the film may be determined with confidence. If the step is sharp, the fringe displacement should be assessed with the aid of white light since it may not be possible to follow the path of a fringe continuously across the step. Examination under the microscope can be made at a sufficiently low magnification to ensure that the film near the step is typical of the film in general. This will be revealed by the linearity of the fringes near the step.

7.3 Machining Marks

Interference techniques are limited to the assessment of markings due to finishing machining. Turning with a lathe tool reveals typically both a regularity of surface roughness due to successive cuts and also a profile due to the cutting edge itself, [3]. Machining is fairly easy to assess since the finished surface is generally quite reflective. It is not necessary to observe a flat machined surface. On a turned bar fringes would be best arranged to run parallel with the bar axis, and any deviation from straightness is then revealed directly in a displacement of the fringe.

Inaccessible parts may be viewed by a replication technique. A plastic replica of the surface is made by allowing a partly-dissolved film to dry on the surface, followed by examination under the microscope. The general magnitude of fringe displacement maxima would then reveal whether, for example, further machining is necessary.

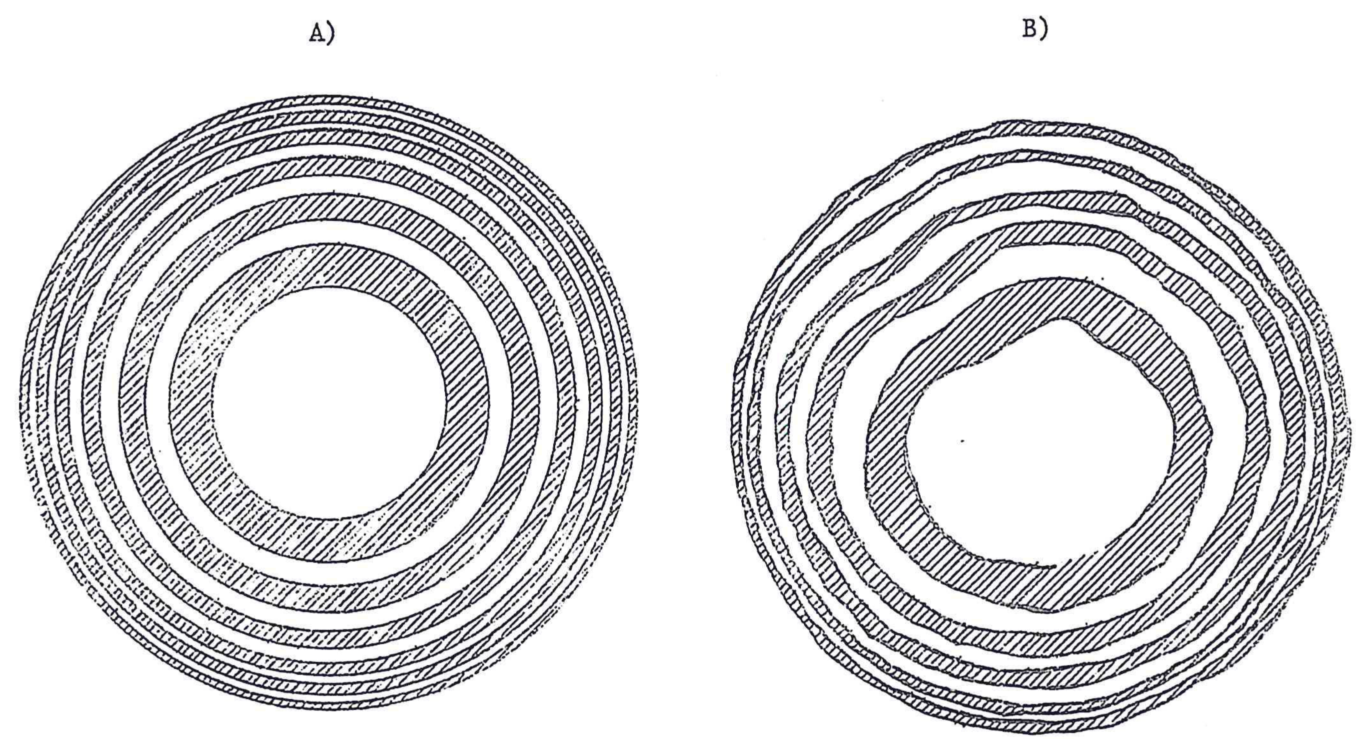

FIGURE 8: SCHEMATIC FRINGE PATTERN FOR A ROUND BALL BEARING A) AND FOR ONE DISTORTED BY OVERLOADING B)

7.4 Crack Tip Deformation

The progress of a growing fatigue crack is accompanied by very localised plastic deformation of the material through which the crack grows. This is true even when crack growth is extremely slow. The nature of the deformation pattern may be quite complex, [5], but if the fringes can be followed continuously, a map of surface displacements can be constructed. Fortunately, analysis to this extent is not usually called for. A simpler pattern for the plastically deformed region round a fatigue crack consists of a valley with progressively steeper sides and a rounded base through which the crack grows, [6]. The fringe pattern exaggerates the apparent depth of the valleys which have a depth approximately one hundredth part of their width.

8. CONCLUSIONS

The advantages and limitations of interference microscopy in engineering measurement may be summarised as follows:

8.1 Advantages

1) The method is very sensitive and highly accurate for the assessment of surface profiles of engineering parts

2) The method is non-destructive, and is applicable to replicas taken directly from the surface to be examined

3) Interference microscopes can have a magnification range from 10x to 1500x so that small non-extended features can be examined

4) The method is applicable to a wide range of metals and non-metals although for direct measurement surfaces must be reflecting

5) Interference adaptors are available which clip on to a standard metallurgical microscope.

8.2 Disadvantages

1) The range of features that can be easily examined is limited at the upper end of the size range at about 10^{-2} mm

2) Interference microscopes equipped for high magnification are expensive.

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