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V-Groove Measurements using White Light Interferometry

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Abstract. White Light Interferometry (WLI) provides a fast and convenient means to measure surface profile. With sub-nanometre resolution and non-contacting operation, WLI is also a promising means to estimate surface roughness parameters. In recent years, however, several articles have concluded that great care must be taken to interpret the output of this type of instrument. For example the measurement of step artefacts often show a systematic error of a few tens of nanometres or so in magnitude, when the step height is less than the coherence length of the source, and surface roughness is generally overestimated by a similar value. Other error sources exist but for the most part systematic errors in WLI are less than, or of the order of, half a wavelength. In this paper, we report for the first time, that WLI should also be used with caution when it is used to measure the profile of V-grooves. We show that an inverted measurement profile with an error magnitude of several hundred microns is possible in this instance. Using a simple ray based model we show that this effect can be attributed to multiple reflections and can have a magnitude. Although, this experiment is somewhat contrived, we maintain that similar discrepancies exist in the measurement of abraded surfaces and discuss the implications of this type of error in the estimation of surface roughness.

Key words: White light interferometry, V-groove measurement, surface roughness measurement, multiple scattering effect.

1. Introduction

White-light interferometry (WLI) is a widely used method for high precision surface measurement[1-7]. Compared with other surface measurement methods such as stylus profilimetry, scanning probe microscopy and phase shifting interferometry, the benefits of WLI in surface measurement are significant. The technique is non-contacting and can be used to measure the profile of delicate membranes or soft materials without risk of damage. Since the light source used in WLI is polychromatic, it has a short coherence length and consequently interference fringes only occur when the path lengths in the interferometer are matched to this tolerance. Consequently, the 2π phase ambiguity that is characteristic of

phase-shifting interferometers[8] is avoided resulting in a virtually unbounded measurement range. Thus WLI is a fast and convenient to measure the surface profile in three dimensions with sub-nanometer resolution in the vertical (scan) direction and sub-micrometer resolution in lateral directions.

Although WLI is clearly a powerful measurement tool, some drawbacks have been reported in the literature. In 1990 Hillmann reported that measurement of a roughness standard by optical methods (a laser focus system and an interference microscope) have significant deviations with the results obtained using the contact stylus method[9]. In recent years, several other concerns have been raised[9-24] that can be summarised as follows:

1. The Batwing Effect: When a WLI is applied to measure step heights, errors have been reported when step heights that are less than the coherence length of the light source [17, 21, 25]. The problem is known as the Batwing Effect, because the shape of the false information.
2. Ghost Steps: When investigating flat substrates, some WLI instruments exhibit so-called ghost steps that appear at a well defined position in the field[19].
3. Slope Dependent Errors: Measurement results can be affected by the slope of the object[12, 17, 19, 20]. The position of ghost steps can also be slope dependent.
4. Materials Effects: Different materials exhibit different phase changes on reflection, and depending on the processing algorithms used these affect the surface height measurement[15, 22].
5. Spatial Frequency (pitch) Effects: The amplitude of periodic structures with square profile are dependent on pitch[24].
6. Surface Roughness. Comparison with stylus and other methods show surface roughness obtained by WLI are over-estimated [9-12, 23, 24].

These effects can be attributed to two main causes; field dependant dispersion in Mirau type objectives[17]; multiple scattering/diffraction effects[25]. Errors of the first kind are instrument dependent and can be mitigated by careful optical design, however, errors resulting from the second source are fundamental to the measurement technique. For the most part errors of the second kind have been reported to result in half-wavelength errors or less. In this paper we report measurements of a known V-groove profile that exhibit gross multiple scattering effects and errors of almost 200 microns in magnitude. Although, this is a extreme case it demonstrates that multiple scattering and diffraction effects deserve further examination.

2. V-groove measurement

A Silicon V-groove specimen with the depth profile shown in figure 1 was purchased. The V-groove was etched into a polished Silicon substrate and has an accurate internal angle of 70.52 degrees defined by the lattice dimensions. A Zygo NewView 5000 White Light Interferometer, fitted with a 50X objective with numerical aperture NA = 0.55, was used to measure the V-groove.

With the top surface of the substrate approximately normal to the optical axis (zero tilt), a typical measurement section is shown in figure 2. At the edge of the field, it can be seen that the top surface of the substrate appears at the expected position. Toward the top of the V-groove walls, the signal quality is poor and the measurement produces noise (in this case a minimum detectable modulation of 1% was set and no filtering or post processing was performed). This again, might be expected because the walls of the V-groove are smooth, and in this case they are inclined at an angle of 54.74 degrees to the horizontal. Rays scattered from this surface are outside the acceptance cone of the objective lens with a (half) angle defined by the NA of $\sin^{-1}$ (0.55) = 33 degrees. However, despite this apparent inability to measure, the V-groove, a good signal is obtained, and an apparently valid measurement is made, at the bottom of the V-groove profile. This measurement deviates significantly from

the known form. We have included an estimate of the V-groove profile as the dashed lines in figure 2. It can be seen that, at the bottom of the groove, the measurements and the known form coincide only at the apex and the measurements show an inverted form (ie a peak rather than a trough).
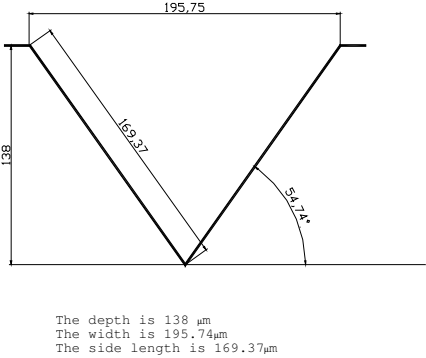

The depth is 138 μm
The width is 195.74μm
The side length is 169.37μm

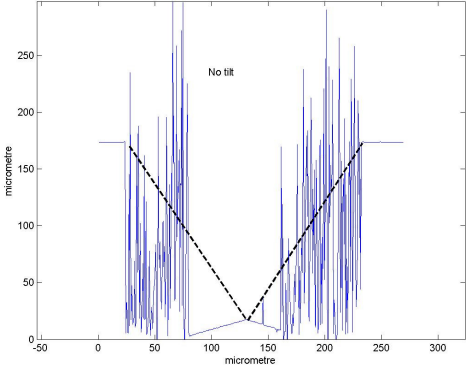**Figure 1. V-groove profile specification**

Figure 2. V-groove measurement profile

3. Analysis

A basic ray analysis readily shows this type of error is due to multiple reflections. Figure 3 shows a cone of rays that appear to come from the measured point but are really reflected from the edge of the groove onto the opposite wall. If the whole round trip is considered, an illuminating ray emitted from the objective will be reflected 3 times by the surface before it is imaged by the objective once again. In essence, current WLI surface measurement algorithms assume erroneously that a single reflection (or scattering event) takes place.
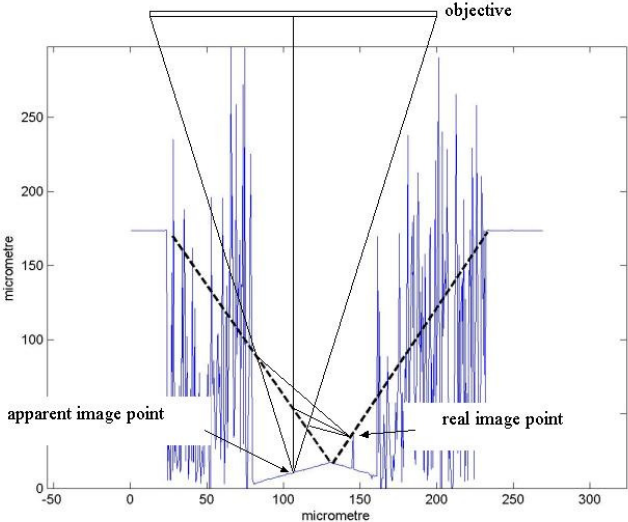

Figure 3. Ray analysis of the multi-reflection between the two side of the V-groove

It is noted that a given ray may or may not be returned within the acceptance angle of the objective depending on the groove angle, image position and the tilt of the object. It can be seen from the results of figure 3 that only image points toward the bottom of the groove reflect light back to the objective. Tilting the object changes the relative efficiency of the objective to collect light from different regions. Figures 4 and 5

show tilts of approximately 21 degrees and 30 degrees respectively showing efficient reflections collected from the right and left hand surfaces respectively. When the sample is tilted at 30 degrees, the profile measured by Zygo NewView has changed dramatically. Here it is noted that the substrate surface at the top left could not be measured since the (single) reflected signal is not within the acceptance cone of the objective. More surprisingly, the substrate surface (top right) is measured to be a plane almost 200 micrometres below its true position.
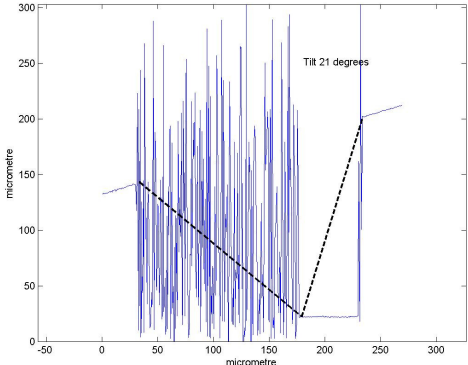

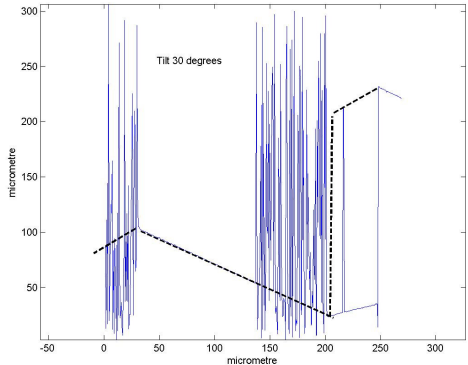**Figure 4. V-groove measurement profile with 21 degrees tilt angle**

Figure 5. V-groove measurement profile with 30 degrees tilt angle

Although, this experiment is somewhat contrived it is noted that a typical machined surface might well consisted of many small V-grooves with a similar profile to that measured here. Figure 4 shows an illustration of the actual and an estimate of the measured profiles that might be expected in such a case. It is clear that an estimate of surface roughness made from data of this kind instrument will produce a substantial over estimate.
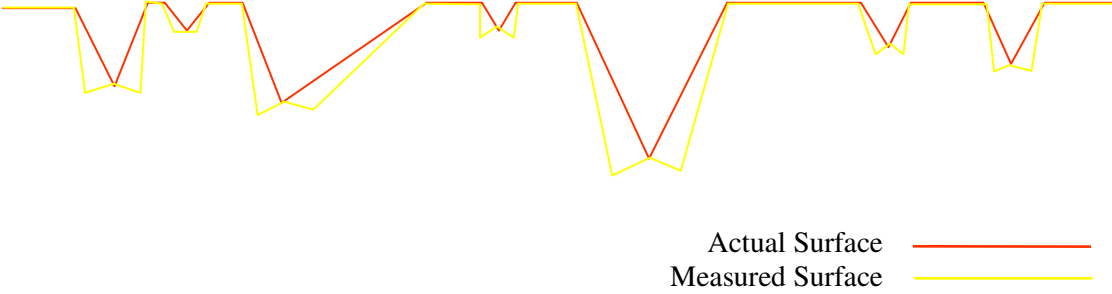

Actual Surface ————
Measured Surface ————

Figure 6. Multiple Reflections/Scattering – Surface roughness over estimation

4. Conclusion

Although WLI is a fast and efficient measurement technique, when examined in detail it exhibits some systematic errors that are attributable to various sources. For the most part these errors are small (less than $\lambda/2$) but are significant with respect to instrument resolution (typically $\lambda/500$). With the exception of ghost steps, the errors documented here are surface related, that is they are only observed with certain surfaces. The errors can, however, be attributed to instrument parameters such as dispersion in the objective and illumination/observation NA.

In addition, we report the possibility of errors of far greater magnitude. In this case we measured a Silicon V-groove with a depth of 138µm and in one instance discovered a depth error of almost 200µm. These errors can be attributed to multiple reflections which are generally assumed to be negligible in WLI. For the particular V-groove geometry studied here we find the returned signal results from 3 surface reflections. It is worth noting that the contrast of the fringes following multiple reflections can be very high and the erroneous measurements cannot be considered as artefacts in the noise floor. However, the presence of errors of this kind can be flagged by taking a series of measurements with different surface tilt and subsequently examining the data for inconsistencies.

Multiple reflection errors have been demonstrated for a single sample of specific dimensions, however, similar errors would be expected for grooves of different depths and angles. A surface roughened with abrasive, for example, will contain many V-grooves with a range of dimensions. Multiple reflections will certainly affect surface roughness measurements and (from the results presented here) would be expected to over estimate the R_a parameter. The over-estimate of surface roughness that has been found elsewhere can therefore be attributed to multiple reflections.

For small scale grooves, with dimensions of a few wavelengths or less, the ray based description of multiple reflections is inadequate and diffraction effects must be taken into account. At this scale it is perhaps better to attribute the errors to multiple scattering rather than multiple reflections. It is also possible to relate the (non-dispersive) Batwing Effect to multiple scattering as measurements around the edge of interest result from the superposition of light scattered from top, bottom and multiply scattered light from the edge itself.

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