ON THE MEASUREMENTS OF SURFACE ROUGHNESS USING LASER SPECKLE

N. El-Kadry, S. G. Yaghmour, A. A. Asriry and K.Adel-Hady**

Physics Dept. King-Abdel-Aziz Univ., K S A

** On leave from Menia University, Egypt*

Abstract

A laser Specklometer has been utilized using an argon ion laser. The near-field speckle patterns have been scanned electronically, analysed and their mean of the normalized average visibilities (MNAV) have been determined. Seventeen samples with different roughnesses, Ra, ranging from 0.05 to 12.7 µm have been prepared and studied. The results showed three distinct regions one of which exhibiting very good correlation between MNAV and Ra as expected theoretically. Discussion of the results indicated the possibility of the extension of the measurable roughness range using speckle technique and the needed creterion are presented. A suggestion of a specklometer for measuring relatively wide range of surface rorghness is presented. It enables measurements of both transparent and opaque samples.

Introduction

The research on speckling phenomena and its application is quite considerable. Its use in scientific and industrial measurements have been investigated theoretically and experimentally, wide spread and still growing [1-6]. One of the fields that received considerable interest is the measurement of surface roughtness. It is well known that the only technique that achieved general usage and wide spread acceptance for measuring surface roughness is the use of mechanical profilometer. This technique measures only the average hight deviations of the surface independent of the correlation width or average slope and the reading is affected by the roughness cut-off. Although it gives reliable results, the stylus often damage the surface under test. Because of these limitations and other draw-backs, substantial efforts have been carried out on optical techniques to replace the mechanical profilometer. Specular reflection [70], light scattering [8], fringe contrast in two-beem interferometry have been used for roughness measurement. In such techniques the roughness must be a small fraction of the wavelength of illumination.

Since the advent of lasers, the speckling phenomena produced by coherent laser radiation received considerable attention and many authors investigated theoretically and experimentally the statistical properties of speckle patterns [9]. Sprague [10] firstly proposed a technique for measurement of surface roughness properties by using speckle patterns produced by quasi monochromatic light. On the other hand Asakura and his colleagues [11-15] has extensively studied the statistical properties of intensity variations produced at the image and diffraction planes of rough surface. The effect of the coherency conditions of illumination and the point spread function of the imaging system was studied.

The present work deals with the effect of surface roughness on the statistical properties of intensity variations of laser speckle patterns. Photographic glass plates were cleaned and polished with emery powders to prepare glass diffusers covering relatively wide range of roughness. The pattern intensity variations has been analysed and their visibilities have been determined. The samples roughness have been determined using profilometer RTH, TALYSURE 5M with diamond stylus. The sampling length taken was 10 mm and the assessment length ranged from 100 to 200 mm.

Intensity Distribution of Image Speckle Pattern :

If z and z' represent the object and image planes respectively, then the complex amplitude, A (z') of the resultant pattern at the observation plane is given by [17].

$$A(z') = \int K(z,z') \cdot t(z) \cdot dz \qquad (1)$$

where K (z, z') is the amplitude spread function characterizing the imaging system. t (z) is the complex amplitude transmission function of the transparent object and can be represented by:

$$t(z) = a(z) \, \mathrm{expi}\,[\phi(z)] \qquad (2)$$

where a (z) and ϕ (z) are he amplitude and phase variations across the object. The latter can be defined through the roughness Ra by ;

$$<\phi(z)> \frac{2\pi}{\lambda}(Ra) \qquad (3)$$

where $<\phi(z)>$ denotes ensemble average. Accordingly, the intensity distribution of the speckle pattern appears at the observation plane is given by

$$I(z') = |A(z')|^2 = \left| \int K(z, z') \,.\; a(z) \,.\, \mathrm{expi}\left(\frac{2\pi}{\lambda}(Ra)\right) dz \right|^2 \qquad (4)$$

This formula shows that the intensity distribution of the speckle pattern is statistical in nature as the spatial form of the rough surface of the object and its value depends on the surface roughness Ra.

Experiment

Fig. (1) shows a schematic diagram of the experimental arrangement used for producing and scanning speckle patterns obtained by illuminating glass diffusers with laser light. The laser beam emitted from an argon ion laser (1) is expanded, spatially filtered and collimated using the lens combination system (2). The size of the laser beam illuminating the object (3) is limited using he limiting diaphragm (4). The formed specle pattern is magnified and projected on the observation plane using the lens system(5). An end-type photomultiplier (6) in conjunction with a pinhole whose diameter is smaller than the speckle size, is used to scan the speckle pattern. The resulted specklograms are displayed on a x-y recorder.

Fig. (2) shows representive examples of the surface profiles of different roughnesses as measured by the profilometer RTH, TALYSURF5M. The sampling length taken was 10 mm and the assessment length ranged from 100-200 mm. Plate (1) shows speckle pattern with high contrast corresponding to an object with Ra = 2.4 μm while plate (2) shows lower contrast pattern due to an object with Ra = 0.06 μm. The drop in the pattern visibility due to very low roughness value is clear in plate (2).

Fig. (3) shows represnetive examples of the recorded specklograms, rate of scan was 2 mm. sec^{-1} and the scan length is about 40-60 cm. The laser power, the photomultiplier voltage and the recorder sensitivity were kept unvried during the scan of the whole diffusers.

Results and Discussion

To find the behaviour of the pattern visibility and the surface roughness of the diffuser with which speckle pattern are utilized, the pattern scan are analyzed and the average visibilities are obtained using he formula:

$$V = \frac{(<I^2 max>)^{1/2} - (<I^2 min>)^{1/2}}{(<I^2 max>)^{1/2} + (<I^2 min>)^{1/2}} \qquad (5)$$

where Imax and Imin refer to maximum and minimum intensities and (.....) denotes an ensamble average.

Fig. (4) shows the variation of the calculated visibility versus surface roughness for Ra< 0.3 μm. curves (a) and (b) were obtained as the power illuminating the object varied from 0.2 W to 0.3 W, while curve MNAV represents the mean of the normalized average

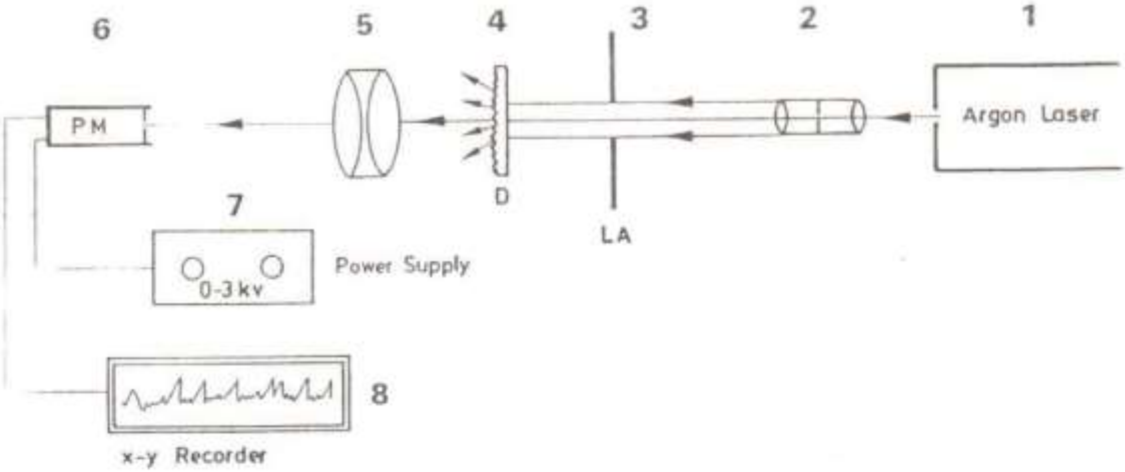

Fig. (1) Block diagram of experimental arrangement used for producing and scanning laser speckle patterns.

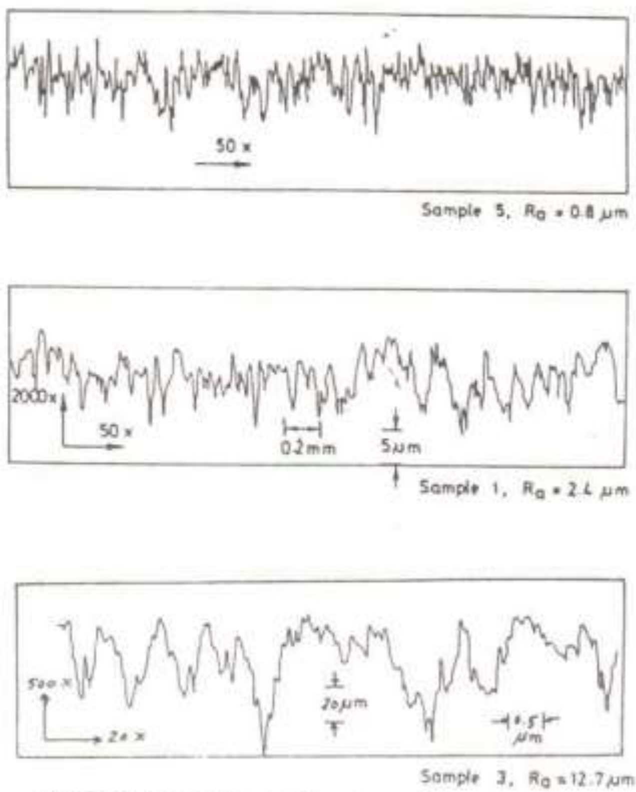

Fig. (2) Surface profile of different samples.

visibility. The calculated uncertainty is found to be less than 0.03. The same behaviour was found by Asakura and his colleagues [16] except for the absolute values with differences ≤ 0.05. This may be due to the fact that they reported their results between speckle contrast versus rms (R_p) instead of speckle visibility versus Ra we used. Also, in their extensive studies, the effect of varying the laser power on the absolute values of the visibility have been not dealt with.

From Fig. (4) it is shown that, for surfaces with Ra ≤ 0.05 μm, the visibility acquires very poor values. This is not surprising since the laser wavelength used is λ = 0.5145 μm and samples with Pa ≤0.05 μm gives rise to wavelets with path differences smaller than λ/2, so that, complete destructive interference no longer occur to give high visibility speckles. By extrapolating the curve from the left, is meets the surface roughtness axis at ~0.03 μm which represents an ordinary optical smooth surface. This means uniform transmitted light and speckle no longer appear.

For surfaces with roughness Ra in the range 0.05 < Ra≤ 0. 2 μm, the visibility varies markedly showing very good proportionality with surface roughness. This permits an adequate range of using laser speckles for measuring surface roughness.

Variation of MNAV with Ra for relatively rough surface, 0.8 ≤ Ra ≤ 12.7 μm, is represented in Fig. (5). It shows that the visibility keeps nearly constant allover the range investigated. This behaviour contradicts with the only published data, according to our knowledge, reported by Sprague [10]. He showed that for 0.5 < Ra < 3 μm, the speckle contrast decrease monotonically as Ra increasing. In fact, such decrease observed by Sprague is not due to surface roughness but rather to the limited coherency of the light he used to illuminate the object. This is expected theoretically since the pattern visibility V drops exponentially with the path difference D between the two interfering waves according to the relation $V = e^{-AD^2}$, where A is a constant depends on the coherency containing the half width of the illuminating light. Therefore no noticeable drop in pattern visibility is

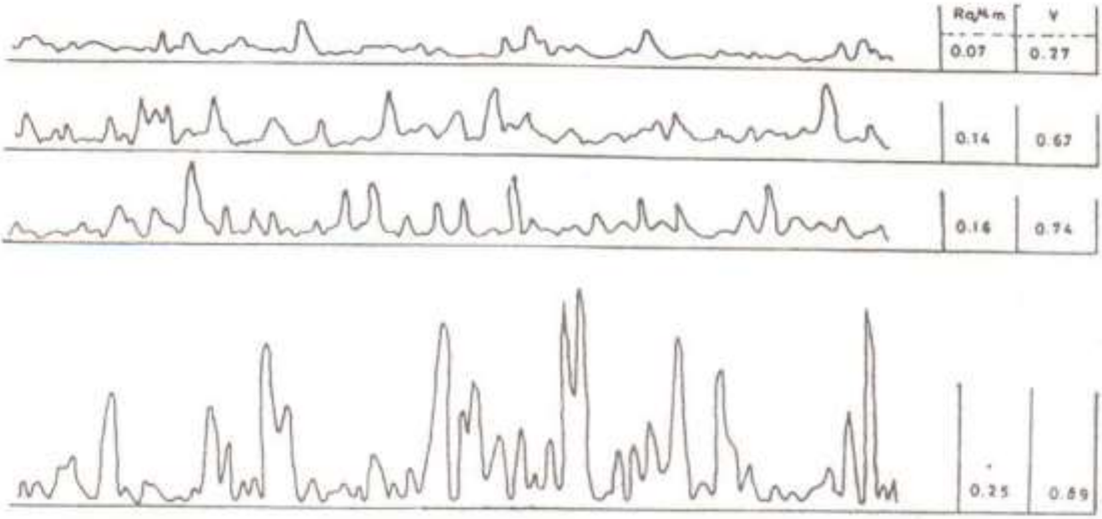

Fig. (3) Speaklograms of different objects. PM valtage = 1000 V
Scan rate. 2 mm/sec

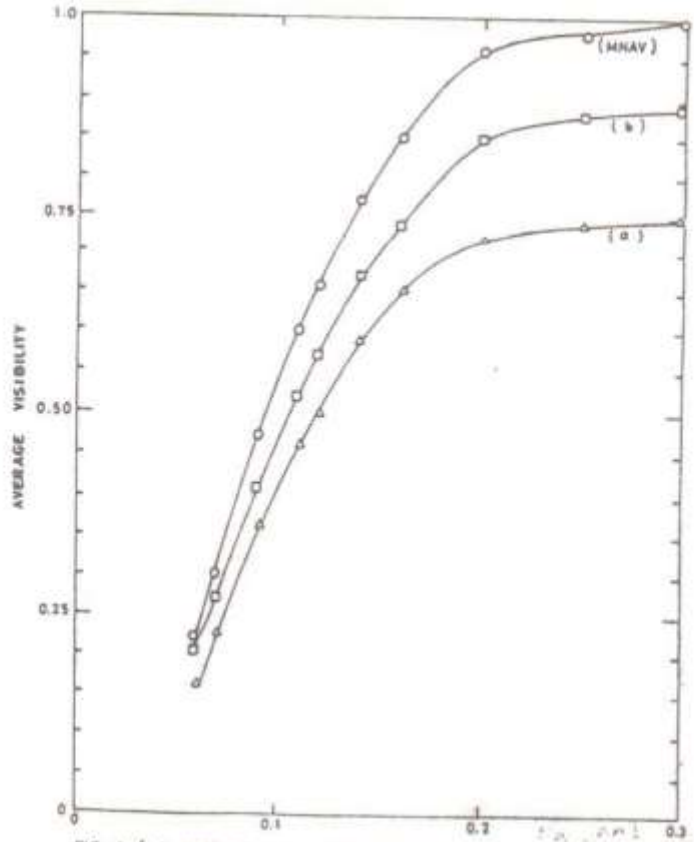

FIG. (4) VARIATION OF AVERAGE VISIBILITY OF THE SPECKLE PATTERN WITH SURFACE ROUGHNESS expected when coherent laser radiation is used even with surfaces of higher roughness values as we proceeded.

Conclusions

Application of laser speckle for measurements of surface roughness have been studied. The results lead to the following conclusions.

1) For surfaces with roughness Ra < 0.05 µm, the path differences between the interfering wavelets are << λ/2,speckles no longer appear and specular reflection technique is quite adequate for measuring surface roguhtness.
2) For surfaces with roughness 0.05 ≤ Ra ≤ 0.20 µm, the pattern visibility varies markedly with Ra and an excellent correlation exists between MNAV and Ra. With this proportionality, measurement of surface roughness is quite possible with high accuracy in this limited region.
3) For surfaces with roughness 0.2< Ra ≤ 12.7 µm, no noticeable variation in laser speckle visibility is observed. Though, speckle technique can be used for evaluating surface roughness in this investigated range or higher by satisfying two criterion:

   a) Using of a quasi monochromatic light to illuminate the rough object, whose degree of coherency is suitable for the roughness range to be measured and causes noticeable drop in speckle visibility. This can be verified with white light source in conjunction with an interference filter.

   b) With the above criteria satisfied and with the aid of few standard diffusers, a calibration curve is preconstructed between MNAV and Ra.

Thus by calculating the mean value of the normalized average visibility of the utilized speckle and satisfying the above two criterion, speckle technique is promising for evaluating surface roughness values, even beyond the range investigated in this work.

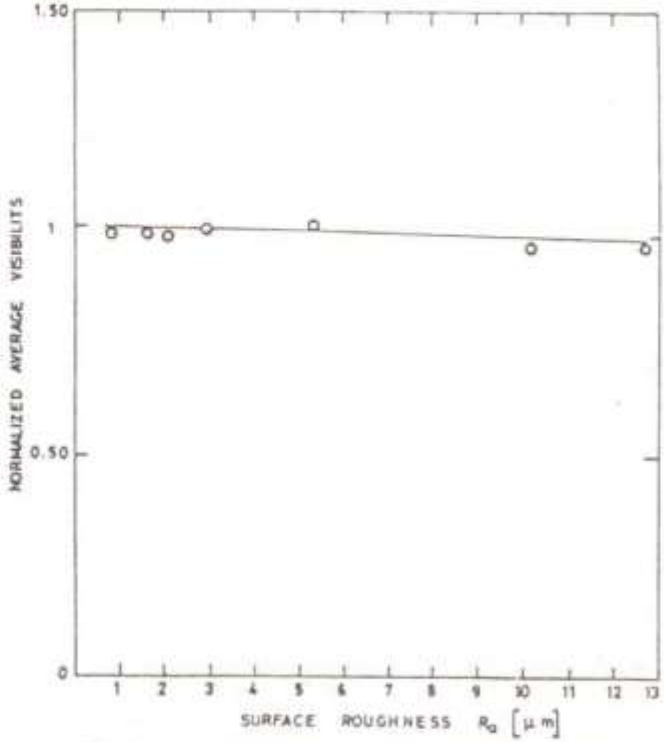

FIG. (5) VARIATION OF THE AVERAGE VISIBILITY OF THE SPECKLE PATTERN WITH SURFACE ROUGHNESS
(SECOND SET)

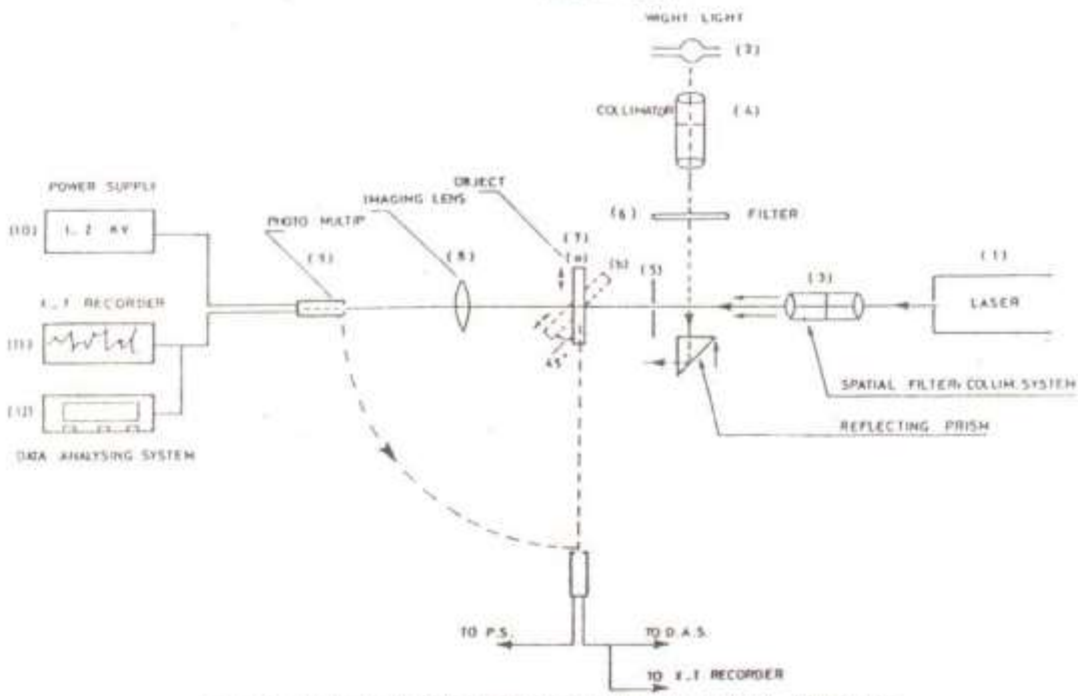

FIG (6) A SUGGESTED SPECKLOMETER FOR MEASURING SURFACE ROUGHNESS

On the basis of the obtained results a suggestion is given for design of a specklometer for measuring surface roughness of both transparent and opaque objects for relatively wide range of roughness values by laser or quasi monochromatic light depending on the range of the roughness values. The measurements can be carried out by laser or quasimonochromatic light e.g. a tungestum-ziroconium lamp, depending on the range of roughness values. This can be achieved by the reflecting prism Fig. (6). The two positioned holder [7] is used for selection for either transparent or opaque objects. The photomultiplier located at the imaging plane and the imaging system (8) can be rotated to be used for the two cases. The detector signal is controlled, analysed and processed by the data acquisition system (12).

References

1) Van Ligten, R. F., J. Opt. Soc. Am., 59, 1545 (1969).

2) Ohtsubo, J.and Asakura, T., Opt.commun. 5, 171 (1972).

3) Francon, M., "Laser Speckle and Application in Optics", translated by H.H. Arsenault (Acad.,N.Y.) (1979).

4) Barakat, N.,Hamed, A. M. and El-Ghandoor, H., Optik, 76 No.3, 102 (1987).

5) Arvind Krumar and Singhok,Appl. Opt. 29, No. 25, 3386 (1990).

6) Barakat, N., Hamed, A. M. and El-Ghandour, H. J. Modern Optics, 37 No. 0 (1990).

7) Birkeback, R.C. Appl. Opt, 10,1070 (1971).

8) Beckamnn, P. and SpizzichensA., "The Scattering of Electromagnetic Waves from Rough Surfaces, Mac Millan, N. Y. (1963).

9) Dainty, J. C., "Laser Speckle and Related Phenomena" Springer - Verlag, Berlin and New-York. (1975).

10) Sprague, R. A., Appl. Opt. 11, 2811 (1972)

11) Fujii, H. and Asakura, T., Opt. Comm. 11, 35 (1974).

12) Fujii, H. and Asakura, T., Opt. Comm. 12, 32 (1974)

13) Fujii,H.and Asakura, T., Nouv. Rev. Opt. 6,5 (1975).

14) Ohtsubo, J.and Askura, T. Novo. Rev. Opt. 6, 189 (1975).

15) Eujii,H., Asakura, T.a nd Shindoy, Opt. comm. 16,68 (1976).

16) Ohtsubo, J.a ndAskura, T. Optik 45, 65 (1976).

17) Erf, Robert K. "Speckle Metrology",Acad. Press, New York (1978).