SYNOPSIS

Surface roughness plays an important role in the functioning of a component. Better surface finishes are sought for better lubrication, wear resistance, appearance, friction properties, etc. Surface roughness / profile characteristics of a component are conventionally measured by mechanical stylus profilometry. This has been the industry standard for many years. However, this method is not suitable for all surfaces, particularly for soft surfaces. Also it is a slow process, and cannot be used in real time. Therefore, proposals were made to use laser scattering techniques for characterising the surfaces. The landmark reference is the monograph by Beckmann and Spizzichino [1963]. Many interesting and useful works are reported on the use of laser scattering from randomly rough surfaces, like ground / lapped surfaces, electro-machined surfaces etc. Also, there is a reasonable amount of work on the study of fibres using optical techniques. In general most of the work on laser scattering from surfaces, understandably, is orientated to provide alternatives to stylus profilometers, which has resulted in quite a few practical instruments. It is mainly aimed at rendering measurement results that agree with the profilometer results, with which industry is familiar. Although this is a prerequisite, one should also look into the possibility of utilising the additional advantage the optical techniques might provide. The laser beam (probe) after interacting with the surface carries detailed information about the surface topography also. In order to extract this information one should have clear understanding of the light scattering behaviour from the surfaces. This work is an attempt in this direction.

Structure Of The Thesis

The thesis is divided into six chapters and each chapter into different sections. Chapter 1 is utilised to formally introduce the problem after highlighting the importance of surface roughness and the role of laser techniques for metrology and materials evaluation. Review of literature on surface evaluation by optical technique is also presented in this chapter. Chapter 2 reviews some of the fundamental concepts that are relevant to this thesis. The topics covered are description of surface roughness, surface characterisation techniques, interaction of light with rough surface, optical scattering methods, and theoretical concepts. Chapter 3 presents our studies on machined surfaces. Chapter 4 is devoted to the studies on surfaces of thin wires. In chapter 5, we discuss the studies on the applicability of laser scattering techniques for surface characterisation in various cases of material evaluation. They are evaluation of artificial heart valve discs, plastic deformation in metals, intergranular corrosion, and laser induced surface modification as discussed earlier. Chapter 6 is a summary recalling important results and also discussing further studies.

Two interesting results are obtained as offshoots of the studies reported in this thesis. These additional results are included as Appendices. Appendix-1 dwells on the existence of blind zones in ultrasonic inspection of wedges. Appendix-2 discusses the simulation of light source moving with velocity greater than that of the light.

Information that is needed for immediate reference is presented as Annexures.
Machined Surfaces

Turned surfaces have been chosen for studying the scattering behaviour in machined surfaces. Turning is one of the most widely used techniques for generating rotationally symmetric components. It is observed that scattering from surface with coarse pitch is predominantly scattering. The fine pitch surface gives rise to diffraction pattern. Using an optical configuration with the laser beam tangential to the grooves, a repertory of V-scattering pattern is obtained from different surfaces of the turned surface standard (JIS B0658) (Fig. 3.1.4 and Fig. 3.1.5). As the pitch of the groove decreases the diffraction phenomena manifests due to interaction between the scattered pattern. It is observed that the diffraction is confined only to the V-region. The turned surface consists of two sets of sides, inclined with respect to each other. Each of these sets scatters the radiation into the V-region, and the interference between them results in the fringe pattern. The angle between the arms of V is related to the tool tip angle. Characteristic scattering patterns are obtained for each of the standard surface in the normal beam configuration (Fig. 3.1.8). The scattering patterns Fig.3.1.4, Fig.3.1.5, and Fig.3.1.8 can be used to compare the surfaces of the standard with the surfaces of actual component.

While studying the coarse surface with an optical configuration where the laser beam is oblique to the surface, it is observed that beyond a critical angle of incidence the incident laser beam gives rise to a stationary beam, whatever be the angle of incidence (Fig. 3.1.9). The occurrence of the stationary pattern is explained using geometrical optics. The theoretical formalism is presented. It is shown that multiple reflections under certain conditions give rise to stationary scattered beam. Expressions are obtained for the apex angle of the groove (Eq.3.1.4) and for the angle between the incident and stationary beam (Eq.3.1.6). An interesting finding is that obliquely incident beam will not reach the trough of the groove. Analytical expressions are derived for the scattered intensities. The theoretical results are compared with the experimental measurements (Fig 3.1.15).

Diffraction effects dominate in the scattering from turned surfaces with fine pitch. An attempt is made to explain scattering pattern in this regime through Fourier analysis. This provides a sound basis to the understanding of these scattered patterns (for example Fig. 3.2.4 and Fig. 3.2.8).

Since each machined surface is unique, in order to have a comprehensive methodology for surface characterisation we should have scattering / diffraction pattern from a variety of machined surfaces. This is rather tedious if not possible. Numerical simulation is a viable alternative to study a variety of surfaces. A methodology is presented to generate machined surfaces and to simulate laser scattering from these surfaces. The scattering configuration chosen is essentially a one-dimensional problem. A four-step process is presented to simulate the machined surfaces (Fig. 3.3.2). Saw tooth profiles are considered. Keeping the depth of the groove equal to zero, optically plane surfaces are studied. Increase in roughness results in drop in specular diffraction and increase in the background. Correlation
between the scattering parameters and the roughness are derived numerically. (Fig. 3.3.5). Systematic study is done by varying the pitch, the depth and the roughness of the grooves. This numerical simulation has demonstrated a systematic relationship between the scattering pattern and the nature of the profile of the machined surface. The spacing between the diffraction peaks decreases with increase in the pitch of the grooves (Fig. 3.3.6). The peak positions shift as a function of the depth of the grooves (Fig. 3.3.7). The study as expected shows that the background intensity increases with roughness. Interestingly there is enhanced scattering in certain directions which resulted in an increase in the intensity of certain diffraction peaks. (Fig. 3.3.8 and Fig. 3.3.9). The simulated studies indicate that sub-micron sensitivities can be realised.

**Surface Of Thin Wire**

Thin wires of different materials are used in a variety of applications. Surface characterisation plays an important role in their performance. A detailed study of laser scattering from thin wire for surface characterisation is presented in the thesis. The optical configuration with oblique illumination is employed in this study. This gives rise to conical scattering. (Fig. 4.1.4.) The scattered light consists of three overlapping components. Two of them are from diffraction due to the edges of the wire. The third is due to specular scattering from the upper surface of the wire. The two diffraction cones that are generated at the two edges of the are separated by about the diameter of the wire (20 to 100 μm). These two interfere to generate interference fringes.

This problem is treated using the theory of boundary diffraction waves. Setting the diameter of the wire to zero, the problem reduces to that of diffraction from a single edge. Numerical results indicate that the intensity distribution of the diffraction due to a single edge truly varies as \( \tan^2(\phi/2) \) for \( \phi \leq 180^\circ \) and when larger \( \alpha \). Deviation sets in when \( \phi \to 180^\circ \) and when \( \alpha \to 0^\circ \) (Fig. 4.2.5). These results corroborate with the asymptotic solutions obtained by Otis and Lit [1974].

It is shown that the interference between the two diffraction components gives rise to fringes on either side of the incident beam, along with the diffracted cone. (Fig. 4.2.8). It is shown that, the spatial position of the fringe minima from the Z-axis is uniform (Eq. 4.2.40).

An important result is that the fringe spacing (position of the fringe minima), along the diffracted cone, is a function of not only the diameter of the wire (Fig. 4.2.8.) but also the angle of incidence (Fig. 4.2.12). However, it is shown that the spatial positions of the fringe minima from the Z-axis are not affected by the angle of incidence (Table 4.2.2). The numerically computed fringe minima are in agreement with the experimental results (Table 4.2.3).

Kirchhoff method is used to compute the intensity distribution of the scattering pattern. This gives a correlation between the scattered intensity distribution and the roughness. When the wire is extremely smooth fringe pattern is observed. (Fig.4.3.2.). When the roughness is introduced the contrast of these fringes is drastically reduced (Fig.4.3.3). A fairly linear relationship is observed between total scattered intensity. (TIS) and roughness (Fig.4.3.4).
The component of the scattering pattern due to specular reflection from the surface of the wire is analysed using geometrical optics approach. A generalised expression for the locus of the specularly reflected beam from the surface of a wire is derived (Fig. 4.4.4). By incorporating the limiting condition of the diameter of the wire being very small compared with the diameter of the scattering pattern, the above result is extended to the scattering from thin wires to explain the formation of a straight circular cone. It is also established that there is one to one correspondence between the linear element on the surface of the wire and the sector in the scattered pattern. (Eq. 4.4.15 and Fig. 4.4.5). The theoretical conclusions are compared with experimental results. The one to one correspondence is demonstrated. (Fig. 4.4.7, and Table 4.4.1). Expressions are derived for the region of analysis (Eq. 4.4.16) and the asymmetry in the scattering pattern (Eq. 4.4.17). These results can be used for characterising the surface of the wire.

Applications

Apart from these two fundamental studies, few applications of laser scattering in materials evaluation are studied in this work. The objective is to demonstrate the feasibility of using the laser scattering for evaluating the quality of the surface of soft materials, and in monitoring physical and chemical phenomena. The methodology for measuring laser scattering parameters is presented. The intensity of the scattering pattern is acquired, for analysis, using either a linear scanner or a CCD camera, depending on whether the scattering pattern is one-dimensional or two-dimensional in nature.

Valve discs of artificial heart valves designed by Sree Chitra Tirunal Institute of Medical Science and Technology are made of high density polyethylene. Use of stylus technique for roughness monitoring will leave scratches on its surface. It is demonstrated that laser scattering can be used as a quality control technique both qualitatively (Fig. 5.3.6.) and quantitatively. (Fig. 5.3.8, Fig. 5.3.10). It is suggested that specular reflection is a better parameter for classifying the heart valve discs (Fig. 5.3.11) compared to FWHM (full width at half maximum of the scattering pattern) (Fig. 5.3.12).

Plastic Deformation is important in understanding the fracture behaviour of metals. Measurement of small amounts of plastic deformation is significant in the studies related to propagation of cracks. Conventional techniques do not have real time capability. Plastic deformation in any material introduces topological changes in its surface, suggesting that laser scattering parameters can be a measure of the plastic deformation. Tapered tensile specimens (Fig. 5.4.1) are used to obtain different known plastic deformations across the specimen under similar conditions. Good correlation is observed between plastic deformation and laser scattering parameters. (Fig. 5.4.4 & Fig. 5.4.5) The saturation behaviour in the response of the laser scattering pattern is explained in terms of the saturation in the generation of striations and microcracks. (Fig. 5.4.6). Specimens of mild steel, aluminum, stainless steel and brass are studied in this work.

The industrial importance of corrosion has led to extensive research on the subject. Conventional NDT (nondestructive testing) tools have poor sensitivity in
detecting the initial stages of corrosion. Corrosion is essentially a surface phenomena. Hence laser scattering is a potential technique to study this phenomenon. In this work intergranular corrosion in AISI type 316 stainless steel is studied. A good correlation is observed between scattering parameters and the extent of corrosion (etching time on sensitised specimens) (Fig. 5.5.4, Fig. 5.5.5. and Fig. 5.5.6.) The role of angle of incidence to tune the range of corrosion is also discussed (Fig. 5.5.7.).

Surface treatment using high power laser is an emerging technology. There is a need to develop suitable NDT techniques for quality evaluation. It is observed that monitoring the power of CO2 laser and irradiation time alone will not provide good control on surface modification (Table 5.6.2). Here again laser scattering technique offers good potential to monitor the modified surface. In this study the surfaces AISI type 316 stainless steel specimens are heat treated using a multibeam CO2 laser. Laser scattering from these irradiated surfaces is studied. It is shown that monitoring the surface modification using laser scattering is a viable proposition for quality control. Good correlation is observed between the shape parameters of the scattering pattern and the classification process. (Fig. 5.6.7)

Additional Studies

While studying the occurrence of stationary pattern from a machined surface it is concluded theoretically that under certain conditions the beam will never reach the trough of the groove. The result is independent of the nature of the beam. This result has implications in ultrasonic inspection of wedges and provides a means for estimating the blind zone that cannot be inspected by an ultrasonic probe (Fig. A1.3 and Fig. A1.4).

While analysing the scattering from the edges of the thin wire it is realised that there exists an analogy between the scattering from a straight edge and radiation from a source moving faster than light. It is well known that if a source is moving faster than the wave generated by the source, a conical shock wave is created. The conical scattered beam is exactly equivalent to this shock wave (Eq. A2-6). This analogy is very useful as a teaching tool.