A LOW COST OPTICAL SYSTEM FOR DETECTION OF SURFACE SCRATCHES

M.A. Younes
Production Engineering Department, Faculty of Engineering,
University of Alexandria, Alexandria, Egypt.

ABSTRACT

The quality of manufactured surfaces affects their appearance, functional performance and life. Besides roughness, defects and scratches have a major role on fatigue life and surface performance. This study is a contribution towards the automatic control of manufactured surfaces quality. Results of an experimental and analytical investigation onto the on-line detection of surface scratches using laser light are presented. The field back scattered from the laser illuminated surface is monitored and traced by a single element Photo Sensitive Device (PSD). A PC-computer is used for data acquisition and analysis. The effect of the scratch orientation with respect to feed marks, and illumination direction on the scattered field is investigated. The resolution of the system is also considered. Shaped, ground and cold rolled surfaces having several scratch orientations were interrogated using a collimated laser beam. The results proved the capability of the system to detect surface scratches, and determine their spacing, and orientation with respect to the feed marks. The system can be integrated with an automated manufacturing line for in-process monitoring and control of surface quality.

Keywords: Scratch detection, Surface inspection, Laser-based systems.

INTRODUCTION

The quality of engineering surfaces controls their appearance and performance. Wear, friction, lubrication characteristics, load carrying capacity, fatigue life and functional performance are all affected by the surface condition. Besides roughness, surface defects, scratches and cracks should be considered due to their major role on surface performance. It is well established that the fatigue life of mechanical components consists of two discrete stages: initiation of finite sized crack and subsequent crack propagation to failure. A scratch on the component surface will definitely be the starting point for the first stage leading to fatigue failure.

Evaluation of roughness and detection of surface scratches during manufacturing safes the loses resulting due to failure of a component during actual service. The evaluation of surface roughness has been the subject of many studies [1,2,3,4,5,6]. Surface and subsurface scratches are evaluated using different techniques. For subsurface defects ultrasonic [7,8] and x-ray [9] are mostly used. For surface defects, scratches and cracks, optical methods are the most widely used, specially for on-line and in-process evaluation. Both metallic [10,11,12] and non-metallic surfaces [13,14] were examined. Stylus type instruments give details of surface roughness profiles however, being mechanical and contact methods, their use is limited. They can damage the examined surface, they are slow, and not suitable for in-process inspection. Moreover, for the case of scratch detection, they may result in confusion regarding the shape of closely spaced scratches and when a skid is used as a datum for measurement.

This study introduces a low-cost, non-contact on-line inspection technique for the control of surface quality. The technique can be integrated with an automated manufacturing system for in-process monitoring of surface quality. Although the study is concerned with the detection of surface scratches the, surface roughness can be monitored too. Another PSD can be added to measure the specular reflectance of the field back scattered from the surface. The R_q roughness value can then be evaluated from the PSD signal [2]. Limits can be set on the R_q value and a feed back signal may then be used to control process parameters.

THEORETICAL BASIS

If a specular surface is illuminated with a laser light, the reflected field shows a single spot. However, the presence of roughness modulates the reflected field. For an isotropic rough surface the reflected field is statistically symmetric over the entire observation plane [12]. On the other hand one-dimensional rough surfaces scatter light onto a single line [4]. Many manufacturing processes produce surfaces with directional feed marks that can be considered as one-dimensional e.g. shaping, grinding, horizontal milling and rolling. If the illumination is in the plane perpendicular to the feed marks, the reflected field will be a straight line perpendicular to feed marks, Figure (1-a). If the test specimen is rotated about its surface normal (z-axis Figure (1)), the reflected pattern will rotate consequently. As the illumination becomes parallel to feed marks the reflected field becomes an arc, Figure (1-b). The presence of a scratch on the surface produces another scatter line superimposed on the original one, Figure (1-c). Under such conditions a scratch acts as a one-dimensional diffraction grating, of lines running along the scratch direction. The orientation of the scratch generated pattern can therefore be determined by its orientation relative to the illumination direction.

In the following sections the experimental setup and the results of the investigation into the detection of surface scratches are presented.

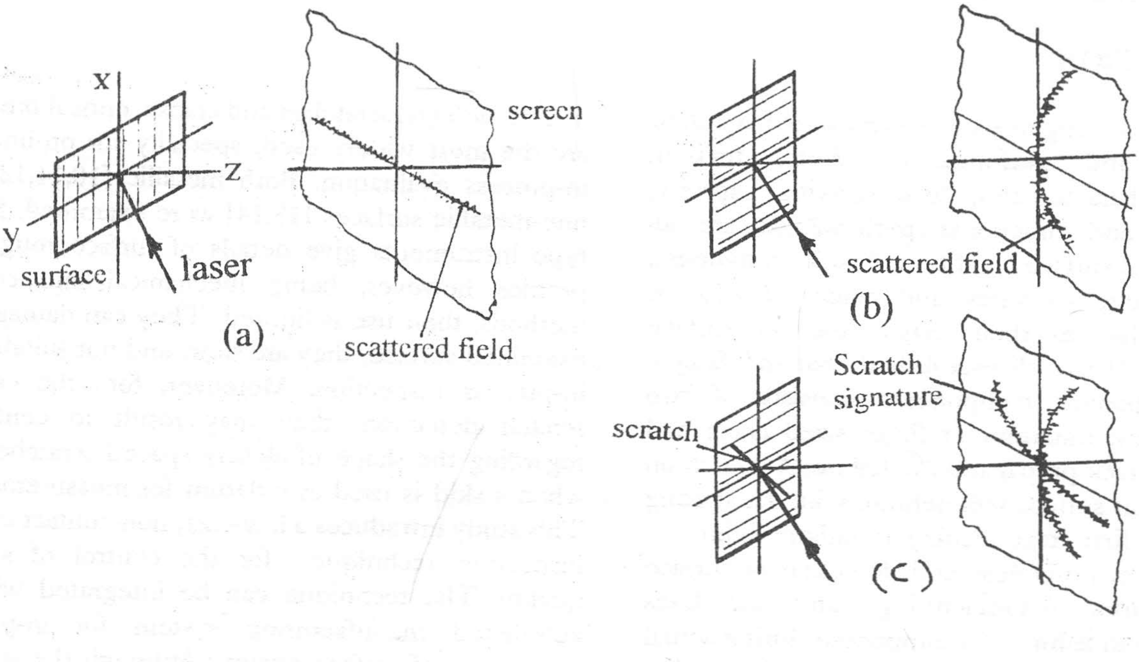

Figure 1. Scattering configuration of a one-dimensional surface, illumination perpendicular to feed marks (a), parallel (b) effect of scratch (c).

EXPERIMENTAL WORK

Two groups of experiments were performed. The first one was carried out to investigate the effect of a scratch on the field reflected from one-dimensional rough surfaces illuminated by a laser beam. The setup shown in Figure (2) was used to trace the field back scattered from a laser illuminated surface. Accordingly, the test specimen is illuminated by a collimated beam of He-Ne laser. The reflected field is traced by the PSD driven around by a DC motor running at 1.2 rpm. The PSD output signal is digitized and then analyzed using the Data Acquisition Unit (DAU), which is controlled by the PC-computer.

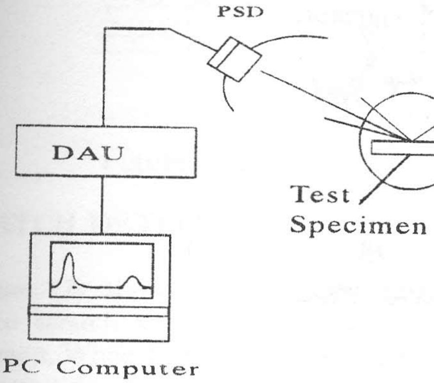

Figure 2. Experimental set-up 1 for recording the scattered field.

The second group of experiments was planned to investigate the possibility of detecting surface scratches and determining their spacing using the setup shown in Figure (3). The laser illuminated specimen is fixed to the movable table. The PSD monitors the reflected field as the laser spot passes across the surface of the moving specimen. The output signal of the PSD is digitized by the DAU. The digitized signal is stored and analyzed by the PC-computer. The movable table was calibrated for linear speed and experiments performed inside the stable part of its travel range.

A set of specimens produced by several manufacturing processes and having different scratch orientation were prepared to investigate the ability of the system to detect surface scratches, determine their spacing and orientation with respect to feed marks. Aluminum and steel surfaces produced by shaping, grinding and cold rolling having different R_a roughness values and several scratch orientations were examined.

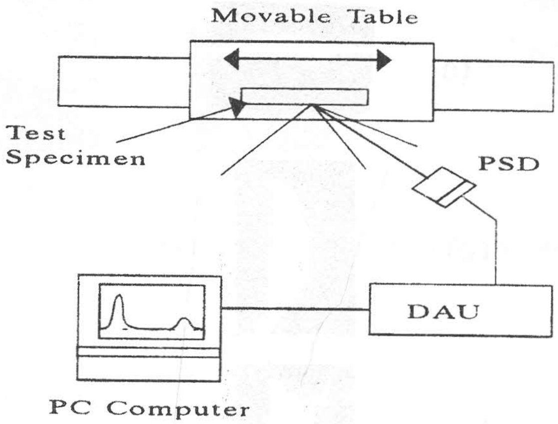

Figure 3. Experimental set-up 2 for scratch detection.

RESULTS AND DISCUSSIONS

Effect of Scratch on reflected field:

Figure (4) shows photographs of the reflected fields observed when a one dimensional rough surface is illuminated by a laser beam. The output signals recorded as the PSD traces around reflected fields of Figure (4) are illustrated in Figure (5). In Figure (4-a) and Figure (5-a), a shaped surface is illuminated in the direction perpendicular to the feed marks. On the other hand Figure (4-b) and Figure (5-b), illustrate the case when the illumination is parallel to feed marks. In fact if the tested surface is rotated around the z-axis, Figure (1) the reflected field will start to rotate respectively and gradually changes from the straight line of Figure (4-a) to the arc of Figure (4-b).

If a scratch is present in the surface , another scatter line superimposed on the original one will be observed Figure (4-c) to (4-e). Byuggren [11] recorded similar plots using infrared radiation. However, infrared measurement requires clean environment to get reliable results. Surface contaminants and dust particles greatly affect the scattered field. The orientation of the scratch relative to the feed marks (angle y, Figure (1-c)) determines the relative orientation of the two reflected lines. The fields reflected from a shaped surface having scratches inclined at angles Ψ=71°, 51°, and 30° to the feed marks are shown in Figure (4-c) to (4-e) respectively.

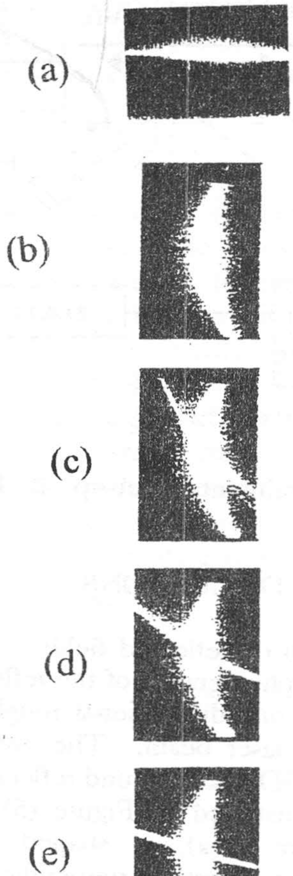

Figure 4. Scattered fields from: perpendicular (a), parallel illumination (b), scratches at angles Ψ 71° (c), 51° (d)m and 30°(e).

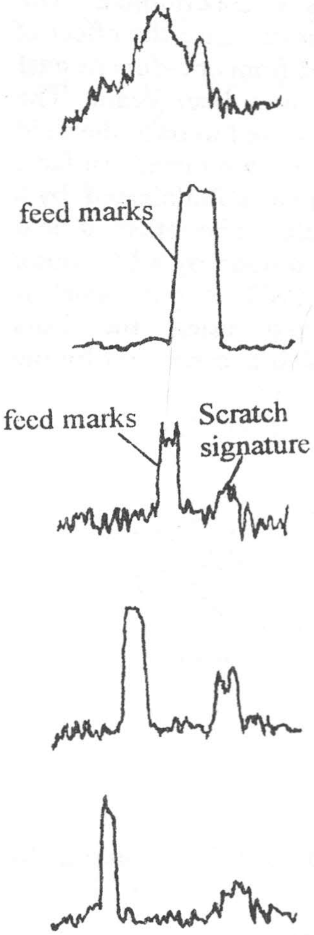

Figure 5. PSD signals for the scattered fields of Figure (4).

Figure (5-c) to (5-e) show the PSD output signals recorded as it traces around the reflected fields of Figure (4-c) to (4-e) respectively. The recorded signal exhibits two peaks, the higher represents the feed marks while the lower one shows the scratch effect. The spacing between the two peaks is a function of the orientation angle ψ. In the recorded signal steep peaks indicate one-dimensional surface. Wide peaks with spikes indicate that the surface is not definitely one-dimensional and the manufacturing process leaves marks in the surface distributed over an angular interval [11]. Thus, the wide spiky signature of the scratches in Figure (5-c) and Figure (5-e) can be attributed to higher roughness along the scratch. Such conclusion is clearly observed for aluminum and steel specimens and for the cases of shaped, ground and cold rolled surfaces. It should be mentioned however that, the type of material and the manufacturing process affect the intensity values but not the pattern of the reflected field.

Figure (6) presents photographs for the field scattered from a shaped surface having a scratch perpendicular to feed marks as the surface is rotated about its normal. The two patterns, representing both the feed marks and the scratch, will rotate.

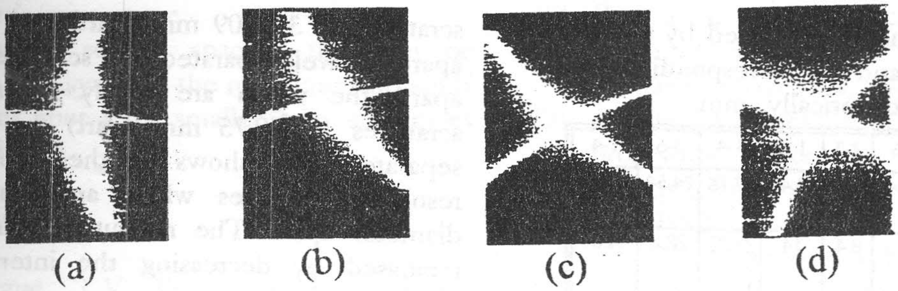
(a) (b) (c) (d)

Figure 6. Scattered fields for surface with a scratch: perpendicular illumination (a), as surface is rotated around its normal, angles of 20° (b), 40° (c), and 60° (d).

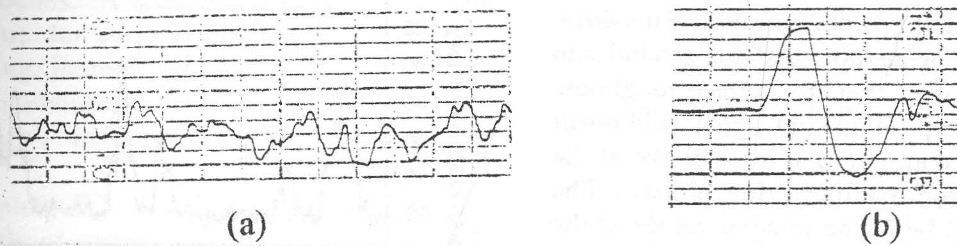
(a) (b)

Figure 7. Typical stylus traces of roughness profile (a), and a surface scratch (b).

SCRATCH DETECTION

Figure (7) shows typical Talysurf traces for a surface scratch and a roughness profile of a test specimen. While Figure (8) presents a typical plot of the output signal recorded using the set up of Figure (3) for a surface having three parallel scratches. Each peak of the recorded signal corresponds to a single scratch. To investigate the ability of the system to measure the distance between scratches, a surface having five scratches, at different spacings, was examined. The recorded output signal is shown in Figure (9). The spacing between the scratches was measured using a Tool Maker's Microscope. The same spacings were estimated from the recorded signal, Table (1) using the following formula;

$$S_s = \frac{N * v_t}{R} \text{ mm}$$

where:

S_s: spacing between two scratches, mm

N: number of sampled points between recorded peaks

R: sampling rate used, Hz

v_t: table traversing speed, mm/sec.

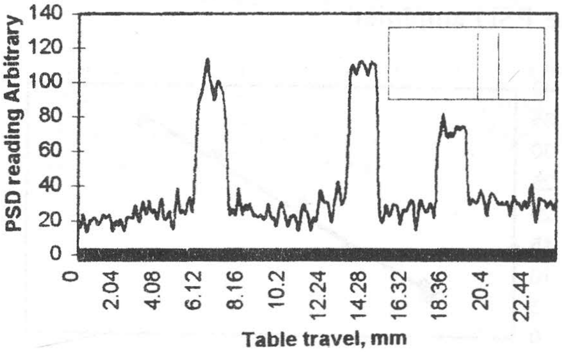

Figure 8. PSD signal for a surface with three scratches.

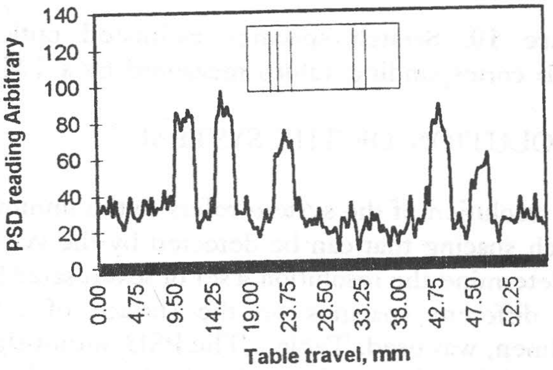

Figure 9. PSD signal for a surface with five scratches.

Table 1. Scratch spacing measured by the Tool Maker's Microscope and the corresponding values estimated optically, mm.

Scratches	1-2	4-5	2-3	1-3	3-4	3-5	1-4
Measured spacing	6.04	7.14	7.4	13.44	17.14	24.54	30.58
Estimated spacing	6.56	6.53	8.4	14	21.27	28.8	34.04

Figure (10) shows a linear relationship between the estimated scratch spacing and their measured values. Similar observations were obtained for ground and rolled surfaces. Provided that the surface roughness is one dimensional, typical out put signals will result for the same scratch configuration irrespective of the type of material or the manufacturing process. The major difference will be in the relative values of the peak readings which are not a controlling factor in this analysis. Moreover, the readings can be adjusted by choosing the appropriate magnification of the PSD amplifier.

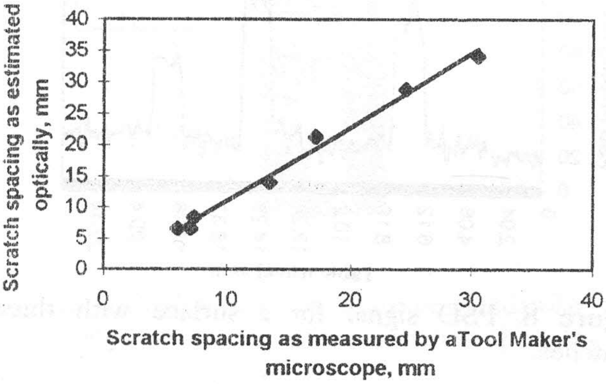

Figure 10. Scratch spacings estimated optically versus corresponding values measured by a TMM.

RESOLUTION OF THE SYSTEM

The resolution of the system refers to the minimum scratch spacing that can be detected by the system. To determine the resolution a set of seven scratches, with different spacings on the surface of a test specimen, was used. Table 2 The PSD output signal recorded for this set of scratches is shown in Figure (11). The beam used was nearly 1 mm in diameter. In Figure (11) it is clear that the peaks representing scratches 2, 3 (2.09 mm apart) and 4, 5 (1.82 mm apart) are well separated. For scratches 6,7 (1.05 mm apart) the peaks are hardly separated. But for scratches 1,2 (0.75 mm apart) the peaks are not separated. This shows that the system is capable of resolving scratches which are nearly one beam diameter apart. The resolution can, therefore be increased by decreasing the interrogating beam diameter.

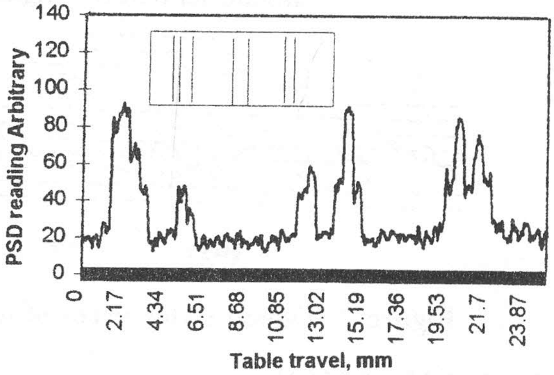

Figure 11. PSD signal for a surface with seven scratches.

Table 2. Scratch spacing, mm.

Scratches	1-2	2-3	4-5	6-7
Spacing	0.74	2.09	1.92	1.05

CONCLUSIONS

From the work undertaken in this investigation the following conclusions can be driven:

1- scratches on shaped, ground, and cold rolled surfaces can be detected by examining the field back scattered from the surface when illuminated by a laser light.

2- The system does not depend on the absolute values of light intensity which is affected by the type of material and the degree of surface roughness.

3- Both scratch spacing and orientation relative to feed marks can be evaluated.

4- A straight line relationship is observed between the scratch spacing estimated from optical measurement and their values measured by a

Tool Maker's microscope.

5- The minimum scratch spacing that can be detected by the system (the resolution) depends on the laser spot size. smaller spot size gives better resolution.

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