Visual inspection of metal surfaces

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INTRODUCTION

The majority of applications of automatic visual inspection have been the case in which a high contrast image can be obtained. This will result from object silhouettes and high contrast reflectivity changes as in printed text. In these cases, the image can usually be successfully segmented by a threshold operation, leading to a two-level or binary image.

The cases that lead to difficulty at present involve the use of reflected light. Here one is faced with shadows and highly variable reflected intensity. This is the case for metal surfaces where the reflected intensity is a strong function of illumination and viewing direction. On the other hand, the inspection of metal surfaces represents an important domain of applications. Of particular interest is the detection of small surface defects such as nicks and scratches.

In order to implement automatic computer inspection of metal surfaces, optical and illumination means must be provided that provide high contrast images of surface defects. In addition, there must be a relationship between image intensity and surface profile. This paper will discuss a number of theoretical aspects of the scattering of light from metal surfaces. This provides a basis for computer modeling of the metal surface. The theory is based on earlier work by Beckmann and Horn. The method has been tested experimentally and several examples will be demonstrated.

SCATTERING THEORY

Several phenomena play a role in the distribution of light scattered from a metallic surface. The most important effects are 1) the variations of the surface normal and 2) shadowing. The variation of surface normal generally occurs on two scales. A fine scale variation is present that represents the basic surface roughness. In the case of surface defects, there exists a more gradual variation corresponding to the surface deformation associated with the defect. The combined variation is illustrated in Figure 1. In the case of shadowing, portions of the surface are occluded by variation in the surface due to defects. This condition is shown in Figure 2 for a crater or pit type defect.

The theoretical situation is best developed for the case of surface normal variations in the presence of random fine scale surface height variations. Beckmann and Spizzichino have explored this case extensively for various scales of surface roughness. In this paper we will only consider the case where the surface is rough compared to the wavelength of light. The reflection coefficient for scattered power in this case is given as

\[
\langle \rho \rangle^* = \frac{\pi R^2}{4kA^2 \cos^2 \theta} \left( \frac{T}{\sigma} \right)^2 \exp \left\{ -V_x^2 \left( \frac{T}{\sigma} \right)^2 \right\}
\]

where

- \( R \) = Reflection coefficient of an equivalent smooth surface.
- \( k = 2\pi/\lambda \) (\( \lambda \) - wavelength of illumination)
- \( A \) = Area of illuminated surface
- \( V = k_xk_y \)
- \( V_x = \text{Component of } V \text{ along the surface normal} \)
- \( V_y = \text{Component of } V \text{ perpendicular to surface normal} \)
- \( k_i = \text{Incident wave vector} \)
- \( k_r = \text{Reflected wave vector} \)
- \( T = \text{Correlation distance of surface roughness} \)
- \( \sigma = \text{Surface height variance} \).

The coordinate system and scattering vectors are defined in Figure 3.

It will prove useful to transform this notation to that introduced by Horn. This notation is defined in Figure 4. It follows that

\[
-\hat{k}_1 \cdot \hat{k}_2 = k^2 \cos g
\]

\[
V^2 = k^2 + k_2^2 - 2k_1 \cdot k_2
\]

or

\[
V^2 = 2k^2(1 + \cos g)
\]

also

\[
V_z = k(\cos i + \cos e).
\]

Horn defines the I, E, G as the cosines of the angles i, e, g respectively. From the consideration above,

\[
V^2 = 2k^2(1 + G)
\]

\[
V_z^2 = k^2(1 + E)
\]

* This appears as Equation 59, p. 88 of Reference 4.
Noting that
\[ V_{xy}^+ = V_x^2 - V_y^2 \]
we finally obtain
\[ \langle \rho \rho^* \rangle E_{0}^2 = \alpha \left( \frac{1+G^2}{1+E} \right) e^{-\frac{\pi k}{2} \left( 1 - \frac{G}{1+E} \right)} \]  
(2)

\[ \alpha = \frac{R^2 A}{\pi \sigma^2} \]  
\[ \beta = \frac{T^2}{4 \sigma^2} \]

Here \( E_{0}^2 \) is proportional to the power scattered by a smooth plane of area \( A \). This is given by
\[ E_{0}^2 = \frac{k^2 A \rho^2}{4 \pi^2 r_0^2} \]
where \( r_0 \) is the distance from the observer to the plane. Thus the result in (2) would be proportional to the scattered power from the rough surface. This form is suitable for interpretation and comparison with experiment.

CASE I—SOURCE AT OBSERVER

If the illumination source is colimated (unidirectional) and located on the axis of the observation, then \( I = E \) inde-
pendent of the direction of the surface normal. In this case we find
\[ P = \langle \rho \rho^* \rangle E_{0}^2 = \frac{\alpha 1}{4 \pi^4} e^{-\frac{\pi k}{2} \left( 1 - \frac{G}{1+E} \right)} \]  
(3)

This is a particularly simple form which can be easily interpreted. The first observation is that \( \beta \) depends only on surface roughness. As the surface becomes rougher \( \beta \) decreases. The exponential term in (3) dominates the behavior of \( P \) and, for large \( \beta \), will lead to a rapid fall off in intensity for \( I \neq 1 \). \( P \) is maximum for \( I = 1 \) which corresponds to the specular reflection condition. Note also that surface reflectivity only affects \( \alpha \) and thus not the angular distribution. Also the peak power is proportional to \( \beta \), which is to be expected, since smoother surfaces concentrate more power into the specular direction.

This expression was tested for a number of surface roughnesses found from a selection of metal industrial parts.
surface was rotated relative to the optical viewing axis and the reflected power on axis is given in Figure 5 for two surfaces. In the same figure a best fit of Expression 3 is shown as solid lines. The agreement is quite satisfactory.

CASE II—GRAZING AND NORMAL ILLUMINATION

From the previous development, it can be seen that the slope of metal surfaces can be deduced from reflectivity measurements. This assumes that both reflectivity and surface roughness are known. The former condition is not easily obtained in practice. Industrial parts are usually dirty and reflectivity can vary rapidly over the surface.

In order to obtain more information it is necessary to provide an additional direction of illumination. The arrangement shown in Figure 6 provides two nearly orthogonal directions. To see the relationship between the power due to each illumination direction consider (2) for each case. It is assumed that the direction of view is along the normal illumination direction.

![Figure 5](image1.png)

**Figure 5**—The experimental and theoretical variation of reflected power with surface normal inclination. The theory in Expression 3 is shown as a solid line.

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![Figure 6](image2.png)

**Figure 6**—An optical configuration for obtaining two directions of illumination.

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![Figure 7](image3.png)

**Figure 7**—(a) A photomicrograph of a surface nick and (b) the resulting S array shown in perspective. The signal variations near the top of the array are due to an unilluminated region.
a) Normal illumination

This is just the previous case, i.e.

\[ I_n = E_n \]
\[ G_n = 1 \]
\[ P_n = \frac{\alpha}{4 I_n^4} e^{-\beta(1-I_n^2)} \]

b) Grazing illumination

\[ G_n = 0 \]
\[ I_g = \sqrt{1-I_n^2} \]
\[ E_g = E_n = I_n \]

So in terms of \( I_n \)

\[ P_n = \frac{\alpha}{(\sqrt{1-I_n^2} + I_n)^4} e^{-\beta(1-I_n^2)} \]

If we assume that the surface normal does not vary greatly from the direction of normal illumination.

\[ I_n \approx 1 \]

Thus

\[ P_g = \frac{\alpha}{(I_n)^4} e^{-\beta I_n^2} \]

Now taking the ratio of power due to grazing illumination and normal illumination we have,

\[ \frac{P_g}{P_n} = 4 e^{-\beta I_n^2} \]

Taking the logarithm of this ratio and dropping subscripts we have

\[ S = \ln \left( \frac{P_g}{P_n} \right) = \ln 4 - \beta I_n^2 \]  \hspace{1cm} (4)

Note that this quantity depends only on surface roughness and slope and not surface reflectivity. It is a reasonable assumption that roughness is constant over a region larger than the size of defects that are to be detected.

A number of surface defects on metal surfaces were imaged using the illumination scheme in Figure 6. Two images were obtained for each case, one for normal illumination, one with grazing light. The quantity \( S \) in Expression 4 was obtained by digitizing the images and performing the indicated calculations.

The first case consists of the nick shown in Figure 7a. The resulting \( S \) array is shown in perspective in Figure 7b. The nick appears near the center of the array with good contrast. The mountainous peaks near the top of the array were due to random sensor noise since that region was not illuminated.

A more striking example is the series of scratches (~.005" wide) shown in Figure 8a. The \( S \) array is shown in Figure 8b. A binary image of the \( S \) array produced by thresholding is shown in Figure 8c.
8b. The signal has enough contrast to allow a reasonable segmentation of the scratches by thresholding the S array as shown in Figure 8c.

As a final example consider the pit (~.010) shown in Figure 9a. The resulting S array is shown as a grey-level image in Figure 9b. The main contribution to S in this case is the occlusion of the grazing illumination. There is good contrast between the pit and surrounding metal even though the surface roughness is on a scale comparable to the defect.

CONCLUSIONS

By considering the theory of scattering from rough surfaces, it has been possible to derive an illumination scheme and method of image analysis that results in good contrast and detectability of surface defects.

It is also noted that the scattering ratio, S, is sensitive to surface occlusions and shadowing. Thus we have a result that provides good contrast for most surface defects. The main drawback to the approach is the necessity to provide two directions of illumination.

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REFERENCES
