External Characteristics of Shot Peened Surfaces

INTRODUCTION

Shot peened components have two important <u>external</u> characteristics. These are:

SURFACE ROUGHNESS and

DIMPLE COVERAGE.

Surface roughness depends mainly upon the size of shot used. There is a simple analogy with the use of emery papers. The coarser the grit size the rougher will be the final finish. Two-stage shot peening involves using a finer grade of shot after a coarser grade. That is equivalent to using a finer grade of emery after using a coarser grade. Average roughness is easily measured and is well understood. The commonest roughness parameter is $\mathbf{R_a}$ which is the average vertical deviation from some reference line. Measurement techniques can be either two-dimensional or three-dimensional and may involve either direct contact or non-contact sensors. Peening is normally applied as a final treatment. The change of surface roughness induced by shot peening will therefore depend on the initial roughness of the component.

Dimple coverage is our prime indicator of the amount of peening that has been applied. The factors affecting coverage are reasonably well understood. Dimple coverage is usually quantified by using the parameter **C**. This is the ratio of dimpled to undimpled area. Measurement techniques vary from simple optical assessments to sophisticated image analysis procedures. J2277 is a standard specification for shot peening coverage determination.

Both surface roughness and dimple coverage change with increasing amounts of applied peening. This article considers the assessment and significance of these changes.

The use of digital scanning to assess the effect of peening is described. It is proposed that this can provide useful, objective, quantitative, information at low cost.

SURFACE ROUGHNESS

Roughness Assessment

Qualitative assessment of surface roughness is very familiar. We can sense substantial differences in roughness using a simple fingernail test. As a fingernail is drawn across a surface, electrical signals are generated and passed to the brain for analysis! Peened surfaces can be distinguished from unpeened ones blindfold. Commercial instruments involve similar principles to that of the fingernail test. A diamond stylus is drawn across the surface that senses vertical changes in its position, see fig.1. The profile of vertical height changes is displayed relative to a derived datum line, **A-B**. The vertical movement of the stylus is electronically amplified relative to its horizontal travel (mountains are made out of molehills!).

The commonest roughness parameter is **Ra** – which is simply the arithmetic average of deviations from a derived datum line. This datum line is automatically derived from the gradual change of displacement that is caused, for example, by roundness of the component. The actual estimation of **Ra** is done by adding up the <u>absolute values</u> of vertical displacements from **A-B** and dividing by the number of measurements. ‘Absolute values’ are those with the plus or minus sign being ignored. The accuracy of measurement increases with the number of points taken.

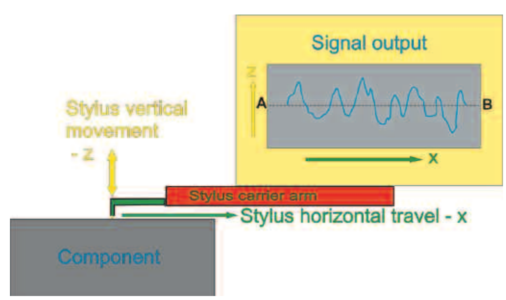


Fig.1 Schematic representation of a ‘profilometer’ instrument.

Roughness induced by Machining and Peening

Most components submitted for shot peening are ‘finish-machined’. Shot peening is normally a final stage of processing. <u>The roughness imparted by machining is quite different from that imposed by shot peening</u>. Machining involves deforming a chip until it fractures away from the surface.

Dr. David Kirk is a regular contributor to The Shot Peener. Since his retirement, Dr. Kirk has been an Honorary Research Fellow at Coventry University, U.K. and is now Visiting Professor in Materials, Faculty of Engineering and Computing at Coventry University.

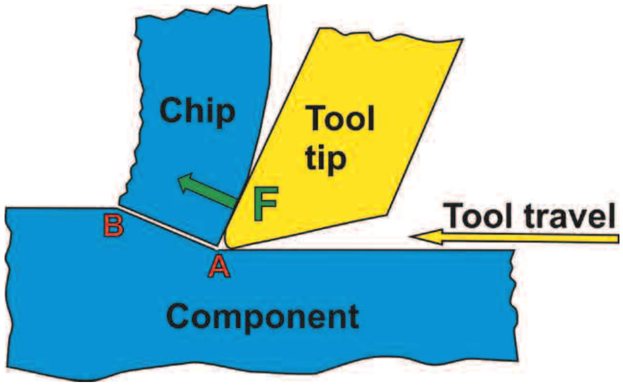


Fig.2 Chip formation during machining.

The phenomenon of chip formation is similar for all types of machining - including grinding, honing, lapping, planing, turning, and milling. Chip formation is illustrated in fig.2. The tool tip presses against the chip with a force **F** causing severe plastic deformation near the tip with consequent shear fracture along a line **A-B**. This mechanism is quite different from shot peening where indents are produced by plastic flow.

The difference in roughness generation mechanisms means that we have different 'textures' for machined as compared with peened surfaces. This is illustrated in fig.3 - showing model profiles of machined and peened surfaces that have the same **Ra** values.

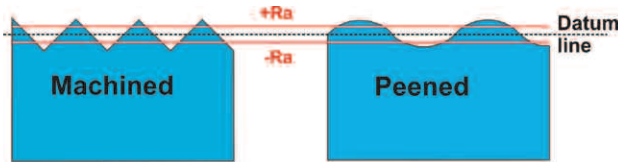


Fig.3 Comparison of machined and peened surface cross-sections.

Although the **Ra** values are the same for the hypothetical situation of fig.3 the 'textures' are different.

Roughness Evolution during Shot peening

As a general rule the roughness of machined components will be less before peening than after peening. During peening the roughness of the component will therefore increase. The evolution of this roughness increase is illustrated in fig.4. For this example, standard and fine-polished Almen A strips have been peened for different numbers of passes. The conditions were maintained as constant as possible using S230 shot, at 20 psi air pressure, 9·4 lbs/min. and a 0·36" nozzle 5·75" directly above clamped strips.

Fig.4 indicates that roughness evolution has the same exponential shape as does saturation intensity curves. Roughness steadies at a maximum value with an amount of peening equivalent to that needed for 'full coverage'. The saturation 'time' of 5·7 passes (same for both sets of strips) was derived using Curve Solver and is shown in fig.4 for comparison purposes.

It is of passing interest to note that the fine polishing treatment actually roughened the strips! In terms of Ra values that for the Standard strips was 0·249μm and for Pre-polished strips 0·327μm. This difference is preserved

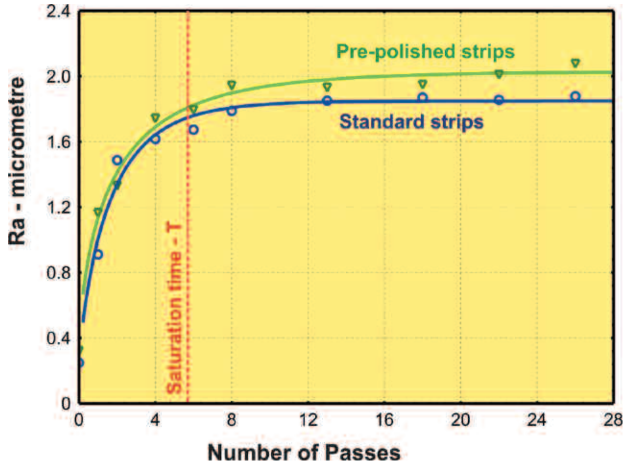


Fig.4 Roughness evolution of Standard and Pre-polished Almen A strips using S230 shot.

during peening so that the pre-polished strips end up with a slightly greater roughness than do the standard strips.

DIMPLE COVERAGE

Dimple coverage is very familiar, with coverage, **C**, being a specified parameter. The mechanism of dimple production and the evolution of coverage have been dealt with in previous articles in this series. The intention here is to concentrate on dimple coverage measurement.

Area versus Linear Measurement

Fig.5 illustrates the essential difference between area and linear dimple measurement.

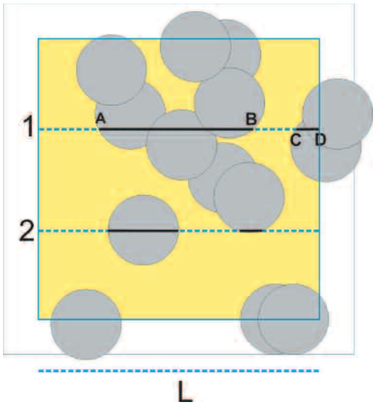


Fig.5 Area versus Linear measurement of coverage.

There are fourteen randomly-placed 'dimples' in the model shown in fig.5. The problem is to estimate, accurately, the coverage within the blue square of side, **L**. Area measurement is a direct comparison of the areas occupied and not occupied by dimples. A simple visual comparison involves the same procedures as those used by a sophisticated image analysis system. The eyes act as a camera producing a retinal image which is then analyzed by the brain. Most readers would perceive that the coverage by 'dimples' in fig.5 is about 50%.

Lineal measurement is a well-established procedure for quantifying coverage. Consider line **1** in fig.5 that has a length **L**. Two parts of the line, **AB** and **CD**, pass through 'dimples'. If **L = 100mm and AB + CD = 62mm** then lineal analysis indicates that the area proportion ([AB+CD]/L) is 62mm/100mm which is equivalent to **62%**. If we apply the same procedure to line **2** the two segments have a combined length of 32·8mm. 32·8mm/100mm is equivalent to **32·8%**. If we now take the average from the two lineal measurements we have (62+32·8)/2 = **47·4%**. That is very close to the 'true' value for fig.5 - which happens to be **49·7%**. This example is intended to indicate the need to take several line measurements because of 'statistical fluctuation'. Lineal analysis is very easy to carry out. Any picture on a computer screen, magnified if necessary, can be scrolled up to the top border and a ruler then used to take measurements of an **L**. **AB**, **CD**, etc.

Lineal measurements only depend on identifying line/dimple-edge intersections.

Area measurements using image analysis is a complex subject and has been discussed in a previous article in this series. A very important point is that the accuracy of image analysis depends on being able to (a) delineate all of the dimple-edge positions and (b) to separate dimpled from undimpled regions.

Delineation of dimple edges severely restricts the accuracy of image analysis.

Several procedures have been developed to try and overcome the delineation problem. One such procedure involves using Adobe Photoshop to manually 'paint' black those areas judged to be dimples. The resulting image is then capable of being image analyzed. Unfortunately a subjective factor is introduced and the technique is very time-consuming.

Lineal analysis can be applied either to enlarged images of peened surfaces (requiring only a ruler as equipment) or directly to the peened surface (using a microscope equipped with a vernier micrometer eyepiece).

Delineation Problem with Dimpled Surfaces

Fig.6 illustrates the delineation problem that besets dimple coverage analysis. It is very difficult to differentiate between peened and unpeened areas! Using a scanning electron microscope, S.E.M., has its advantages and disadvantages (apart from non-availability on the shop floor). A major advantage of an S.E.M., for most studies, is that it has a greater depth of focus than has an optical microscope. Dimples, however, are shown up by their depth as much as by their edges. Hence an S.E.M. does not offer any significant advantage over a simple optical microscope.

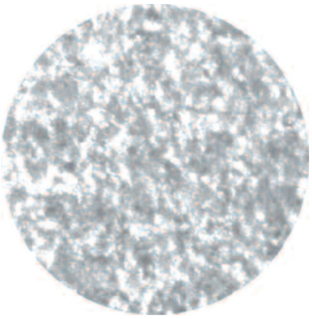


Fig.6 Digital optical microscope photograph of Almen strip peened with S230, x8.

The main reason for our delineation problem is the wide-angle 'field of view' that is inevitable with either optical microscopes or the human eye. We see light from a wide range of angles, all at the same time.

Fig.7 illustrates the origin of the wide-angle field-of-view feature. Light reflected from any particular point on the surface will enter the microscope's objective lens – provided that it lies anywhere within a (three-dimensional) cone angle of 2α – about 70°. This means that light from a wide range of angles around a dimple will be imaged – resulting in low contrast.

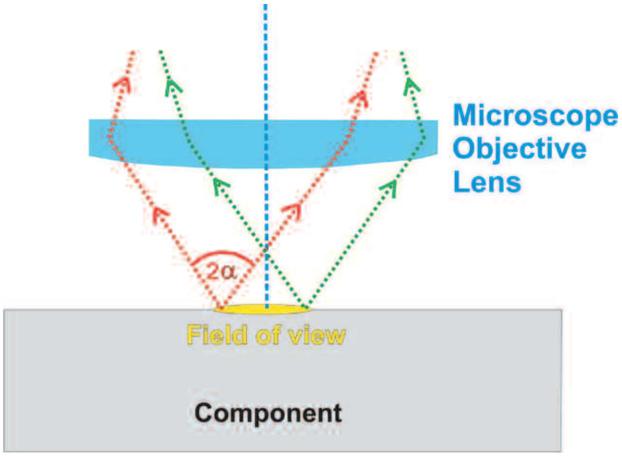


Fig.7. Wide-angle field of view for optical microscopes.

SCANNED IMAGES

Scanning involves a very narrow-angle field of view—leading to much higher dimple resolution than is obtained using conventional optics. Scanners are readily available, so that scanned images are a viable alternative to camera images. Scanned images can be quantitatively analyzed using graphic image manipulation. Hence we have a low-cost, simple, technique for assessing coverage. The term "graphic image manipulation" is the main part of "G.I.M.P." which is a freeware program downloadable from the internet.

Image Resolution and Delineation

A grayscale scanned image is different from that of an optical photograph. Fig.8 illustrates the difference when compared with fig.6. Scanned images are very dark when high coverage levels have been imposed. The dimples deflect incident light much more when scanned than when photographed.

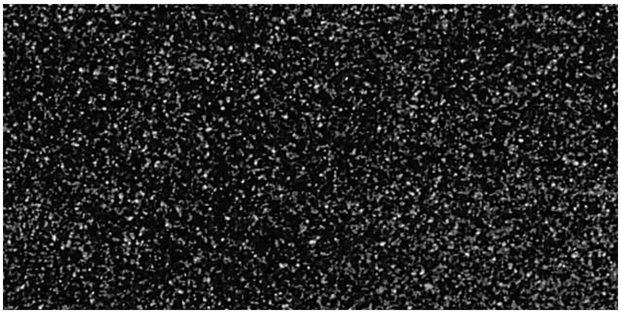


Fig.8 Scanned image of Almen strip peened with S230, x8, 1200 dpi.

The reason for the high deflectivity of scanned peened surfaces lies in the mechanics of scanning. Thousands of CCD (charge coupled device) elements are arranged in a long thin line. The 'field of view' is therefore very restricted (at a given instant of the scanning) leading to enhanced delineation. Each CCD samples a minute area of the surface generating an analogue voltage that is converted to digital values by an analogue-to-digital converter. The scan head is moved along lines and to new line positions using precision stepper motors. Image brightness is remarkably constant for a given deflectivity of scanned area.

Scanned Image Manipulation

Scanned images are stored as, for example, jpeg files that can subsequently be analyzed. Image manipulation programs allow the image to be analyzed for 'pixel darkness' - with the results being presented as a histogram. Fig.9 shows an image of a set of Almen strips produced using a standard scanner at 1200 dpi.

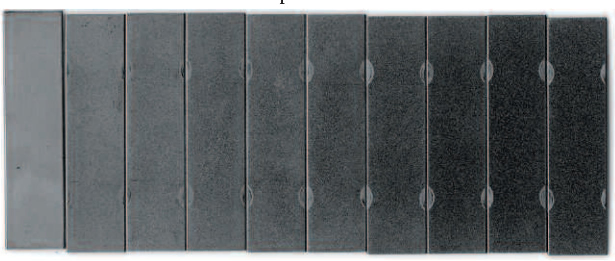
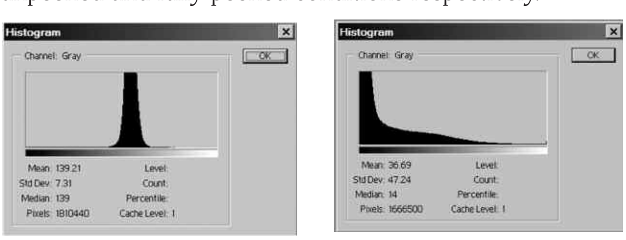


Fig.9 Scanned image of a set of pre-polished Almen strips having progressive peening levels.

All ten strips in the set were scanned at the same time and are arranged left to right in terms of increasing amounts of peening. The 'darkness' of the strips increases with increased peening - readily discernable to the naked eye.

Quantitative analysis of strip darkening is readily done by using the histogram feature of a graphic image manipulation program. Keen photographers may well be very familiar with histogram analysis. Fig.10 shows histograms for two of the strips shown in fig.9 – corresponding to unpeened and fully-peened conditions respectively.



(a) Unpeened (b) Fully-peened

Fig.10. Grayscale histograms of unpeened and fully-peened Almen strips.

For the type of histogram shown in fig.10 <u>the horizontal scale represents 'reflectivity' on a scale of 0 to 255</u>. The 'gradient bar' shows a corresponding variation from perfect black to perfect white. For the unpeened strip the mean value of the histogram corresponds to a 'light gray' whereas the fully-peened specimen has a mean value that is a 'very dark gray''. Quantitatively we are told that the reflectivity has gone down from 139·21 to 36·69 (mean values).

Scanned Image Analysis

Histograms of scanned samples represent a new way of analyzing the external surface changes induced by peening. Consider, for example, the histogram means for the ten strips shown in fig.9. These are presented in fig.11 as a function of the amount of peening that has been applied. There is a progressive reduction in reflectivity (equivalent to the histogram mean) as peening proceeds. The reduction is a close approximation to the exponential function that has been included in fig.11.

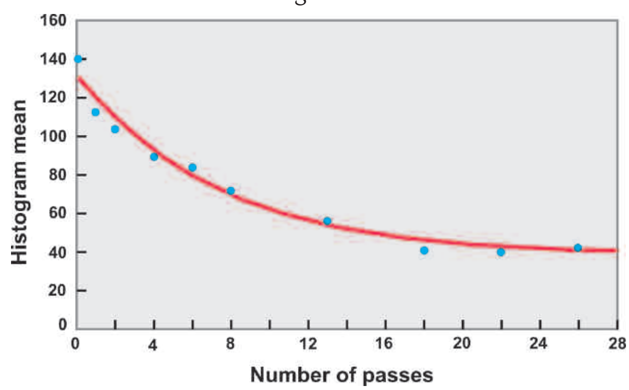


Fig.11. Histogram means as a function of amount of peening.

DISCUSSION

Shot peening changes the external appearance of components. Quantitative assessment of appearance change on the shop floor is, however, difficult. Coverage assessment is normally a specification requirement. Fortunately we are not normally required to provide <u>quantitative</u> coverage assessments. The photogenic quality of peened components varies enormously. Published photographs of peened surfaces are invariably from relatively-photogenic components. The specimens imaged in fig. 12, on the other hand, defy accurate analysis – even when armed with state-of-the art digital optical microscopes, scanning electron microscopes and sophisticated image analysis software.

Profilometers provide an accurate, quantitative, method of determining roughness changes. These are, however, normally too expensive to be an acceptable option. Optical measurements based on simple portable magnifiers are essential for <u>qualitative</u> coverage measurements. Digital cameras provide images that can be analyzed using image analysis techniques. Camera images, however, have very low resolution (mainly due to the wide angle field of view) for most peening situations. Fig.12 is a digital camera photograph of the same set of strips shown in fig.9. This clearly shows a relatively low level of contrast. Image analysis of most peened surface pictures is very time-consuming and also has a subjective element.

Fig.12. Digital optical photograph of a set of Almen strips peened after pre-polishing.

Digital scanning shows considerable promise as a technique for measuring, quantitatively, surface appearance changes. It must be stressed that it is change that can easily be measured. Hence we must determine the histogram before and after peening – using the same scanner and scanner settings. The reflectivity of the unpeened component depends on several factors – especially machining. Conventional flat-bed scanners restrict the range of components that can be examined. Portable 'pen' scanners are now available and are becoming more refined. Much more research will, however, need to be carried out before scan procedures can be implemented as standard practice.

Surface roughness, coverage and scan reflectivity all follow an exponential path as more and more peening is applied. This implies that all three parameters are directly related.

It has been shown that surface roughness increases (for fine-machined or polished surfaces) with increased peening. The roughness is exponential to a value that will be directly proportional to the size of shot that has been used. Surface roughness can therefore be used by the user as a measure of the shot size that has been applied to fully-peened components.

The increase in surface roughness induced by most peening operations is not necessarily detrimental to service performance. Consider the situation presented schematically in fig.13. A 'furrow' produced by machining will force applied tensile stress lines around its tip. Hence the furrow acts as a stress raiser. The concentration of stress lines is analogous to the isobars on a weather map. Very close isobars indicate severe weather!

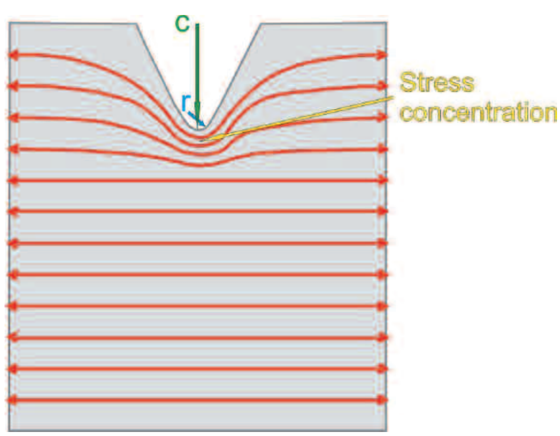


Fig.13. Concentration of 'stress lines' around the tip of a machined furrow.

Standard theory indicates that the stress concentration factor, **S**, is given by:

$$\mathbf{S} = \sqrt{(\mathbf{c}/\mathbf{r})} \qquad (1)$$

where **c** is the depth of the crack and **r** is the crack tip radius.

If the depth of a machined furrow is some nine times that of its tip radius then application of equation (1) would predict a stress raising factor of three. With peened surfaces the radius of the dimples is much larger than the dimple depth so that stress concentration is negligible. Very fine machining imparts correspondingly-small values of **c** and therefore smaller stress concentrations than for coarse machining. A fully-peened surface will have dimples replacing all of the machining furrows.