ACADEMIC STUDY
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Variations on the Almen Technique

INTRODUCTION

First instigated in 1942 with a patent submission, the Almen technique has now provided a reliable and universally accepted method of measuring peening intensity based on the deflection of standard strips when exposed for different times to a shot stream. This article considers various alternatives to and variants of the Almen technique. These alternatives and variants are those developed by the author in his Coventry University Shot Peening Laboratory—set up in order to facilitate studies of shot peening variables. A common thread was to question every aspect of the standard Almen technique. Principal considerations included Materials, Shape and Deflection Monitoring.

MATERIALS

Test Strips

University laboratories have the luxury of not having to be bound by prescribed procedures, including the materials from which standard Almen strips are manufactured. Currently most Almen strips are manufactured from ferritic steels that have been hardened and tempered to a condition associated with that of spring steels. Almen strips are also made from other metals—such as stainless steels and aluminum alloys.

One important question is "Why is hardened and tempered steel normally used as Almen strip material?" We can only speculate as to what was in Almen's mind when he first established his technique using such material. Perhaps he felt that his test strips should be made from the same material as the springs that had showed fatigue life improvement when blasted. If that was the case it begs the question, "Why should it have to be of the same material and have very similar hardness?" We now know that peening intensity measurements are needed in order to assess the ability of a shot stream to produce a work-hardened, compressively-stressed surface layer. They are not intended to be a form of hardness testing. Nevertheless, most shot-peened components are made from hard metals. It therefore seems logical that test strip materials should also be made from hard metals.

Hardness depends primarily on the melting point of the base metal but also depends on alloying. Hence aluminum is much softer than mild steel but can be alloyed to have twice the hardness of mild steel.

The relationship between component hardness and indent diameter has been established ("Prediction and Control of Indent Diameter", TSP, Spring, 2004). For that research, experiments were carried out in order to establish the reaction of different materials to a constant shot stream. Strips were manufactured to Almen strip dimensions from readily-available materials—mild steel, pure aluminum, copper and brass. Every material yielded saturation curves that had the same shape. The only difference being that the "10%" arc height decreased with increasing hardness. Indent diameters were found to depend on the "fourth root" of the materials hardness for a constant shot stream. The range of hardness for available strip metals is approximately sixteen to one. It follows that indent diameters will only vary by a factor of about two to one for a given shot stream.

Stability of strip deflection is an important consideration. The surface of peened strips is very heavily cold-worked and is therefore thermodynamically unstable. Raising the temperature of cold-worked metals induces structural changes, classically described as "Recovery, Recrystallization and Grain Growth." Even at room temperature, the arc height of a peened Almen strip diminishes, if only to a small extent, after peening has been completed. Fig.1 is a schematic representation of the two post-peening temperature-induced phenomena, recovery and recrystallization, which may affect arc height. The third phenomenon, grain growth, only occurs at high temperatures and will not normally affect arc height significantly. The shape of the curves shown in fig.1 is characteristic of body-centered-cubic (b.c.c.) metals such as ferritic steels. Initially there is a small exponential decay

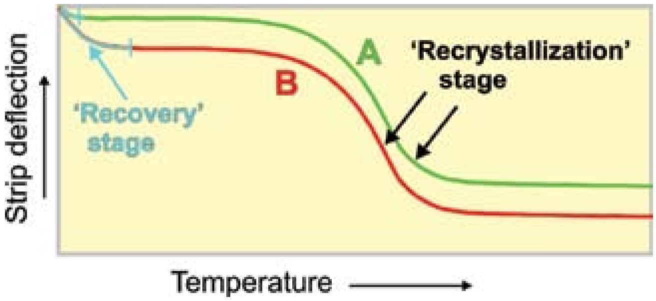

Fig.1. Temperature-induced strip deflection changes for b.c.c. metals.

(shown in blue). For curve A, recovery contributes only a tiny reduction in arc height. Curve B, on the other hand, indicates a significant reduction of arc height due to recovery.

The standard steel used for Almen strips is ferritic, which is synonymous with it being b.c.c. Experience shows that its behavior is equivalent to that of curve A. In effect, apart from a tiny reduction of arc height immediately after peening, the arc height remains stable unless it is subsequently heated. Tests involving repeated arc height measurements on the same steel strips have shown that their arc heights remained unchanged, even after thirty years, when kept at room temperature.

The shape of curves for heated face-centered-cubic (f.c.c.) materials, such as aluminum and austenitic steels, is different from that for b.c.c. metals. The classic curve is of exponential decay. This predominates throughout the recovery, recrystallization and grain growth stages. Fig.2 illustrates the type of behavior resulting from heating strips to a substantial temperature. Recovery mechanisms occur first, followed by recrystallization and finally grain growth. The rate of strip deflection decay depends upon the temperature.

Standard Almen strips, made from spring steel, have to be heat-treated to achieve required hardness levels. One hazard associated with this heat treatment is decarburization. If decarburization is allowed to occur then there will be a relatively-soft surface layer. Deflection of such strips will be reduced for a given shot stream.

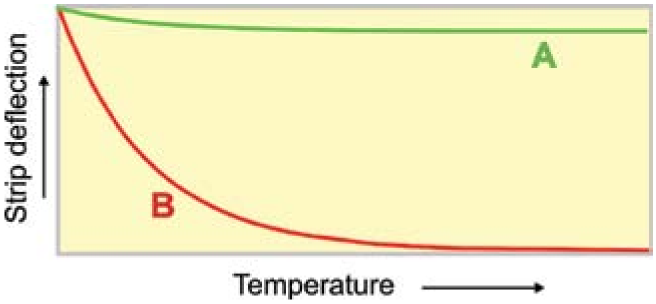

Fig.2. Temperature-induced strip deflection changes for f.c.c. metals.

Curve A in fig.2 is characteristic of peened hard aluminum alloy strips maintained at room temperature. Curve B is characteristic of peened pure aluminum strips. Pure aluminum would therefore be quite unsuitable for peening intensity measurements. Post-peening deflection reduces quickly, even at room temperature.

Component Contamination

The use of alternative strip materials, such as stainless steel and aluminum alloys, is determined by component contamination. Two main effects are involved:

(1) Material transfer and

(2) Corrosion cells.

(1) Material transfer

Three factors combine to promote material transfer both from shot particle to component and vice versa. These are: (a) breakdown of the protective oxide skins of component and shot particle, (b) impact velocity and (c) generation of heat at the shot/component interface.

(a) All components are covered with a very brittle oxide skin. This is shown schematically in fig.3 together with a region AC that is about to be impacted by a shot particle. ABC represents the dent's curved surface. As the shot particle forces its way into the component, the circular area AC is replaced by the dent's curved surface ABC. The dent's curved surface area is larger than the original (prior to indentation) circular area. The following is a specimen calculation that indicates the ratio of areas. This calculation reveals that the curved surface area is some 16% greater than the circular area. Since the ductility of metal oxides is well below 1%, it follows that multiple fracturing must occur. This fracturing is illustrated schematically in fig.3 and pictorially in fig.4 (page 30).

Ratio of circular area and curved indent area for a given dent.

Let us assume that the length AC is 20 (arbitrary units), the depth, h, of the dent is 4. The area, A_C, of a circle is given by $A_C = \pi * D^2/4$ - where D = diameter of the circular area. Hence, for this example, $A_C = 100 * \pi$. The area, A_D, of the dent's curved area (technically called a "spherical cap") is given by $A_D = \pi * (D^2/4 + h^2)$. Hence, again for this example, $A_D = \pi * (100 + 16)$ or $A_D = 116 * \pi$. A_D is therefore 16% larger than A_C.

At the instant of dent creation, the shot particle itself will suffer oxide skin breakdown.

(b) Shot particles impact components at a high velocity. Fracture of any brittle material occurs more readily at high velocities than it does at low velocities. A simple demonstration is what happens if a sheet of glass is struck violently with a hammer as compared to a low velocity blow.

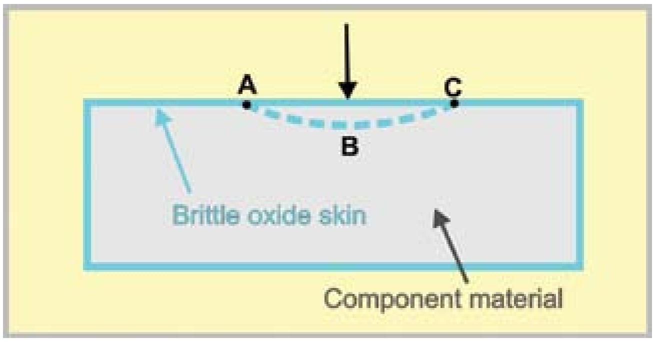

Fig.3. Brittle oxide skin about to be impacted by a shot particle.

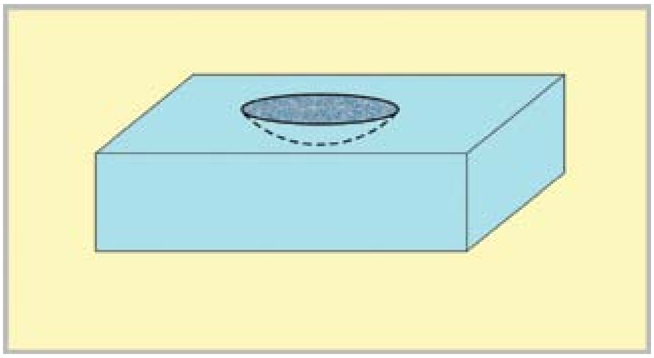

Fig.4. Pictorial representation of fractured oxide skin at the instant of dent creation.

(c) High temperatures are generated at the particle/component interface. This is due to the work done when forming the dent.

The three factors described combine to generate almost perfect conditions for metal transfer. The first two factors would be sufficient to induce "cold welding," aka "cold fusion." Cold welding is a process in which joining takes place without melting being required. The two surfaces are "nascent" (free of any form of surface coating) and are pressed together. In this situation there is no way that the atoms can feel that they belong to two different pieces. Cold-welding conditions are generated, because of oxide fracturing, at huge numbers of places on the dent/shot interface.

Fig.5 illustrates the cold-welding at a single place where two nascent surfaces of the same metal are pressed together. Two tiny fractions of a shot crystal and of a dent crystal are in contact along a line AB. The structure of the interface, indicated as a dotted line, is identical to that of a grain boundary. There is now no way for the atoms to know that they are in two different pieces of metal. Cold welding therefore becomes inevitable. It should be noted that each

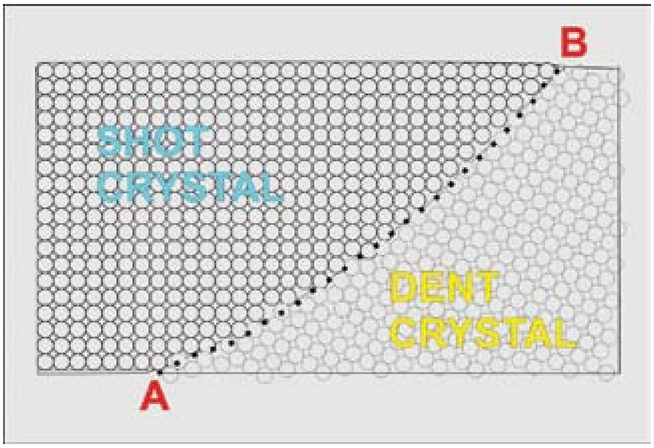

Fig.5. Interface structure for two identical nascent surfaces in contact.

cold-welded area is minute. However vast numbers of these minute areas are produced as a dent is being produced. Because of relative movement (between the shot particle and the dent) each cold-welded area will be torn apart. That means that material will be transferred—either to the dent surface from the shot particle or from the dent surface to the shot particle.

Material transfer rates will depend on the relative compositions of component and shot. The highest rates will occur if the two are identical. The lowest rates will occur if they are completely different—such as ceramic beads being used to peen steel components. Intermediate rates would occur if, for example, a standard ferritic steel strip holder was used to hold stainless steel Almen strips. Best practice dictates that the strip holder should also be made from stainless steel.

(2) Corrosion cells

Corrosion is the bane of all metallic components and is, of course, an enormous subject in its own right. As a general rule, single-phase materials (such as fully-austenitic stainless steel) are more corrosion-resistant than multi-phase alloys. The individual phases in a multi-phase alloy have different "electrode potentials." These phases can be ranked in what is called the "electrochemical series." A phase that is higher in the electrochemical series will act as a cathode and induce anodic reactions in a phase that is lower in the series—hence promoting corrosion. The situation can be likened to the way that a battery operates.

One study of corrosion cell promotion during peening concerned different stainless steel compositions. This study (Kirk, D and Payne N J, "Transformations induced in austenitic stainless steels by shot peening," ICSP 7, Warsaw, 1999, pp15-22) showed that there was a great difference between the behavior of 304 and 316 grades. For the 304 grade, peening transformed about 50% of the austenite into martensite—hence producing a two-phase structure that reduced corrosion resistance and also magnetized the steel. For the 316 grade, on the other hand, peening did not induce any transformation to martensite. Fig.6 (page 32) is a schematic representation of the vastly-different behavior. After peening, 304 grade becomes a mixture of interlaced martensite needles (colored red) and untransformed austenite (colored blue). 316 grade, on the other hand, retains its single-phase structure.

One moral for peening intensity measurement equipment is that stainless steel strips and holders should be made from a non-transformable grade such as 316.

SHAPE

Traditionally, peening intensity measurements are carried out using three different thicknesses of rectangular strips. The different thicknesses are needed in order to accommodate the

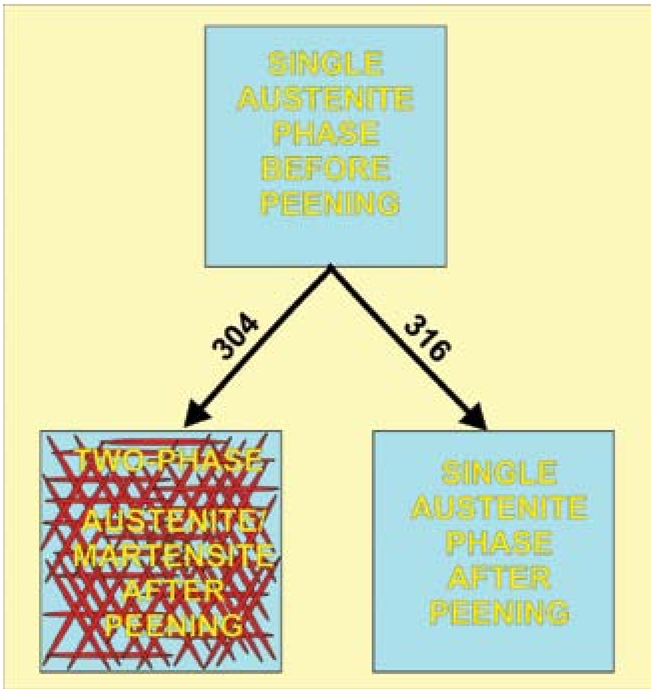

Fig.6. Differing effects of peening on phase structure of 304 and 316 stainless steels.

wide range of peening intensities that are currently employed. Smaller rectangles are manufactured for when intensities have to be measured in confined regions of components.

Circular discs were introduced in 1993 (Kirk, D, "Interactive Shot Peening Control", Proceedings of ICSP5, pp9-14). A linear variable displacement transformer (L.V.D.T.) was used that continuously monitored displacement as shot stream exposure time increased. Fig.7 is a schematic representation of the technique (being fig.4 of the quoted ICSP5 article).

A circular shape of test disc has the advantage that it corresponds to the circular cross-section of most air-blast shot streams.

Fig.8 is a schematic representation of a simplified version of that shown in fig.7. The simplification is to omit the L.V.D.T. This means that the curvature of the discs has to be measured after peening has been carried out—just as happens with the Almen strip technique. The arrangement shown in fig.8 could be employed if deflection was to be monitored using a series of discs, each peened for different times. With this very simple arrangement multiple holders could be jigged around complex components more easily then when using conventional rectangular strip holders.

A feature of shot-peened rectangular Almen strips is that they adopt two different curvatures. The curvature in the longitudinal direction is different from that in the transverse direction. As an approximation, the longitudinal contribution to deflection is about twelve times that for the transverse contribution. That contrasts with the fact that the length of an Almen strip is about four times greater than its width. Curvature is parabolic in both directions as opposed to being circular. A detailed discussion of Almen strip curvature was presented in 1999 (Kirk, D. and Hollyoak, R. "Factors affecting Almen Strip Curvature," Proceedings of ICSP7, pp 291-300).

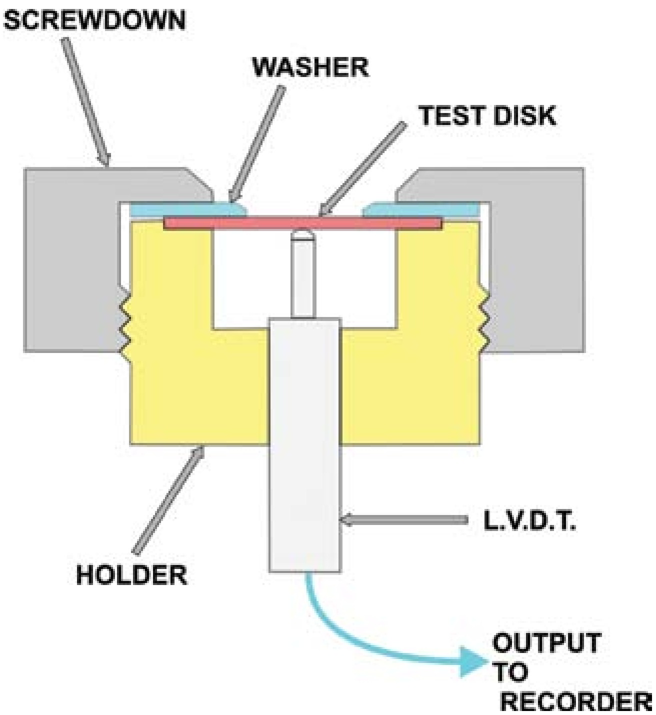

Fig.7. Circular test disc with L.V.T.D. monitoring.

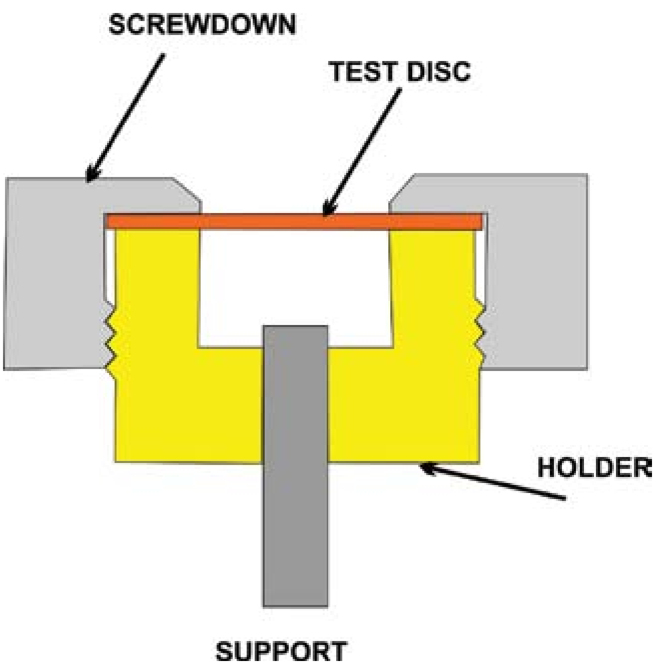

Fig.8. Circular test disc arrangement for intermittent peening.

For a circular test disc, the contribution to deflection will not be affected by direction.

DEFLECTION MONITORING

Peening intensity monitoring has, since 1942, been based on deflections of a set of Almen strips with each strip having been exposed to the shot stream for a different time. So-called "saturation curves" were fitted to the data points. A selected point on the saturation curve was chosen as representing the peening intensity value. This gave rise to terms such as the "10% rule" and the "20% rule." Over a period approaching three-quarters of a century, there have been no fundamental changes to the technique. Major improvements have, of course, been made to instrumentation and to methods of saturation curve analysis.

One constant factor has been the employment of dial gages to monitor deflection. Analogue gages require an operator to be able to read the gage whereas digital gages display deflection directly. With the relentless march of technology, digital signals are more appropriate as they can now be linked directly to computers for intensity evaluation. A common alternative for accurate displacement measurement is the L.V.D.T. as illustrated in fig.7. J. O. Almen would not have had access to L.V.D.T.'s in 1942. That does not mean that we have to use his original dial-based system.

The use of strain gages in conjunction with interactive displacement monitoring was described at ICSP6 (Kirk, D. "Developments in interactive control of shot peening intensity", pp 95-106). Although interesting as an academic experiment, strain gages are not a realistic alternative for industrial situations.

There is a fundamental, important, difference between rectangular strips and circular discs in terms of required relative movement. For rectangular strips, the shot stream is generally moved parallel to the major axis of the strip. That is necessary because the shot stream's cross-section is normally smaller than the major axis length. SAE J443 requires that rectangular strips must have received uniform denting. Previous articles in this series have, however, pointed out that the coverage must vary. Hence denting cannot be precisely uniform. There is no mention of requiring that the axis of the shot stream has to coincide with the major axis of the Almen strip. Inevitably, a slight difference in strip curvature will be induced depending on the difference between the shot stream travel axis and the major axis of the strip.

Fig.9 illustrates axis displacements for a given shot stream. For A, the shot stream travel is co-axial with the major axis of the Almen strip (colored yellow). For B, the shot stream travel is offset from the major axis of the strip. The effect on strip curvature will depend on the diameter of the shot stream, the degree of offset and the variation of shot velocity across the shot stream.

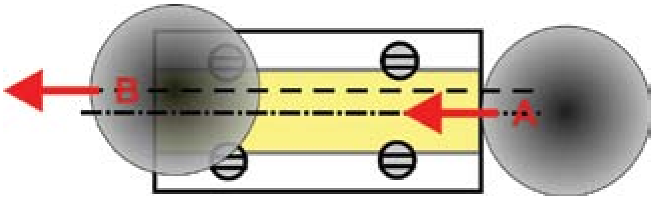

Fig.9. Co-axial and displaced shot stream travel along an Almen strip.

If circular test discs are being employed, there is no need for relative movement of shot stream and disc. For setting-up, an over-sized version of that shown in fig.8 could be employed to confirm axial coincidence of disc and shot stream centers.

CONCLUSIONS

Several variations on the Almen technique have been presented in this article. There is no doubt that the standard technique, based on sets of rectangular strips, is both robust and reliable. That does not mean, however, that there is no place for alternatives. The twin concepts of circular test discs and continuous monitoring do offer advantages in specific situations. Peening intensities can be measured in less than a tenth of the time needed for the conventional Almen technique. Since only one disc is involved, confirmation testing generates a complete saturation curve that can be compared with the original set-up curve.

FACTOIDS

The Top Ten Most Dangerous Jobs in the World

We've added commentary on the more surprising ones.

10. Truck drivers - *Long hours and massive vehicles put truck drivers on the list*
9. Stunt men/women
8. Sanitation workers - *Heavy materials and toxic or hazardous substances place sanitation workers at risk*
7. Firefighters
6. Miners
5. Loggers - *Falling timber, unpredictable wildlife, and chainsaws are risky enough; in addition, loggers often work in remote locations where help can be slow in coming*
4. Bush pilots - *Rough terrain and hostile weather make bush flying very dangerous*
3. Deep sea fishermen *The #1 most dangerous job in the United States*
2. Landmine removers
1. Astronauts - *448 astronauts have gone into space as of April 2016; 34 have died. With a morality rate of 7.5%, this profession is the most dangerous in the world.*

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