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Development of Shot Peening Control and Residual Stress Patterns

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ABSTRACT

This paper involves a consideration of the advantages and disadvantages of existing methods of shot peening control. A new method of control is proposed based on the use of linear variable displacement tranducers to monitor the progress of curvature during the peening process. It is further proposed that the traditional rectangular test strip could be replaced by a circular disc. The residual stress patterns induced by shot peening are considered with particular reference to the stability of the pattern under the influence of thermal or strain treatments. The proportion of induced curvature that is due to residual stress rather than inhomogeneous plastic deformation is analysed.

KEYWORDS

Controlled peening. Curvature. Interactive control. Residual stress. Stress relief.

INTRODUCTION

Commercial shot peening can vary between a very coarsely-applied process to one which involves the careful control of several important peening parameters. Within the confines of this paper only selected aspects of that control can be considered. The need for some form of control has been recognised for many years. The shot peening industry relies heavily on the "Almen Gauge" introduced by J. O. Almen in 1943. Rectangular steel strips of controlled composition and thermal history are peened whilst being held flat and the deflection on release is measured. The deviation from flatness is the "Almen Arc Height", **H**, and is presented for strips of one or other of three thicknesses. These three thicknesses accommodate the wide variation of peening intensity that is presented by the use of different particle masses and velocities. Essentially the total work done on the peened strip, **W**, is being monitored. **H** is proportional to **W** without being a linear function. **W** can be expressed by means of the following equation:

$$W = \sum_{0}^{t} p.\tfrac{1}{2}.m.v^2.n.dt \qquad (1)$$

where p = proportion of the kinetic energy, $\tfrac{1}{2}mv^2$, absorbed by the strip when it is struck by an individual particle of the n particles that strike the strip in an interval of time, dt, within the total peening time, t.

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Eq. (1) epitomises the problems associated with shot peening control. The proportion of energy absorbed, p, will vary with each individual particle as will the mass and the velocity. The rate of delivery of particles, n/dt, will not remain constant. The great advantage of the Almen Gauge is that it reflects the total work done in the peening time, t, and therefore accommodates unavoidable variations in each parameter. The major disadvantage of the Almen Gauge, however, is that it is retrospective in the sense that it looks back at the total work done rather than being interactive. An interactive control would allow communication of control during the actual peening process. There are some useful techniques that involve a degree of interactive control of specific aspects of shot peening. Devices are available for both the monitoring and flow control of shot peening media[1]. Coverage control can be exercised by using the "Peenscan" process[2] although this is rather more retrospective than interactive. All peening equipment involves some form of interactive control through such factors as air pressure, nozzle distance and peening time.

INTERACTIVE PEENING INTENSITY MEASUREMENT

Fig.1 shows the prototype of our interactive peening intensity measurement device. A conventional Almen strip is held in spring-loaded jaws (rather than being held flat by 4 screws as in a conventional device). Compression of the strip is effected by the screw shown on the left of the device until the flat strip is just held securely without being bent. The upper surface is peened and adopts a curvature as shown. The displacement from the initial flat shape is monitored using a linear variable displacement transducer (LVDT) connected to a displacement/time recorder. The handle shown on the right of the photograph was to facilitate laboratory experiments invoving sliding of the device under a fixed shot peening nozzle. In hundreds of tests we found that the strip remained secured in the jaws.

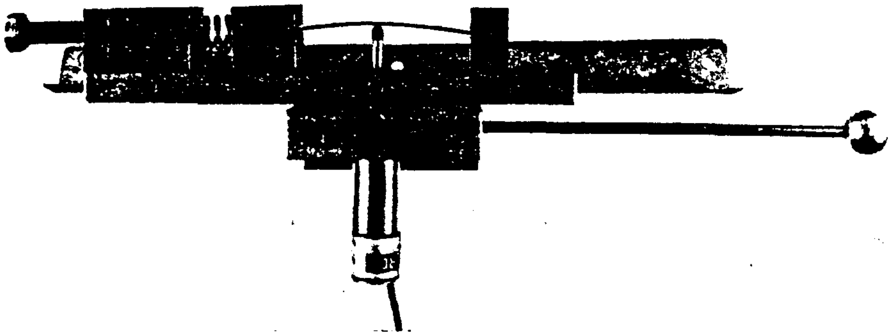

Fig.1: Interactive peening intensity measurement device.

Studies[3,4] have shown that there is excellent correlation between the displacement of the LVDT and the Almen Arc Height registered for identical shot peening intensities. Table 1 shows the results of a typical correlation test. It will be noted that the LDT displacement using the interactive device is some five times as large as that for a corresponding Almen strip.

Almen Arc Height - mm	LVDT Arc Height - mm	Peening Time - s
0.10	0.40	3
0.19	0.85	8
0.24	1.05	11
0.35	1.60	28
0.45	2.05	45
0.49	2.30	72
0.50	2.40	91
0.52	2.50	102

Table 1: Correlation between Almen Arc Height and LVDT Arc Height.

For the experimental results shown in Table 1 a fixed air pressure of 34 psi was used with S330P steel shot at a stand-off distance of 195mm for Almen "A" strips. A feature of the standard Almen test is that the peened strip shows two different curvatures corresponding to the major and minor axes of the rectangular strip. We have investigated the alternative of using a circular test strip held in the device shown in Fig.2. A 40mm diameter steel of very similar composition and thermal history to Almen strips were clamped using the annular ring. A LVDT was positioned so that the probe just touched the disc specimen through the central hole. The lugs on the device facilitate positioning at different distances from the fixed peening nozzle.

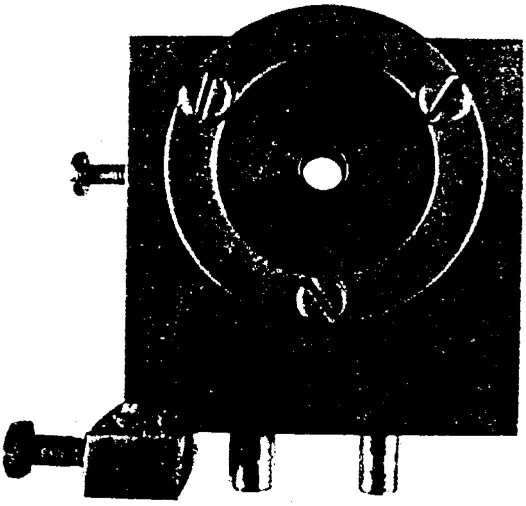

Fig.2: Clamping jig for disc-shaped LVDT Arc Height specimens.

Again excellent correlation has been found between the LVDT Arc Height measured using this device and that from standard Almen strips given the same peening intensity. A virtual one-to-one correlation can be achieved by adjusting the disc diameter. The advantages of using disc-shaped specimens are that a single curvature is induced and a more compact design is effected which is better suited to the rigours of an industrial peening environment. The LVDT is contained within a robust enclosure integral with the holding device. Our latest development[5] of the interactive peening intensity measurement device is to connect the LVDT output to a "traffic light" display box. As peening progresses a green light is illuminated within the peening cabinet. When the required peening intensity is approached an amber light is illuminated followed by a red light when the required intensity has been achieved. The activation of illumination is readily adjusted to specific LVDT Arc Height values. The object here was to introduce a system that would be more suited to industrial peening situations rather than a system more appropriate to laboratory conditions. Tests have shown that with both rectangular and disc-shaped specimens the progress of strip deflection during peening is very similar to that of "saturation curves" produced by using several Almen strips peened to different times. A single specimen therefore allows interactive peening control to be effected in the sense that peening can be terminated as soon as the required intensity has been achieved rather than relying on reproducing the conditions dictated by the Almen test.

RESIDUAL STRESS PATTERNS

The primary objective in shot peening is to induce a surface layer of compressive residual stress. The nature of the sub-surface residual stress profile is well-established and depends primarily on the yield point of the peened material for its magnitude and the size of the shot used for its depth. Residual stress patterns are caused by the tensile plastic deformation of the surface. The magnitude of the surface compressive stress and the subsurface profile cannot, however, be deduced from the Almen Arc Height. This height is due to two separate factors - the residual stress pattern and the tensile plastic deformation itself. The relative contribution of the two factors can be deduced by stress-relieving peened Almen test strips. It is invariably found that only a proportion of the curvature is recovered by stress-relieving. Table 2 shows the results of isochronal annealing experiments carried out on shot peened Almen 'A' strips.

Temperature - °C (1 hour)	**Longitudinal radius - mm**	**% change**	**Transverse radius - mm**	**% change**
200	682	4.4	397	0.5
300	716	15.9	448	13.1
325	857	22.4	683	28.4
350	901	27.8	820	41.1
375	803	29.7	581	52.5
400	1023	39.0	703	52.5
425	809	25.6	561	35.8
450	935	39.6	684	52.7
475	978	39.5	701	52.1
500	892	38.9	666	52.4

Table 2 Influence of isochronal annealing on curvature of peened Almen 'A' strips.

The results indicate that only about half of the curvature is recovered by thermal treatments well in excess of those required to effect full residual stress relief (separate X-ray residual stress measurements showed that stress relief reached 95% at 400°C). With different materials we have found that the recovery varies between 10% and 60%. The anomalous behaviour at 425°C is thought to be related to phase changes induced by thermal treatment of heavily cold-worked material. The precipitation of a separate phase that contains a high level of compressive residual stress due to volume expansion can induce tensile stress in the matrix material. X-ray residual stress analysis is unique in that it measures the residual stresses in specific crystalline phases. Grossly anomalous behaviour has been observed in shot peened Nimonic alloys which developed high matrix tensile stresses on elevated temperature treatment. These highly-complex alloys are, fortunately, exceptional in exhibiting such behaviour.

The effect of small amounts of tensile plastic strain on shot peened materials is very significant. Fig.3 shows the results of experiments carried out on a classically simple material - annealed O.F.H.C. copper. The residual stress profile for the as-peened material shows the classic shape with the maximum compressive stress occurring just below the peened surface. It should be noted that the maximum level of stress is a large proportion of the yield strength of material in the heavily cold-worked state rather than of the yield strength of the unpeened material.

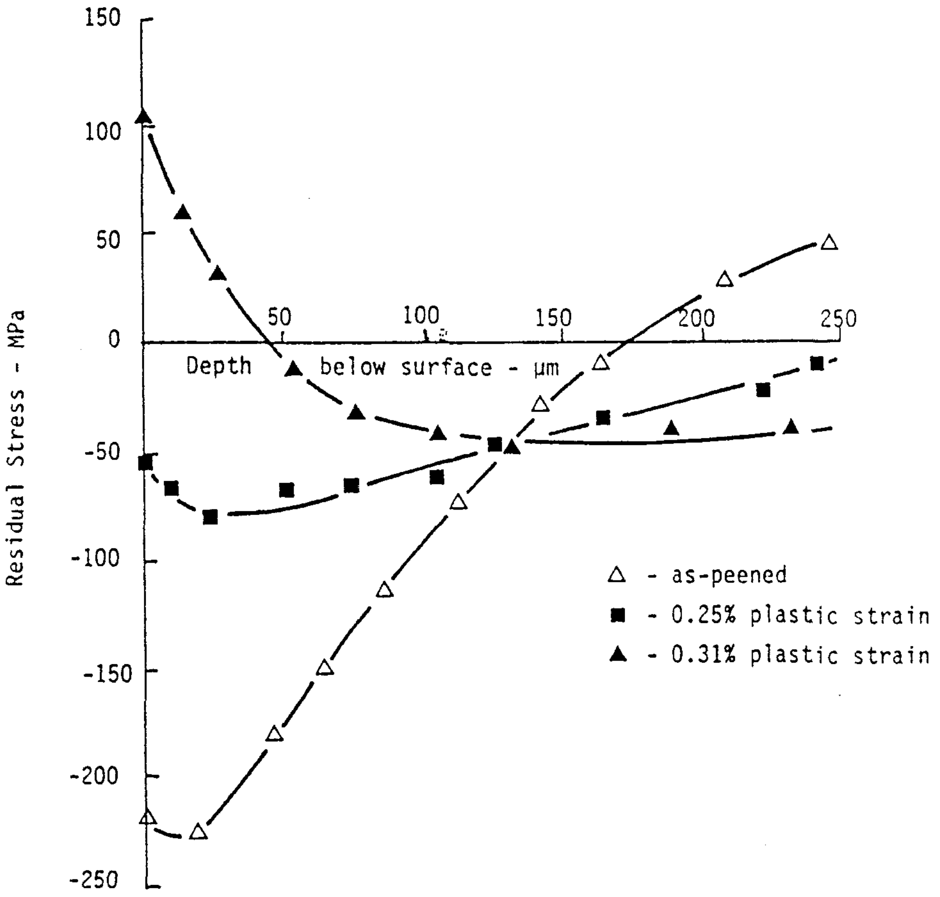

Fig.3: Residual stress profiles for as-peened and plastically-strained O.F.H.C. copper.

The experimental procedure involved shot peening flat tensile test pieces on both major faces followed by tensile stretching. As plastic tensile strain proceeds the surface compressive residual stress falls rapidly until at about 0.28% plastic extension the surface stress changes from compressive to tensile. Further plastic deformation induces a high level of tensile surface residual stress. Similar behaviour has been observed in such a wide range of materials that it can be assumed to be the expected outcome of applying tensile plastic strain to shot peened components. The critical plastic strain for inducing tensile surface residual stress in steels has been found to vary between 0.12% and 1.1% depending upon the composition. The presence of a surface tensile residual stress in a shot peened component would not be a desired situation! Even small plastic strains must therefore be avoided even more rigourously than thermal stress relief.

DISCUSSION

The extent of knowledge concerning the effective control of shot peening continues to grow rapidly. There are, however, a number of areas where further developments are urgently needed. These include the application of interactive means of controlling the peening intensity and studies of induced residual stress patterns and their mechanical and thermal stabilty. Too much reliance has been placed on traditional Almen tests which are essentially restrospective and only reflect the response of one particular material. The use of one, standard, material is necessary when the absolute.peening intensity has to be measured. Rectangular strips are not necessarily the best shape of test specimen and consideration should be given to the introduction of disc-shaped specimens as standards. Interactive techniques should be developed and would be particularly useful for individual, or small runs of, components. Interactive techniques, such as the one presented here, can be used not only with a standard strip material but also with strips simulating the material of the actual component. More work needs to be done on the understanding of how the residual stress pattern develops, particularly in multi-phase materials, and how the stresses are distributed between the separate phases.

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