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FACTORS AFFECTING ALMEN STRIP CURVATURE READINGS

D. Kirk and R. Hollyoak
Coventry University, Coventry, U.K.

ABSTRACT

This study considers the actual shape of deformed Almen strips, the source of that shape, variations in strip parameters and peening variables affecting curvature readings. It is shown that deformed Almen strips have a shape based on three-dimensional parabolic curvature. This shape can only be induced by the generation of uniformly-distributed surface forces. Complex curvature found in clamped, peened, strips is explained in terms of hold-down bending moments. Batches of Almen strips have been found to have remarkable in-batch consistency of hardness and dimensional properties. Inter-batch variation of hardness is, however, significant. Hardness has been correlated with tensile properties. X-ray analysis showed that Almen strips do not possess crystallographic preferred orientation. The torque applied to the hold-down screws has been shown to have a small but insignificant effect on curvature readings. Air pressure variations have a much greater influence on induced curvature.

KEY WORDS

Almen strips, curvature, bending moments, torque, preferred orientation, hardness, tensile properties.

INTRODUCTION

The Almen gauge has been the primary shot peening intensity control device since its introduction in the 1940's. Fuchs[1] gave a definitive analysis of the defects and virtues of the Almen Intensity Scale. The curvature of a peened test strip is measured using the gauge under specified conditions[2]. Increased sophistication of the gauge itself has allowed readings on a given strip to become both more objective and reliable[3]. Several authors, including Happ and Rumpf[4] have investigated the variability of Almen test strips themselves.

Almen strip intensity is determined by the deflection of the strip when it has been released form a block that held it down at four points. It is tacitly assumed that the strip adopts a curvature that is circular in two dimensions, see Fig.1.

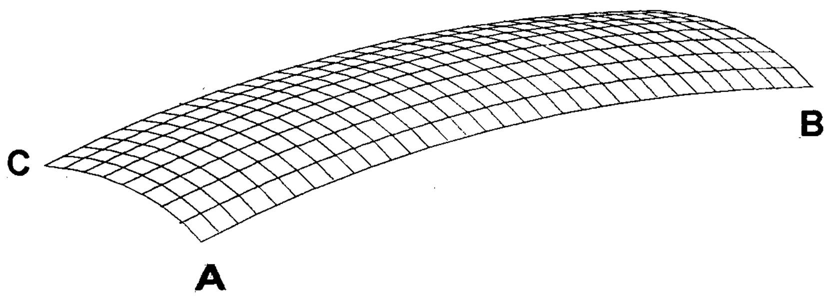


Fig.1 Assumed Almen test strip circular curvature about arcs AB and AC.

Assumptions are also made that the observed curvature is caused by a residual stress system induced by the peening. It has, however, been shown that most of the curvature is retained even if the curved strip is given an intense stress relieving treatment[5].

Manufacturers produce Almen test strips to a given standard specification[2]. Of the several factors listed perhaps the most noteworthy is the permitted hardness variation. This is quoted as 44-50RC, which is equivalent to a Vickers hardness range of 441-547. Also noteworthy is that the hold-down torque is not specified. This might be a significant variable since the shape change induced during peening bears some relationship to the sheet metal working operations of cupping and deep drawing. The essential difference between those operations is that for one the hold-down pressure is high and for the other it is low.

For this research the assumption of circular curvature is examined together with variations in test strip properties and peening parameters.

EXPERIMENTAL METHODS

Curvature of deformed Almen strips

The curvature of deformed Almen strips has been examined using a computer-controlled X-Y-Z co-ordinate measuring system. This system includes a Kemco 600 co-ordinate measuring machine and QCT-3d measuring software operating with digitised points.

Dimensional variations

Variations of length, width and thickness were estimated using standard workshop vernier micrometers. Weight variations were determined using a laboratory balance having an accuracy of 100μg.

Mechanical properties

Hardness measurements were made using a calibrated Vickers Hardness Tester. Tensile properties of ultimate tensile strength and ductility were determined using a calibrated Monsanto tensile testing machine on specimens machined from as-received Almen test strips.

Preferred orientation

Crystallographic preferred orientation was examined using back-reflection X-ray diffraction to produce Laue photographs. Chromium K_α radiation was employed with a film-to-specimen distance of 100mm.

EXPERIMENTS and RESULTS

Curvature of deformed Almen strips

Two peened N strips were initially examined in order to determine any deviation from circular curvature. One strip had been 'free-formed' by peening, using S170 shot, and held in an early type of interactive intensity measurement facility[6]. With that facility the strip is held in spring-loaded jaws at each end and is free to deflect during peening. The other strip had been peened, using S170 shot, to standard specification conditions. Hence the extremes of clamping were being tested. Measurements were made along the longitudinal and transverse central axes of the peened faces. Figs.2-5 gives all of the data points together with best-fitting curves and their equations. Surprisingly the curvatures in both directions for both specimens are almost perfect quadratic parabolas of the form $y = ax^2 + bx + c$. This finding is contrary to the assumed circular curvature.

Curvatures of clamped and then released Almen strip

In view of the previous curvature findings, measurements were made on a peened N strip (a) after peening but while still clamped on its block and (b) after release from the block. The corresponding data points are given in Figs. 6 and 7. In Fig.6 the axes of the hold-down bolts have been marked as A and B. The curvature after release from the block was parabolic in both directions being very similar to Figs.2 and 3. Fig.8, below, gives a schematic representation of the complex curvature displayed by a clamped, peened, Almen strip.

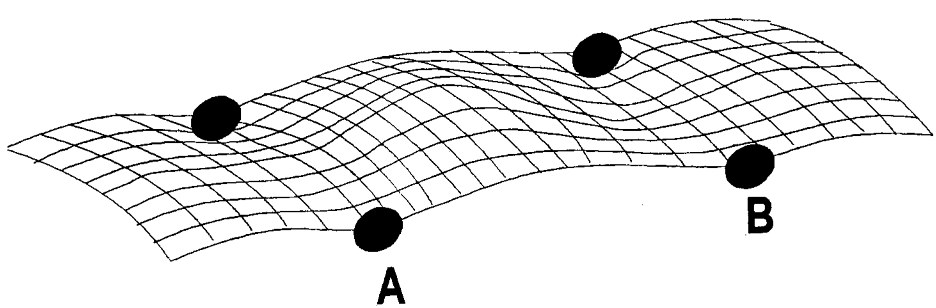


Fig.8 Complex curvature of peened Almen strip clamped with pairs of bolts at A and B.

The clamped, peened, Almen strip shown above is in contact with the holding block at eight points corresponding to the four corners and beneath the four hold-down bolts. The longitudinal curvature is complex but the transverse curvature appears to be parabolic along the whole length of the strip. It should be noted that the vertical displacements have been amplified relative to the strip's planar dimensions in order to highlight the variation of curvature.

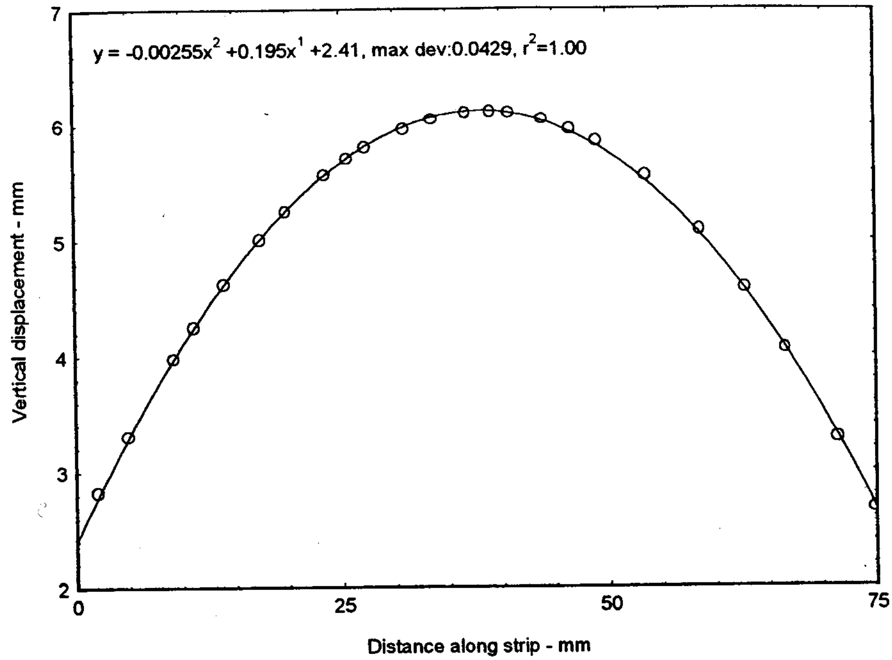


Fig.2 Longitudinal curvature variation for free-formed Almen N test strip.

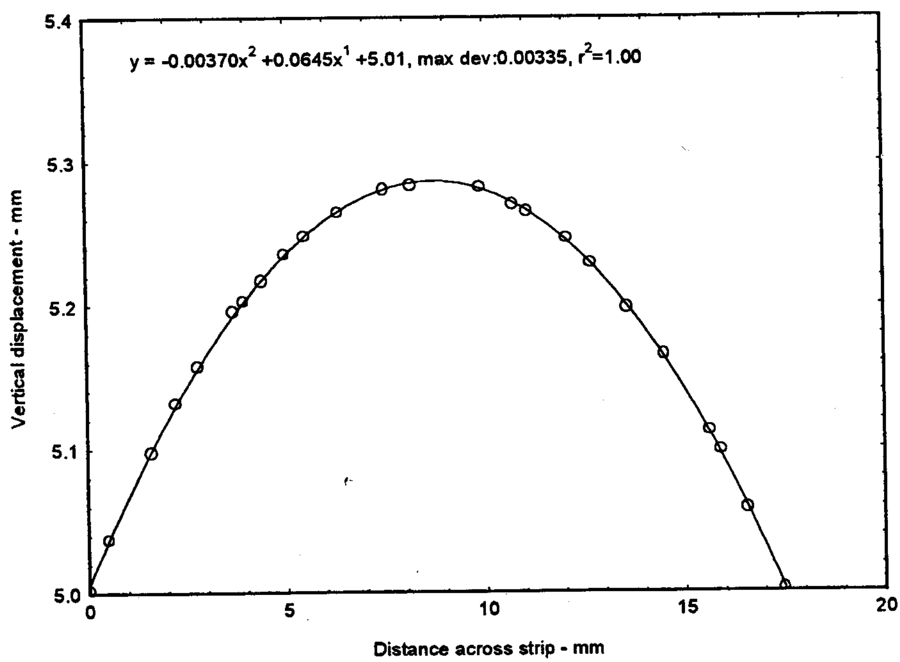


Fig.3 Transverse curvature variation for free-formed Almen N test strip.

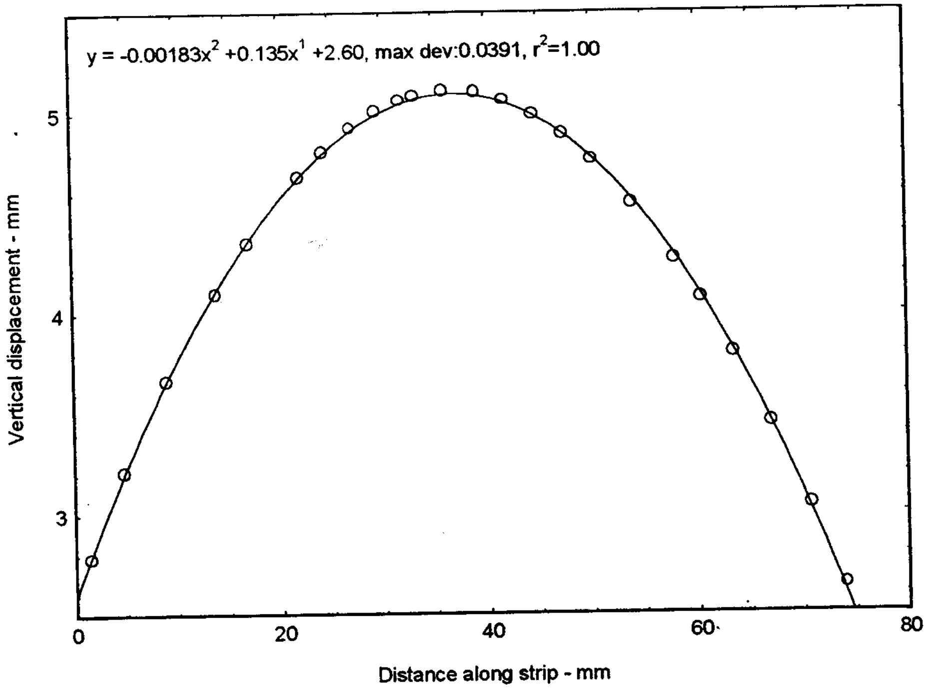


Fig.4 Longitudinal curvature variation for Almen N strip peened using standard conditions.

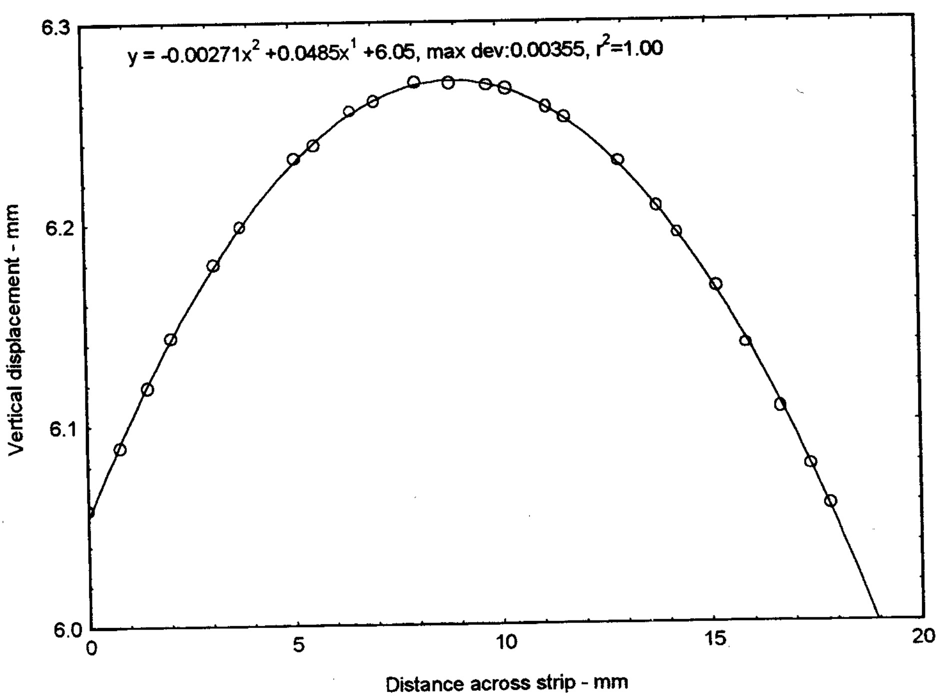


Fig.5 Transverse curvature variation for Almen N strip peened using standard conditions

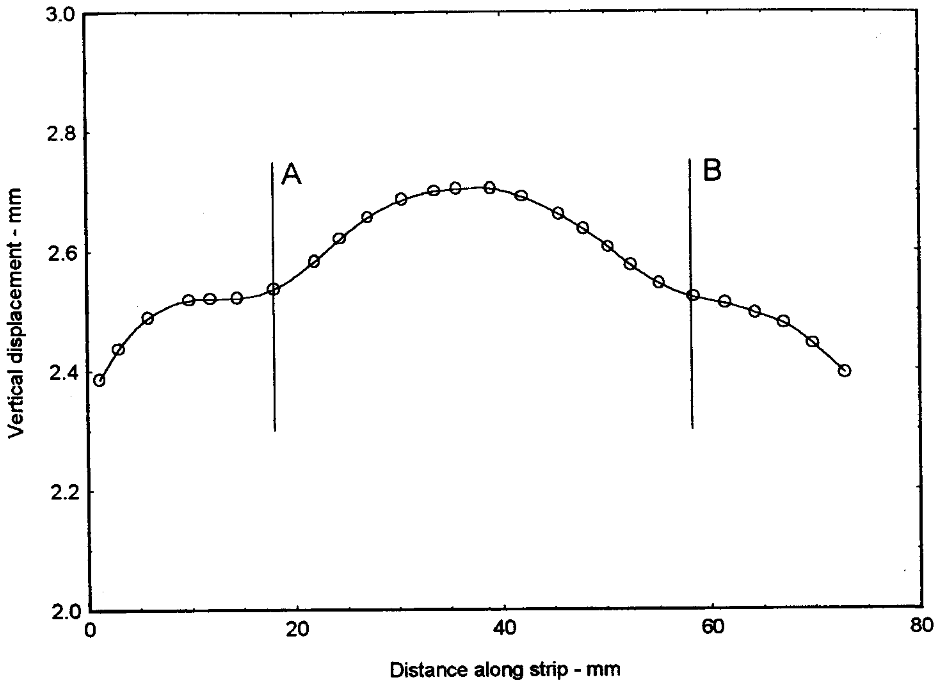


Fig.6 Longitudinal curvature variation for as-clamped, peened Almen N strip.

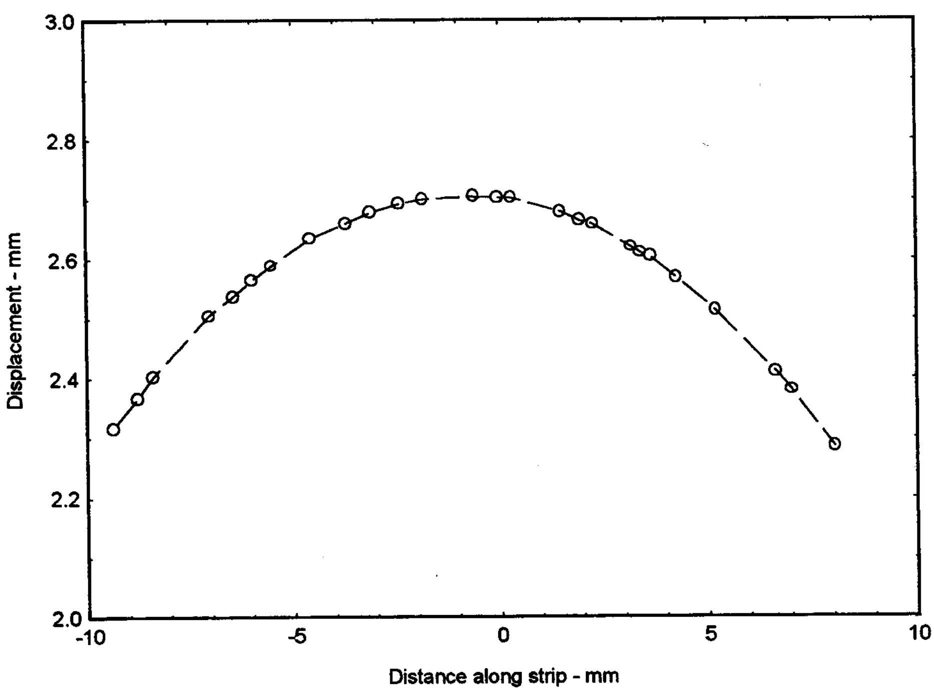


Fig.7 Transverse curvature variation for as-clamped Almen N strip

Property variations of Almen test strips

Batches of 48 A and N thickness Almen strips were examined for variation of length, width, thickness, mass and hardness. Single measurements were made for each of the strips. The findings are presented in Table 1.

Table 1 Property variation for batches of N and A Almen test Strips.

Almen Strip type	Length - mm	Width - mm	Thickness - mm	Mass - g	Hardness - HV20
N	m =76.09 σ = 0.046	m = 19.04 σ = 0.04	m = 0.776 σ = 0.003	m = 8.8042 σ = 0.02444	m = 507.3 σ =5.7
A	76.04 σ = 0.036	19.00 σ = 0.01	1.287 σ = 0.005	14.4523 σ = 0.04200	492.2 σ = 8.5

Where m = mean of 48 readings and σ = standard deviation of 48 measurements.

Sets of 10 hardness measurements along individual N and A strips, taken randomly from the batches, gave m = 502.4, σ = 4.8 and m = 482.7, σ = 3.7 respectively.

Tensile Properties of Almen test strips

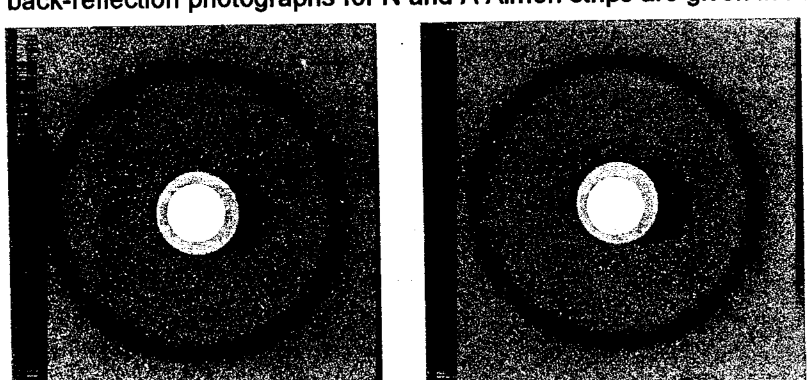
Table 2 gives the findings for tests carried out on N strip and A strip tensile specimens.

Table 2 Tensile Properties for N and A Almen test strips

Sample No.	U.T.S. - MPa	Elongation - %
N1	1617	4
N2	1666	4
N3	1688	5
	Mean = 1657	
A1	1577	7
A2	1626	7
A3	1576	7
	Mean = 1593	

Preferred orientation

Laue back-reflection photographs for N and A Almen strips are given in Fig.9



N strip(a) A strip

Fig.9 Laue back-reflection photographs for Almen test strips.

Effect of hold-down torque

Previous unpublished work had indicated that there could be a relationship between hold-down torque and Almen arc height. This possibility was examined by fixing the peening conditions (S170 steel shot, 5 bar pressure, 300mm stand-off distance) for peening of 20 Almen N strips. Each author carried out tests independently on pairs of specimens held down with each of 5 different torques applied to the hold-down bolts. Seven measurements of arc height were made for each specimen. The findings are summarised in Fig.10 that shows that, for a given author, there is a slight but insignificant variation of height with torque. More significantly it was observed that the average values obtained by each author were slightly different. This has been ascribed to insensitivity of air pressure regulator settings.

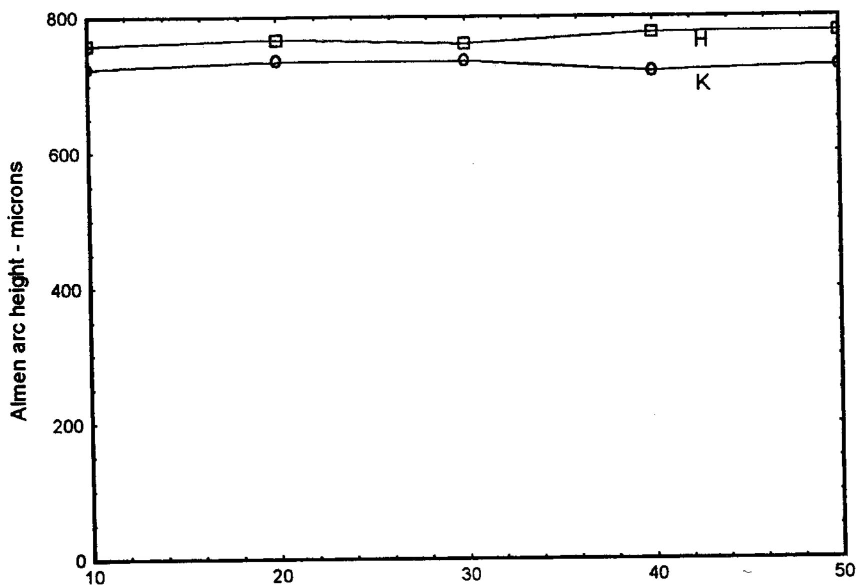


Fig.10 Effect of hold-down torque on Almen arc height readings.

DISCUSSION

Curvature of Almen strips

A major finding has been that deformed Almen strips have parabolic rather than circular curvature on release from the holding block. This curvature extends along both major strip face axes. The source of the parabolic curvature is the uniform loading that is applied to the strip – equivalent to the parabolic deflection of a uniformly loaded constant section beam reported in all standard texts on beam bending. If we consider the bending that would be applied by four-point loading to a parabolically-bent beam we have the situation illustrated in Fig.11. If we assume that equal hold-down forces are being applied at the bolt positions S1 and S2 we have the classic bending situation with a constant moment between S1 and S2. In the central region the applied moment is insufficient to neutralise the induced bending so that a positive deflection remains. At S1 and S2 the applied moment more than offsets the induced moment so that we have the relative depressions shown at A and B in Fig.8.

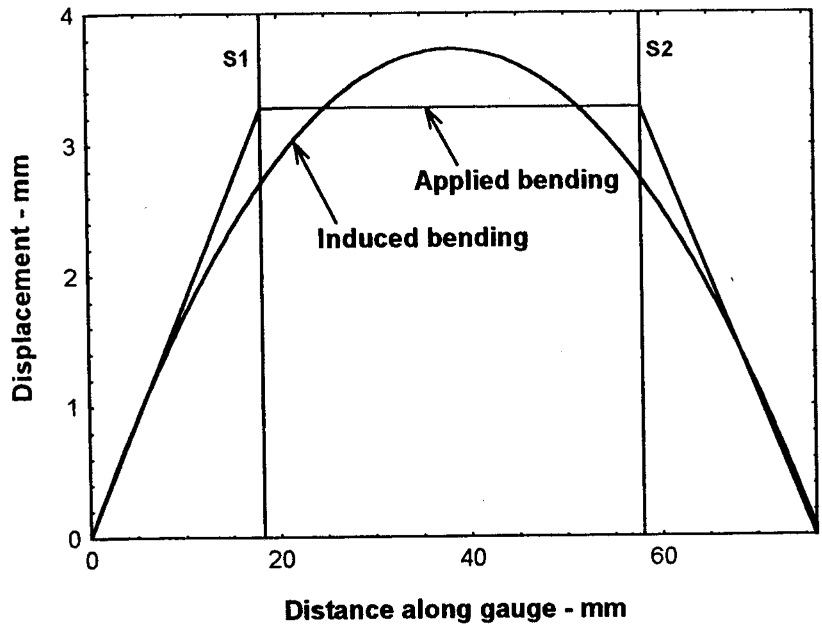


Fig.11 Displacements associated with induced bending and applied bending moments.

The measured deflection at the centre of a clamped-down strip is obviously much less than after release from the block. This small deflection could, however, form the basis of another interactive peening intensity measurement device. Parabolic deflection reinforces the observation that care should be taken to centralise Almen strips on the Almen gauge. In this connection the provision of 'end stops' on some gauges is significant.

Property variations of Almen test strips

The observations on property variations have indicated that commercial Almen strips are produced with a high degree of consistency within given batches. Physical dimensions are relatively easy to maintain so that the observed uniformity is to be expected. It was found that mass was the easiest parameter to monitor accurately. Hardness variations within a given batch were very small, as would be expected. The hardness difference between N and A strips was significant. The N strips were harder than the A strips which is consistent with their higher U.T.S. and lower ductility. It would be expected that a softer strip would harden more rapidly than a harder strip. Since Almen deflection is proportional to the amount of work done on the strip, softer strips will give a different Almen intensity value than harder strips for a given peening treatment. This has practical importance as the allowed specification range for hardness is rather broad. Neither type of strip showed any significant preferred orientation which was unexpected bearing in mind the difficulty of avoiding the effect in heavily-worked metals.

Effect of hold-down torque

The absence of any significant variation of Almen height with hold-down torque is useful since torque does not feature in standard specifications. This work does, however, highlight the importance of maintaining air pressure at known levels. Air pressure is a primary factor influencing peening intensity as it governs the velocity of shot accelerated towards the workpiece. Shop-floor pressure variations depend on a number of factors including the size/capacity of air ballast tanks, compressor capacity and variations in demand. Commercial practice often involves variable take-off from a central air pressure supply. Sensitive interactive regulators would be necessary to maintain a constant gun air pressure in the face of fluctuating demand. Obviously 'end-of-line' peening cabinets and facilities with limited compressor capacity are very much at risk.

CONCLUSIONS

- Peened Almen strips adopt a parabolic curvature in both major dimensions.
- Clamped Almen strips adopt a complex curvature on peening and before release.
- Commercial Almen strips have a high level of consistency in terms of dimensions and mass and do not contain significant preferred orientation.
- Significant variations have been found between the hardness of different batches of Almen strips, which would affect intensity measurements.
- Hold-down torque has only a very small effect on peening intensity.

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