ACADEMIC STUDY

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Hardness Testing

INTRODUCTION

Fortuitously, for shot peeners, their hardness testers don't measure hardness! Classically, hardness is defined as the resistance of a material to abrasion. Tests such as that of the Mohr's Scale, arranged substances according to their ability to scratch any material below it. Hence diamond heads the scale with a value of 10 whilst talc, with a value of 1, is at the foot of the scale. Methods have later been developed that have much greater precision and accuracy. These, however, are based on the size of indent produced using a known force to an indenter. The applied force divided by the surface area of the indentation gives the so-called hardness value.

The Brinell test, devised in 1900, involves pressing a hardened steel ball into the test piece's surface. Brinell hardness is then given by Applied Force/Surface area of impression. The Vickers Hardness Test uses a diamond in the form of a square-based pyramid. This does not deform to the same extent as does a steel ball. For a given applied force, Vickers hardness value increases as the diagonals of the indentation decrease. Ludvik invented the first differential depth hardness tester in 1908. The Rockwell differential depth hardness tester, devised in the USA in 1914, was aimed at rapid routine testing of samples. This is because the Rockwell value is displayed directly on a scale, without the need for operator intervention. Different combinations of indenter and applied force became available. All of the methods rely on resistance to indentation—which is at the heart of shot peening control.

This article concentrates on the applications of the Rockwell test. A central problem arises when different companies test nominally identical samples such as batches of Almen strips. Proper comparison can only be achieved if the test method employed is precisely identical: ASTM E-18 (USA) and ISO 6508 (International) are appropriate standards.

BASIC PRINCIPLES OF ROCKWELL HARDNESS TESTING

Fig.1 is a schematic representation of the Rockwell's operating principle. A minor force is applied to a diamond indenter, pushing it into the surface of a test piece. This is followed by a major force which pushes the indenter further into the test piece. The corresponding movements of the diamond's position are used to derive a Rockwell hardness value. Standards indicate that the diamond has a tip radius of 0.2 mm and an enclosed angle of 120˚. The tip radius greatly reduces the incidence of tip damage.

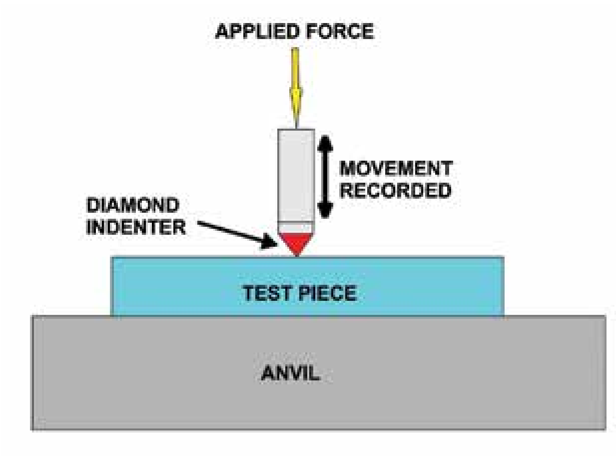

Fig.1. Schematic of Rockwell Diamond hardness testing.

Fig.2 represents the relationship between the three diamond positions, A, B and C, and the depth, D, which is converted into a Rockwell hardness value.

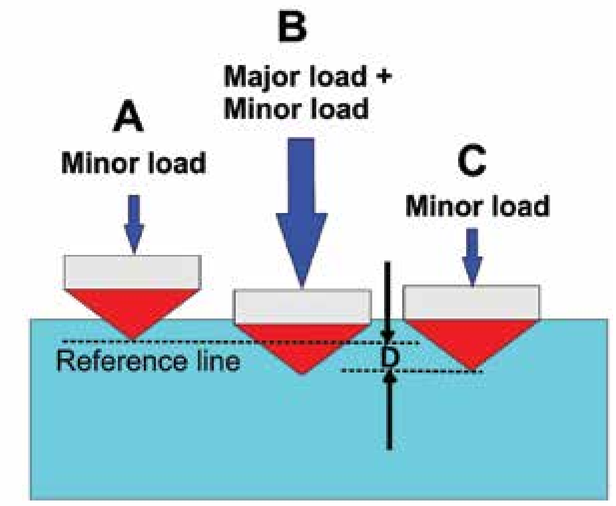

Fig.2. Diamond positions during Rockwell testing.

A minor load is first applied pushing the diamond down into the test piece, A. The depth reached defines the reference line. A major load is then added to the minor load, pushing the indenter much further into the test piece, B. The total load (major plus minor) also causes elastic deformation. This effect is relieved by removing the major load whilst retaining the minor load, C. The vertical difference between diamond positions at A and C, D, is inverted to give the Rockwell hardness. The smaller the value of D the greater is the resistance to indentation—hardness. The Rockwell test is very cost-effective as it does not need any optical equipment. The depth, D, converts to Rockwell hardness using the formula:

$$\textbf{Rockwell hardness} = 100 - D(\text{mm})/0.002(\text{mm}) \quad (1)$$

It follows that an error of only 0.002 mm in the measured value of D produces an error of 1 HR unit.

ALMEN STRIP TESTING

Almen strip testing is an excellent example for showing how errors can occur. Every Almen strip has a small amount of pre-bow. The anvil shown in fig.1 is presumed to be perfectly flat. When a strip is placed on the anvil it can be either "curve up" or "curve down". The effect of this on Rockwell measurements is illustrated in fig.3. The pre-bow has been deliberately exaggerated.

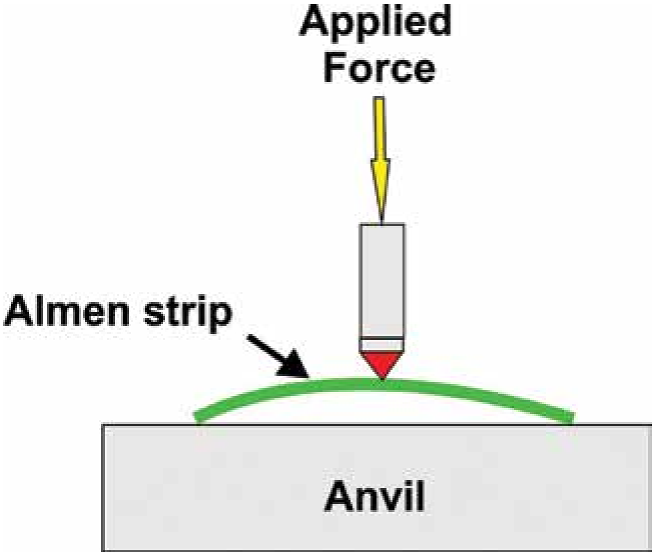

Fig.3. Rockwell indenter applied to curved-down Almen strip.

The minor force applied by the Rockwell indenter, typically 10 kgf, is sufficient to flatten a pre-bowed Almen strip as illustrated in Fig.4.

Elastic flattening will not occur if the strip is curved upwards as illustrated by fig.5.

Table 1 details preliminary tests on Almen strips aimed at confirming the effect of Almen strip pre-bow flattening on indicated Rockwell hardness. The measured curve-down values are all slightly higher than the curve-up values. This indicates that minor load strip flattening induces a small, but significant, increase in the indicated Rockwell diamond hardness value.

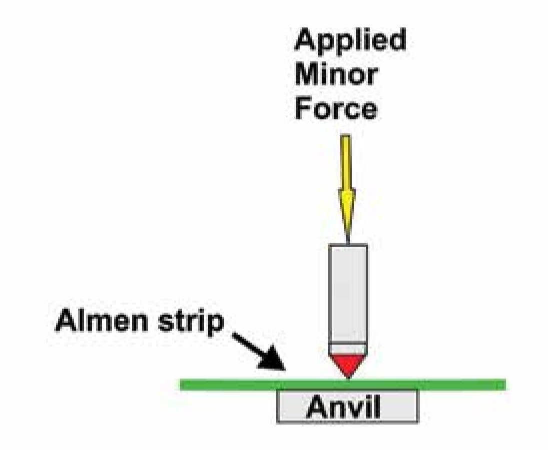

Fig.4. Applied minor force flattening pre-bowed Almen strip.

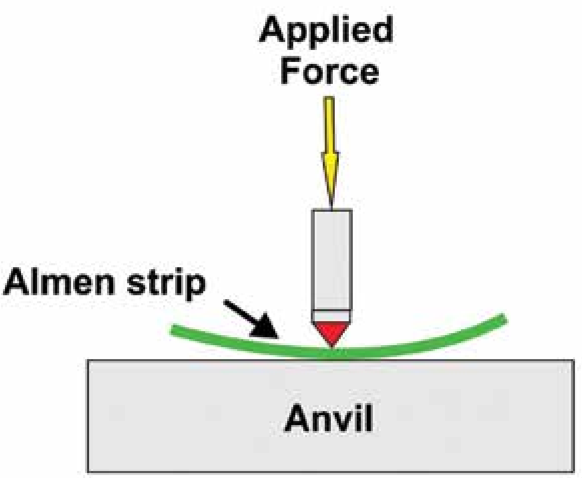

Fig.5. "Curve up" of Almen strip removes elastic flattening error.

Table 1. Effect of Pre-bow on Rockwell Hardness

Reading Number	Strip A		Strip B	
	Curve Up	Curve Down	Curve Up	Curve Down
1	48.1	49.2	48.0	49.2
2	48.1	48.6	48.3	48.5
3	48.3	49.2	48.3	49.1
Average	48.2	49.0	48.2	48.9
Difference		**+0.83**		**+0.73**

ELASTIC FLATTENING EFFECT ON ROCKWELL HARDNESS

Elastic flattening of pre-bowed strips appears to have a small but significant effect on indicated Rockwell hardness value. This section describes a study that attempts to both confirm and also to explain the effect.

Confirmation of the effect centred on measuring much larger numbers of Almen strips. Different amounts of pre-bow were also included in the study. This showed that the effect of flattening increased with increase in amount of pre-bow.

Tables 2 and 3 summarise the main results of the study.

Table 2. Effect of Elastic Flattening on Indicated Rockwell Hardness of Almen N Strips.

Batch of 10 strips	HRA Hardness Concave	HRA Hardness Convex	Hardness Difference
1	73.81	73.92	+0.11
2	74.28	74.34	+0.06
3	73.79	73.86	+0.07
Average	73.96	74.08	+0.08

Table 3. Effect of Elastic Flattening on Indicated Rockwell Hardness of Almen A Strips.

Batch of 10 strips	HRA Hardness Concave	HRA Hardness Convex	Hardness Difference
1	46.74	46.75	+0.01
2	47.09	47.69	+0.60
3	45.69	47.16	+1.49
Average	46.51	47.20	+0.70

With over a hundred hardness measurements involved, it is clear that testing the convex side of Almen strips results in a larger indicated hardness value than does testing the concave side.

EXPLANATION OF ELASTIC FLATTENING EFFECT ON INDICATED ROCKWELL HARDNESS

This explanation is based on the fact that the minor loading induces strip bending. This bending, in turn, sets up a stress system. The induced stress system involves compression of the previously convex side and tension on the previously concave side.

Fig.6 illustrates how the induced stress system is developed. Application of the Minor Force is expected to be sufficient to flatten a pre-bowed Almen strip as shown as the inset picture. The applied Minor Force applies a bending moment, M. Therefore the upper face of the Almen strip becomes compressed whereas the lower face goes into tension as shown in the main picture. It is the compressed side that is being hardness-tested.

Compression of the upper side involves compressive stress on the indentation. Hence when the Major Force is applied, indentation is then resisted by the combination of this compressive stress and the strip's own inherent resistance to indentation. This combination effect is illustrated by the plan view shown as fig.7.

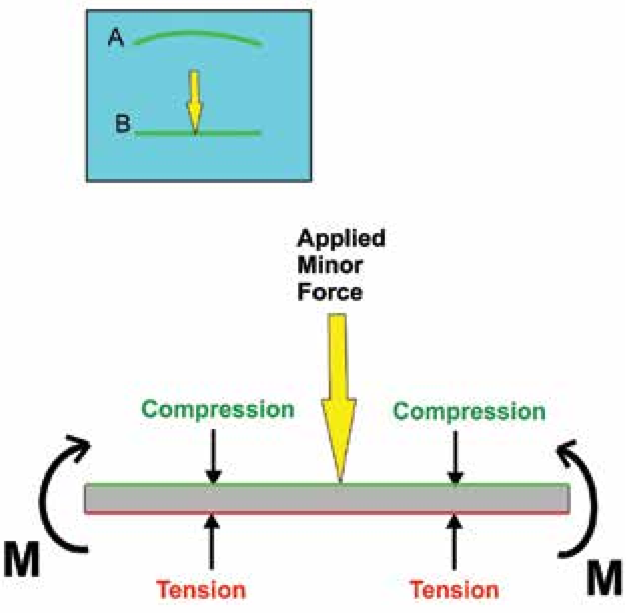

Fig.6. Stress system developed by imposing Minor Force.

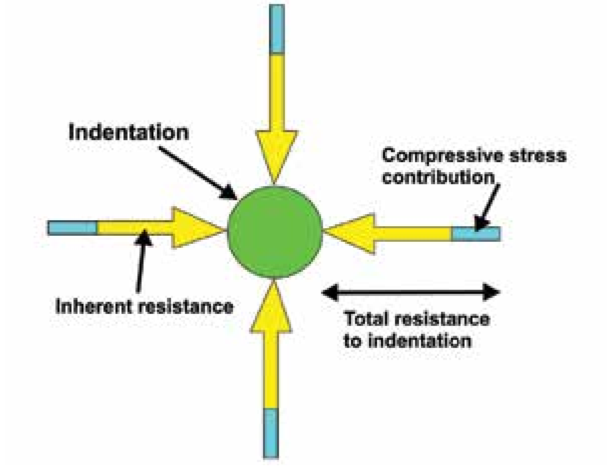

Fig.7. Combination of compressive stress and inherent resistance to indentation.

With the two factors combining to resist indentation, the indicated hardness is slightly increased. The magnitude of the compressive stress contribution depends on two factors. First is the degree of pre-bow. Second is the thickness of the Almen strip. Greater pre-bow increases the contribution. Almen A strips, being thicker than N strips, will also induce a larger contribution. This second factor is illustrated by fig.8. Being thicker, (0.051" cf 0.031"), A strips suffer larger bending moments, M, imposed by the minor load. Hence, larger compressive stress contributions will occur at the surface. Note that the vertical scale of the drawings has been increased for clarification of the effect. Because of the larger induced surface compressive stress, Almen A strips will indicate larger Rockwell hardness values as shown in Tables 2 and 3.

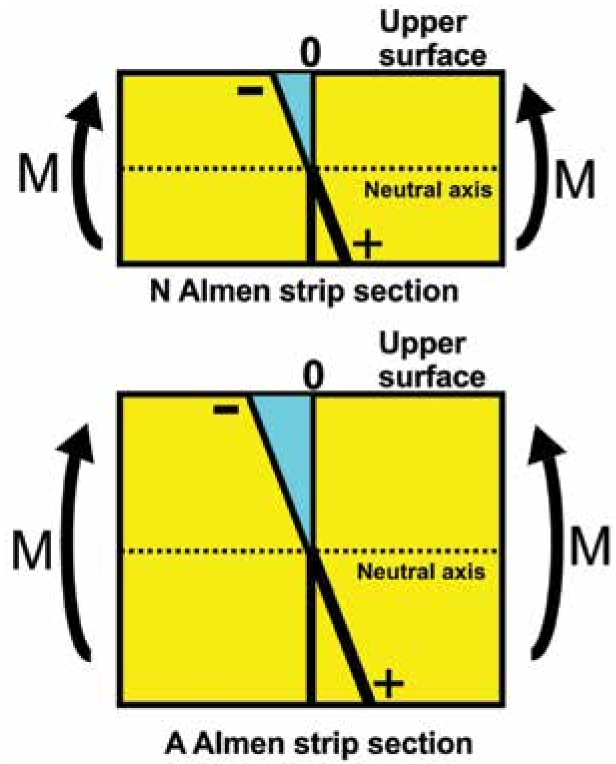

Fig.8. Bending inducing stress system.

DISCUSSION

The Rockwell test was introduced in order to provide a simple, speedy method of indicating component hardness. Operator skill was minimised as it simply required hardness values to be read off from a dial. Load changing, Minor and major, was originally manual. Although Rockwell hardness testing is excellent for its intended uses it has limits on accuracy. Modern Rockwell equipment simplifies operator involvement, with automatic load changes and digital hardness indication. Evolution of the test has increased the precision of indicated hardness without necessarily increasing its accuracy. As an analogy consider a standard wristwatch. Having a second hand increases precision but does not increase accuracy.

There is an excellent publication* by S.R. Low, 107 pages in length, that mainly deals with the large number of errors that can arise that affect Rockwell hardness values. Even standard calibration blocks were shown to vary in hardness over an individual block's test surface.

*S.R. Low, NIST Recommended Practice Guide, Special Publication 960-5 "Rockwell Hardness Measurement of Metallic Materials."

Rockwell hardness measurements should be carried out with the scale that Almen strip standards call for. For example, with SAE-J442 this should be Rockwell C scale for A strips and Rockwell A scale for N strips. Conversion from one to the other can lead to errors.

The tests carried out for this article have shown conclusively that indicated Rockwell hardness values are always slightly higher for measurements made on pre-bowed strips when tested curve down than when tested curve up. The cause of this difference is explained as being due to the compressive stress system that is produced by strip flattening. Increased pre-bow of Almen strips increases the "curve up" to "curve down" hardness difference.

CONCLUSIONS

Three major conclusions can be drawn from this article's study:

(1) Rockwell hardness tests should always be carried out with pre-bowed strips being placed "curve up" on the anvil. If the "curve up" side is not marked then tests should be carried on both sides and the higher reading rejected. Testing is now so quick and easy that this could be preferred to single-side testing.

(2) There are so many sources of error in Rockwell hardness testing that standard specifications should be adequately broad. SAE specifies 44.0 – 50.0 HRc for A-strips, a 6-point range and 72.5 – 76.0 HRa for N-strips, a 3.5-point range. A 3.5 range would appear to present difficulties for process control.

(3) With tighter tolerance requirements of aerospace: for A strips 45-48 HRc and N strips 73-74.5 HRa and a Rockwell hardness tester being "calibrated" per ASTM E18 when measuring within ±1 scale point to the selected certified reference block, the challenge becomes apparent.