ACADEMIC STUDY
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Hardness Matters

INTRODUCTION

Hardness, for shot peeners, is resistance to localized plastic deformation induced by impacting shot particles. We therefore have two areas of interest: the hardness of the component being peened and the hardness of the shot particles themselves. The hardness of the component is normally out of our control. One exception is the hardness of the Almen strips that are peened in order to establish the intensity of shot streams. Hardness appears in specifications for both shot particles and Almen strips and therefore requires testing.

It is common for peeners to blindly accept specified hardness values and test methods at face value. Unfortunately, hardness testing then becomes a minefield. There are three key areas that need to be considered if we are to be able to navigate through this minefield. These are (1) **sample heterogeneity**, (2) **test method** and (3) **indent size**. Metallurgists are, of necessity, relatively expert at matters concerning hardness testing of metals and alloys.

Hardness testing for shot peeners normally invokes reference to one or more of **Rockwell**, **Vickers** and **Knoop** techniques. The Brinell technique is commonly employed by component manufacturers. Details of these techniques are readily available via the Internet so that only selected features are discussed in this article.

The best approach when trying to optimize hardness testing is to follow Murphy's Law in the sense that "if anything can go wrong then it will go wrong"!

SAMPLE HETEROGENEITY

Sample heterogeneity can be divided into micro-heterogeneity and macro-heterogeneity. Micro-hardness and macro-hardness testing can be employed in order to monitor these two divisions.

Micro-heterogeneity

Virtually all components and shot contain more than one constituent, aka phases. Fig.1 is a useful analogy to a multi-constituent metal. It was selected as giving appropriate visual impact! A typical fruit cake contains hard particles (nuts), soft particles (fruits) and some pores (centers of stoned cherries) as well as the matrix cake mixture. This is analogous to the situation encountered in many metal alloys.

The fruit cake analogy is also useful in gaining an appreciation of component work-hardening. Imagine, or even try, squashing a piece of fruit cake using fingers. One thing is apparent—the hard nut particles do not deform.

Fig.1. Fruit cake composition (with acknowledgement to Simply Recipes).

This is precisely parallel to what happens when a piece of metal is plastically deformed—the hard particles (phases) offer greatest resistance to deformation. Soft matrix material deforms first and work-hardens. The hardest particles may never deform.

Macro-heterogeneity

Examples of macro-heterogeneity include peened component surface layers (as compared with sub-surface material), decarburization and steel shot particles. Micro-hardness testing is generally employed for studying these phenomena. Fig.2 exemplifies the macro-homogeneity induced by decarburization. Indentation location requires navigating between the constituent features and the indentations must be of an appropriate size.

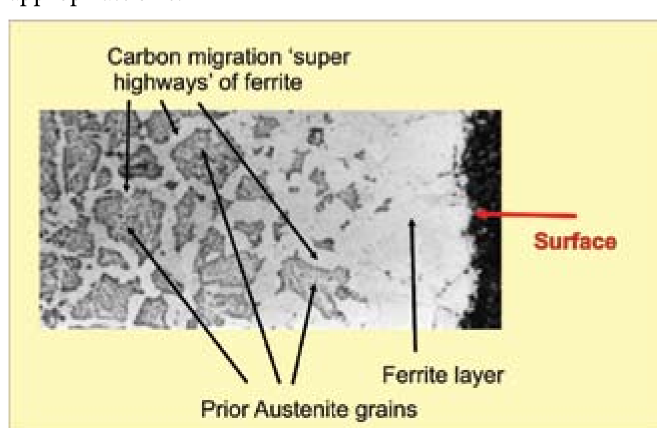

Fig.2. Macro-homogeneity of decarburized steel.

BRIEF HISTORY OF MAIN HARDNESS TEST METHODS

As mentioned earlier, details of these methods are readily available via the Internet. A brief look at their history shows, however, how well-established hardness testing has become.

The **Brinell** technique, employing a spherical indenter, was invented in Sweden in 1900 and named after its inventor. A hard ball is pressed into the sample's surface and its diameter measured on a projection screen. Hardness is then calculated with reference to the load and ball diameter being employed.

The **Rockwell** technique, which can have spherical or square-base diamond-shaped indenters, was patented in the USA in 1919 and named after its inventors. This is a differential-depth technique where a smaller load is applied followed by a larger load. The differential-depth measurement of hardness was in fact conceived much earlier, in 1908, by a Viennese professor Paul Ludwik in his book Die Kegelprobe (crudely translated as "the cone test").

The **Vickers** technique was developed in 1921 by Robert L. Smith and George E. Sandland at Vickers Ltd in the U.K. and was named after their employer. The Vickers test uses a square-base diamond indenter which can be used for all materials irrespective of hardness.

The **Knoop** technique was developed in 1939 by Frederick Knoop and colleagues at the then National Bureau of Standards, USA. This technique produces elongated impressions from an extended pyramid diamond indenter.

Rockwell, Vickers and Knoop techniques can all be used for micro-hardness testing by applying small loads resulting in small indentations.

INDENTATION SIZE

Knowledge of indentation size is vital for the proper application and understanding of hardness testing. "Large" indentions are associated with macro-hardness testing and "small" indentations are associated with micro-hardness testing but what is "large" and what is "small"?

Prediction of Vickers and Knoop indentation size is straightforward because they are both based on measuring the length of indentation diagonals. Prediction of Rockwell indentation size is complicated because it is based on the indentation's depth. All hardness values are based on dividing the force, F, applied to the indenter by the area, A, of the indentation. The larger the force the larger the indentation. Indentation size can be calculated for each measuring technique using known sample hardness and magnitude of the applied load.

Keeping with the fruit cake analogy, fig.3 represents what might be regarded as a "large" indentation. This would be equivalent to a macro-hardness indentation on a multiphase metallic sample. The indentation is large enough to embrace all types of phase and gives us an **average** hardness value.

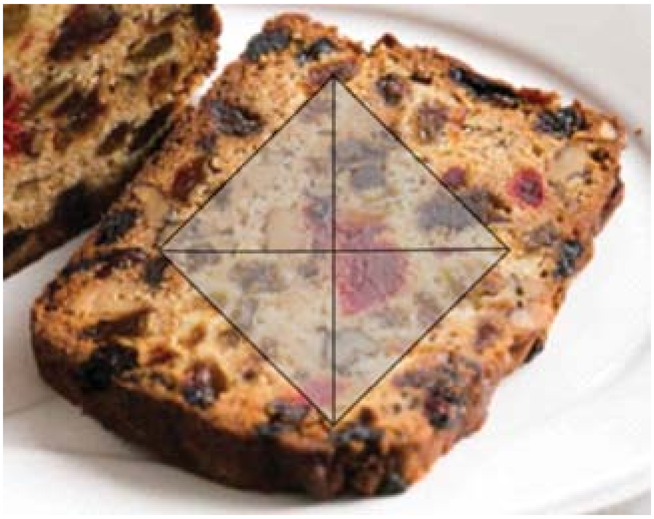

Fig.3. "Large" indentation analogy.

Calculation of Brinell Indentation Size

A Brinell hardness value, $\mathbf{H_B}$, is the applied force, F, applied to an indenter divided by the area, A, of the resulting indentation. The area of the indentation is given by:

$$\mathbf{A = \pi.D\,[D - (D^2 - d_B^2)^{0.5}\,]/2}$$

Where **D** is the diameter of the ball and $\mathbf{d_B}$ is the diameter of the impression. Applying algebraic manipulation to **F/A** shows that:

$$\mathbf{d_B = [D^2 - (D - 2F/H_B{*}\pi{*}D)^2]^{0.5}} \qquad (1)$$

Estimation of indentation diameter using equation (1) is easily achieved by employing an internet-sourced calculator. For example, Googling "Brinell Hardness Number Test Equations Formulas Calculator" reveals the Ajdesigner's excellent program. Entering a Brinell value of 443, ball diameter 1 mm, and 500 gf load indicates an indentation diameter of 0.038 mm.

Fig.4 on page 32 represents "small" indentations equivalent to those for micro-hardness testing. A variety of indentation sizes is indicated—attempting to represent different phase locations.

Calculation of Vickers Indentation Size

A Vickers hardness value, **HV**, is the applied force, F, applied to a 136˚ diamond indenter divided by the area, A, of the resulting indentation. The area of the indentation is given by:

$$\mathbf{A = d_V^2/\,(2{*}\sin(136^\circ/2)) = d_V^2/1.8544} \text{ so that:}$$

$$\mathbf{HV = F/A = F{*}1.8544/d_V^2}\ (\text{kgf.mm}^{-2}) \text{ and therefore:}$$

$$\mathbf{d_V = [F{*}1.8544/HV]^{0.5}} \qquad (2)$$

In SI units, Nmm^{-2}, $d_V = [F{*}0.1891/HV]^{0.5}$.

Fig.4. "Small" indentation analogy.

As an example, consider the 500 gf (0.5 kgf) recommended for testing shot particles. If the hardness of a particular particle was 500 HV then $d = [0.500*1.8544/500]^{0.5} = [1.8544/1000]^{0.5}$ or d = 0.043 mm. Fig.5 is a graphical representation of equation (2) for a hardness range of particular relevance for shot peeners and uses only the two commonly applied loads.

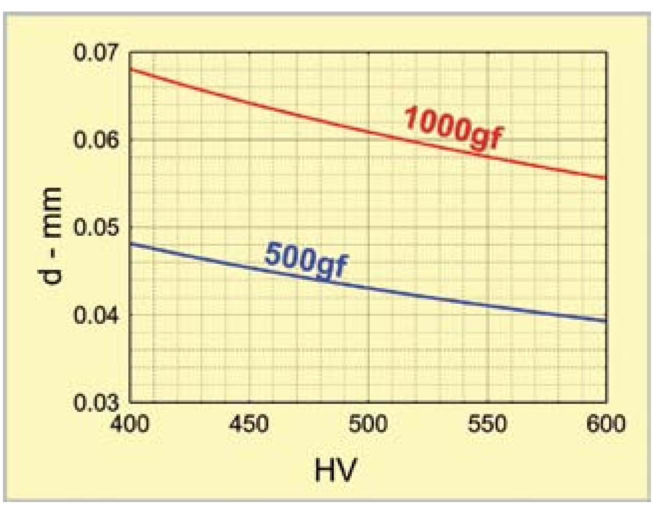

Fig.5. Effect of hardness and load on Vickers indentation size.

Conversion of Rockwell hardness values to equivalent Vickers hardness values can readily be achieved by using internet sites or the following relationships:

$$\mathbf{HV = (223*HRC + 14500)/(100 - HRC)} \text{ and}$$
$$\mathbf{HRC = (100*HV - 14500)/(HV + 223)}$$

Fig.6 is a graphical representation of Rockwell/Vickers hardness conversion.

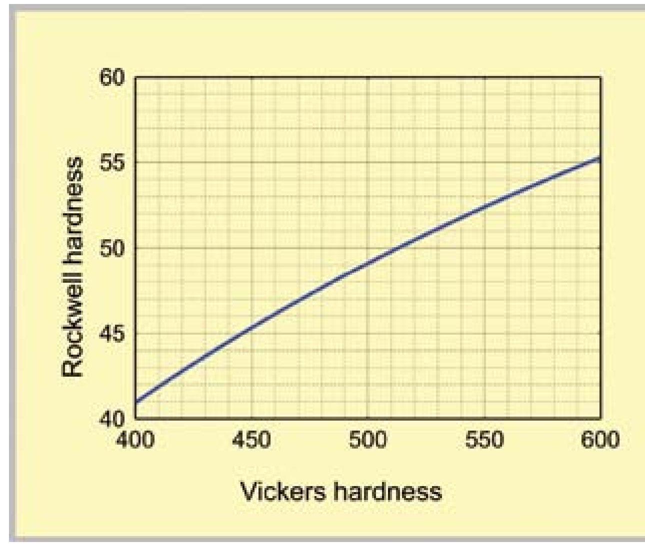

Fig.6. Rockwell/Vickers hardness conversion.

Estimation of Rockwell Indentation Size

Rockwell indenters have a 120° included angle as opposed to the 136° included angle of a Vickers indenter. This means that for a given applied load the following relationship applies:

$$\mathbf{d_{Rockwell} = 0.966*d_{Vickers}} \tag{3}$$

Looking back at the previous example (where a 500 gf was applied to a material having a Vickers hardness of 500 HV) a diagonal of 0.043 mm was predicted. Applying equation (3) indicates that a Rockwell indentation would have a diagonal of 0.042 mm. The difference is small!

The derivation of equation (3) is as follows:

Area of Vickers indent $= A_V = d_V^2/\ (2*\sin\ (136°/2)) = d_V^2/1.8544$ whereas

Area of Rockwell indent $= A_R = d_R^2/\ (2*\sin\ (120°/2)) = d_R^2/1.732$

Both Vickers and Rockwell indenters stop indenting when the same stress, F/A, is being applied on the same material. When the same force, F, is being applied on both indenters, it follows that:

$$F/A_R = F/A_V \text{ therefore } A_R = A_V \text{ so that}$$
$$d_R^2/1.732 = d_V^2/1.8544 \text{ or}$$
$$d_R^2\ /\ d_V^2 = 1.732/1.8544 \text{ hence}$$
$$d_R/d_V = (1.732/1.8544)^{0.5} \text{ or}$$
$$d_R/d_V = 0.966$$

Estimation of Knoop Indentation Size

The equation for calculating Knoop hardness, HK, is given by:

$$HK = 14.229F/L^2$$

Where **L** is the length (in mm) of the longer indentation diagonal, see fig.7.

It follows that:

$$L = (14.229*F/HK)^{0.5} \qquad (4)$$

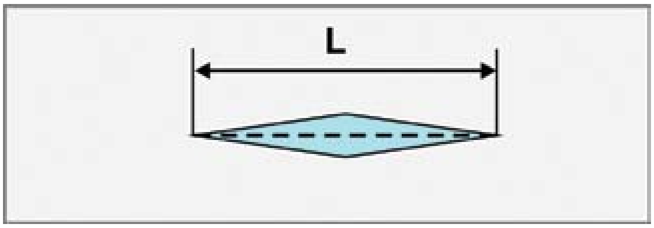

Fig.7. Measured longer diagonal for Knoop Hardness Test.

As an example, consider the 500 gf (0.5 kgf) recommended for testing shot particles. If the hardness of a particular particle was 500 HK then $L = [0.500*14.229/500]^{0.5} = [14.229/1000]^{0.5}$ or L = 0.119 mm. This can be compared with the diagonal length of both Vickers and Rockwell indentations (using the same load) of 0.043 mm. The long diagonal of a Knoop indentation is some three times the diagonal length of Vickers and Rockwell indentations made on metal of the same hardness. This ratio is commonly quoted.

Fig.8, based on equation (4), shows how the length of a Knoop diagonal varies with the two commonly applied loads and Knoop hardness.

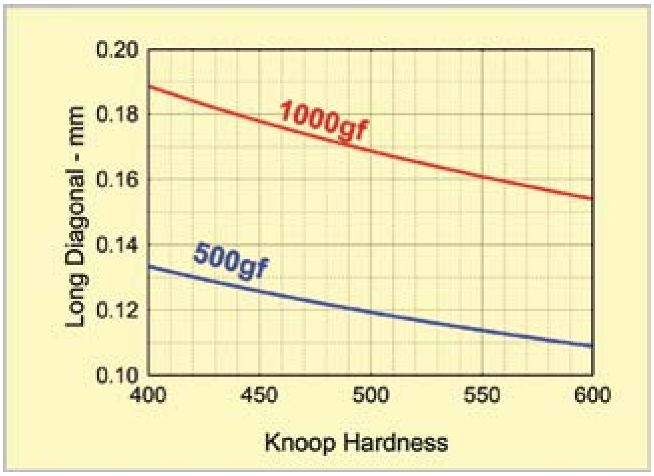

Fig.8. Effect of hardness and load on Knoop long diagonal.

SHOT HARDNESS TESTING

Shot hardness is of vital importance to shot peeners. To avoid superficiality, only testing of steel shot will be discussed. All hardness tests are, however, based on two considerations:

(1) **Technique to be employed** and

(2) **Procedure to be employed when applying the selected technique.**

(1) Technique to be employed

The technique to be employed by shot manufacturers is normally dictated by specification requirements. Unfortunately, published specifications are not always very clear as to which technique (Rockwell, Vickers or Knoop) is to be employed—or why. There is a gray area between macro- and micro-hardness techniques. This is exemplified by the nineteen-to-one range of standard shot diameters as indicated in Table 1.

Table 1. Nominal Shot Diameters Derived Using J444

Shot	Diameter	
	-inch	-mm
S70	0.0070	0.1778
S110	0.0110	0.2794
S170	0.0170	0.4318
S230	0.0230	0.5842
S280	0.0280	0.7112
S330	0.0330	0.8382
S390	0.0390	0.9906
S460	0.0460	1.1684
S550	0.0550	1.3970
S660	0.0660	1.6764
S780	0.0780	1.9812
S930	0.0930	2.3622
S1110	0.1110	2.8194
S1320	S1320	3.3528
Ratios highest/lowest	19:1	19:1

It is important to relate indentation size to shot diameter. Consider, as an example, that 450 Knoop hardness for S70 shot had been specified using a 500 gf applied load. Fig.9 on page 36 shows that the long diagonal 0.127 mm of a centrally placed indentation would then be a very large fraction of the 0.1778 mm nominal diameter! The deformation area around the indentation would certainly reach the shot's surface. On the other hand, for larger shot sizes this fraction reduces rapidly. This would then not be too much of a problem if the shot was uniformly hard from surface to center but that would be very exceptional. The obvious alternatives would be to employ either Vickers or Rockwell techniques. For 500 gf loads the Vickers/Rockwell indent diameter would be only 0.047 mm as included in fig.9. It should also be remembered that cast steel shot has a range of diameters. At the bottom end of this range the diameters of some S70 particles would be much less than 0.127 mm!

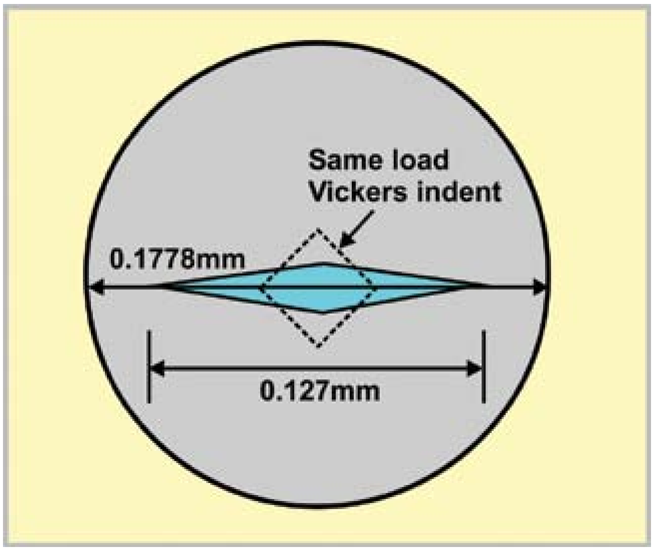

Fig.9. 500 gf Knoop indentation for 450 HK S70 shot particle.

(2) Procedure to be employed when applying the selected technique.
Some specifications include directions for the procedure that has to be employed for selected techniques. AMS 2431 gives extensive guidance on micro-hardness testing using either Knoop or Vickers techniques. SAE J827 contains the following specific guidance as to the procedure to be employed:

> **10.2 Sample Mounting for Testing.** Shot samples used for testing for hardness, microstructure and objectionable defects shall be mounted one layer deep in Bakelite or other suitable strong metallurgical sample mounting media.
>
> The mounted sample shall be ground to the center of the particles and polished by methods acceptable for microscopic examination. When grinding and polishing the sample, care must be taken not to overheat the sample and affect microstructure and/or hardness.
>
> **10.3 Hardness Testing.** Hardness measurements shall be taken at the half radius on a minimum of 10 particles in the mounted samples.
>
> The hardness shall be determined by using ASTM E 384 and using a 500 g load for HCS S280 and finer, and 500 or 1000 g load for sizes HCS 330 and larger. Other microhardness test methods may be used as long as a reliable hardness conversion can be obtained by calibrating the test machine against known standards. Approximate conversion to Rockwell C Hardness Numbers can be obtained from ASTM 140 and from manufacturers of hardness testers.

Having to take measurements at half radius appears to rule out employing Knoop testing for shot particle hardness!

The guidance on sample mounting raises the question "What effect will shot diameter variation have?" We cannot assume that every shot particle in a sample will have the same diameter. Fig.10 illustrates, schematically, the effect of diameter variation. Following the instruction: "The mounted sample shall be ground to the center of the particles" is tricky! There will be a range from what is obviously over-ground, some particles disappearing, to under-ground, where all particles present less than their diameters. A further complication is that the individual particles may well vary in hardness from surface to center.

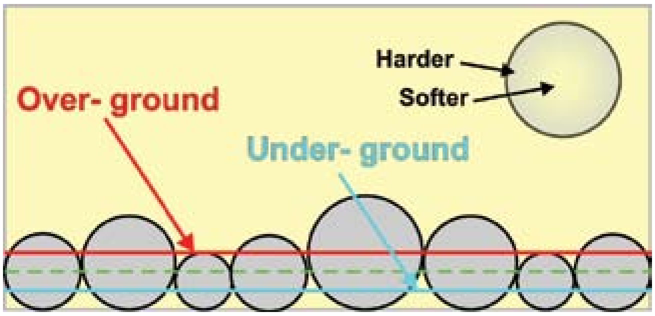

Fig.10. Schematic representation of mounted sample grinding.

HARDNESS TEST ALTERNATIVES

Hardness testing requires specialised skills and equipment not commonly available to shot peeners themselves. The question arises: "Are there useful alternatives to conventional hardness tests?" One possibility could be to use an inverted Scleroscope procedure. As an introduction, imagine holding the top of a (cheap) ball-point pen and then dropping it from a height onto a very hard surface. It will bounce up after impact.

With the Scleroscope procedure the impacting ball is harder than the target material. Inverting the procedure we could use shot particles as indenters and a target material that is much harder than the shot particles. On impact it would be the shot particle that deformed rather than indenting the target. The rebound height would therefore increase with hardness of the shot particle. An appropriate parallel to a pen's ball-point is indicated schematically in fig.11 on page 38. The rest of the device would be similar to that of a Scleroscope.

CONCLUSIONS

Being able to predict the size of hardness indentations gives us a much better understanding of their significance. For specific applications, such as shot particle hardness, care has to be taken to relate indentation size to shot diameter. Only Vickers and Rockwell techniques appear to be appropriate and Knoop to be inappropriate.

The inhomogeneous nature of hardness for most objects must be taken into account when applying micro-hardness tests. Mounting of a sample of shot particles introduces another source of hardness measurement variability.

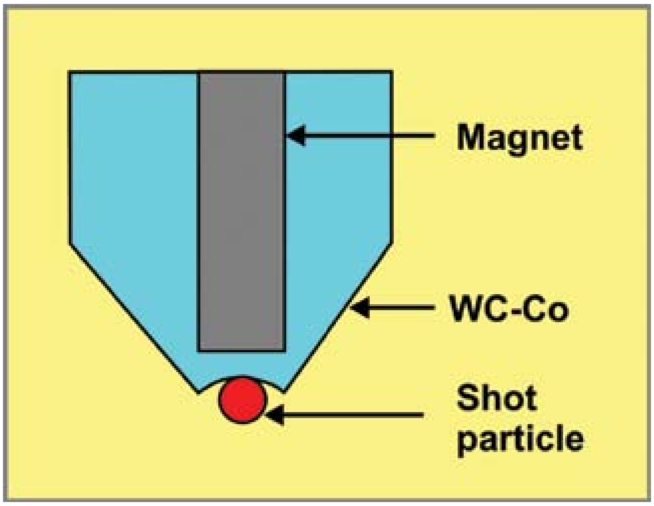

Fig.11. Schematic representation of proposed indenter point.

Alternatives to conventional hardness test procedures should be considered such as one based on fig.11. A secondary use of that device would be to assess toughness of shot particles. The device could be employed by monitoring the drop height needed to fracture particles.

Finally, it appears obvious that hardness measurement variability is unavoidable—even with the most careful application of existing specified procedures.

Clemco Goes Green

CLEMCO INDUSTRIES has received a $47,348.12 incentive from Ameren Missouri's BizSavers® program. Ameren Missouri is an American power company. It covers 64 counties and more than 500 communities including the greater St. Louis area. The incentive was presented to Clemco following extensive energy-efficiency renovations to the company's international headquarters located in Washington, Missouri.

"This is a great energy saver for us," said Mark Buersmeyer, Clemco Maintenance Manager. "The Ameren Missouri BizSavers team was easy to work with during this nearly yearlong process. We are now running a "greener" operation, which not only helps Clemco, but also the environment," he added.

Improvements to Clemco's office and manufacturing plant included replacing all interior lighting with highly energy-efficient LED lights, as well as replacing the majority of the facility's exterior lighting with LED lights. In its plant, Clemco replaced 268 high-bay fixtures, 114 ceiling-level fixtures, and 37 flat-panel fixtures. In the front offices, 670 lights bulbs were installed.

This new lighting will save Clemco an estimated $32,700 a year in electrical costs, which likely means a complete return on the company's $79,000 investment in 2.4 years. This translates into a savings of more than 348,000 (kWh) annually, which is equivalent to powering 43 average US homes for a year.

"Our BizSavers energy-efficiency program helps commercial and industrial customers reduce the cost of upgrading to more energy-efficient equipment," said Rich Wright, Manager, Ameren Missouri Energy Efficiency. "Companies like Clemco benefit by saving on the upgrade cost today and saving on energy costs for the life of the equipment."

Representatives from Ameren Missouri present the incentive check for Clemco's energy-efficiency renovations.