Understanding Residual Stress Effects and Corrective Action for Die Casting Tools — Part 2

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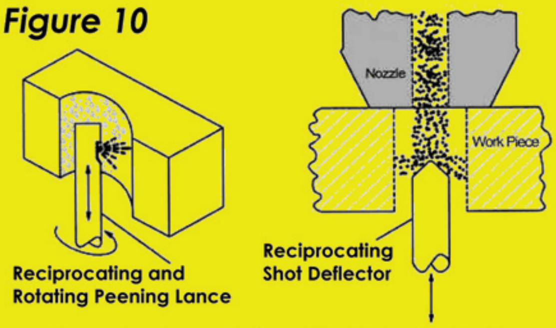
Introduction

In mid-2007, NADCA published a *User's Guide for Relieving Stresses in Die Casting Dies*. The guide discusses two means of accomplishing this: heat stress tempering and shot peening. Much has been written about the benefits of heat stress tempering; however, proper shot peening technique remains a mystery or unknown proven quantity for many die casters. In Part 1 of this series, published in the September issue of Die Casting Engineer, some facts were presented surrounding mechanically induced compressive stress along with its history, definition, stress curves, depth considerations and the manufacturing effects that shorten the life and performance on a far too significant number of die casting dies. Part 2 continues the discussion regarding the special controls used to maximize the Metallife® compressive and surface modification benefits, new technologies in the field and some case studies.

Line of Sight Restrictions and Solutions

The accessed area is limited to line of sight application unless special equipment is used. When the depth of an internal blind bore is greater than the diameter of the hole, it cannot be effectively processed by external methods. Use of special internal lances or internal shot deflectors (ISD) eliminate this limitation; however, the method must be used under closely controlled conditions (Figure 10). By using this special equipment, it is possible to peen holes as small as 0.096 inch (2.4 mm) in diameter. Potential applications for internal shot peening include shot sleeves, centrifugal casting dies, internal cores and slides, as well as applications outside the scope of die casting, such as coolant water lines for nuclear reactors and hydraulic cylinders.

Figure 10



Lance Peening and Internal Shot Deflector Peening

Dual and Intensity Peening

The proprietary procedure utilizes special dual and tri-peening processes that further enhance the fatigue performance from normal shot peening operations. As the dual or tri-peening process is used, the peen results are often doubled, tripled or more. Fatigue life improvements from this typically exceed 300%, 500% or more. The purpose of these multiple peenings is to further enhance the compressive stress at the outermost surface layer, thereby improving the shape of the resultant compressive curve. The surface is where fatigue crack initiation begins. By further compressing the surface layer, additional fatigue crack resistance is imparted to the tool.

The additional operations also dissipate the asperities from the first operation, resulting in an improved and uniform compressive stress surface finish. Dual peening is performed on the same surface, but with a different media and intensity each time. This second and third peening operation, in conjunction with very special controls, makes the process unique. Figure 11s and 11a show the surface finishes from the single and multiple peening at 30X magnification.

Figure 11 SEM Photo of Single Peen Surface Finish

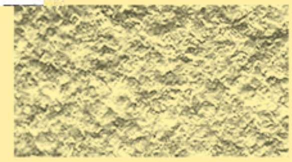


Figure 11a SEM Photo of Dual Peen Surface Finish

Controlling the Process

Controlling the process varies from most standard manufacturing processes in that non-destructive methods to confirm the operation was performed to the desired specifications are relative and not always conclusive. Without the use of special control monitoring, the part may have to be sacrificed using x-ray diffraction to confirm the generation of a full compressive depth profile analysis. Therefore, to ensure repeatable peening specifications are followed on production lots without destruction of the tool, the following process controls are used and critical to maintaining process integrity:

- Media
- Intensity
- Coverage
- Equipment & Process Integrity

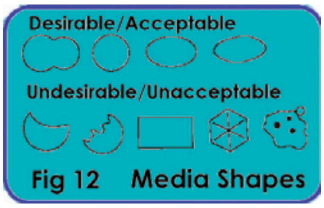
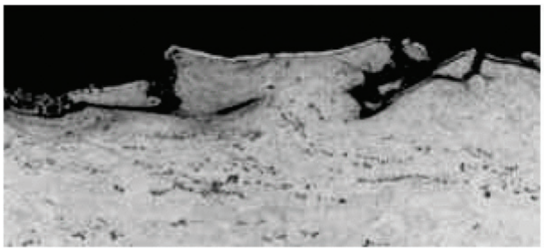


Fig 12 Media Shapes

Peening media must be predominantly round. Figure 12 demonstrates acceptable and unacceptable media shapes. When media breaks down from usage, the broken media must be immediately and effectively removed to prevent surface damage upon impact. Figure 13 upper (100X magnification) demonstrates the potential for surface damage and crack initiation from using broken down media as compared to the use of proper media in Figure 13 lower.



Damaged Surface from Broken Media

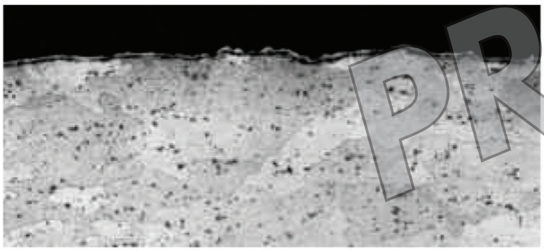
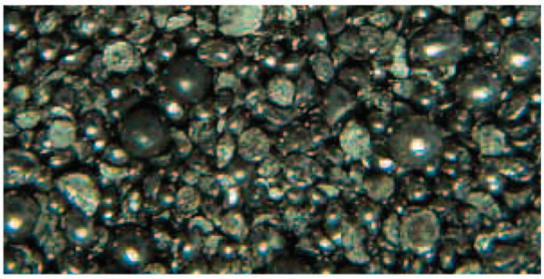


Figure 13 Surface from Proper Media

Peening media must be of uniform diameter. The impact energy imparted by the media is a function of its mass and velocity. Larger media has more mass and impact energy. If a mixed size batch of media is used for peening (Figure 14 upper), the larger media will create a deeper residual compressive layer in some places. This results in a non-uniform residual compressive layer and will correlate into inconsistent fatigue results. Figure 14 lower shows a batch of media with proper size and shape characteristics. To properly remove under-sized, over-sized and broken or improperly shaped media, a real-time screening classification system during all steps of processing can be utilized.

To properly remove broken media, this process meters the shot cycled to a spiral separator consisting of inner and outer flight paths. The system is based on the rolling velocity of spherical media versus broken media. Shot will arrive via the channel above the cone near the top (Figure 15). The media will fall to the cone and roll down the inner flight. Spherical media will gain enough velocity to escape to the outer flight. This media can be re-used after it is automatically screened to the proper size. Broken-down media, however, rolls very poorly and will stay on the inner flight path where it will be discarded. This metering method assures the size and shape control that is necessary during the process to ensure repeatability and consistency.



Poor Quality Shot Peening Media

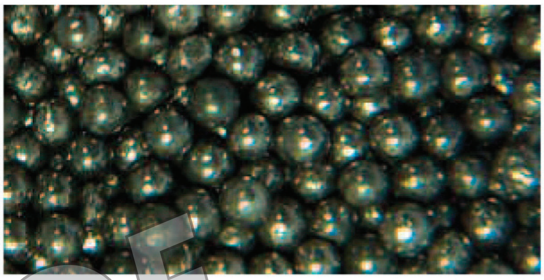


Figure 14 High Quality Shot Peening Media

Intensity Control

Shot peening intensity is the measure of the energy of the shot stream and an essential means of ensuring process repeatability. The energy of the shot stream is directly related to the compressive stress imparted into a part. Intensity can be increased by using larger media and/or increasing the velocity of the shot stream. Other variables are the impingement angle and peening media. Intensity is measured using an Almen strips, a strip of SAE1070 spring steel hardened to 44-50Rc and then peened on only one side. The residual compressive stress from the peening will cause the Almen strip to bend or arc convexly towards the peened side (Figure 16). The Almen strip arc height is a function of the energy of the shot stream and is very repeatable.

Figure 15 Spiral Separation System for Shot Media Classification

Three Almen strip designations used depending on the peening application are:

- "N" Strip: Thickness = 0.031" (0.79 mm)
- "A" Strip: Thickness = 0.051" (1.29 mm)
- "C" Strip: Thickness = 0.094" (2.39 mm)

More aggressive shot peening utilizes thicker Almen strips.

The Almen intensity is the arc height (as measured by an Almen gage) followed by the Almen strip designation. The proper designation for a 0.012" (0.30 mm) arc height using the

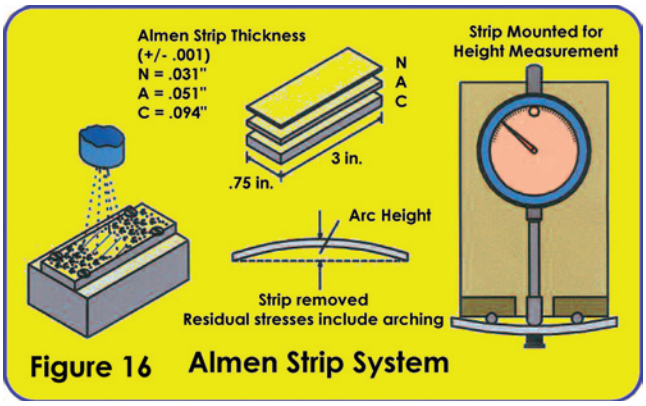


Figure 16 Almen Strip System

A strip is 0.012A (0.30A). The usable range of an Almen strip is 0.004" – 0.024" (0.10 – 0.61 mm). The next thicker Almen strip should be used if intensity is above 0.020" (0.51 mm).

The intensity value achieved on an N strip is approximately one-third the value of an A strip. The intensity value achieved on a C strip is approximately three times the value of an A strip (N ~ 1/3A, C ~ 3A).

Almen strips are mounted to Almen blocks and are processed along with the tool (Figure 16) or similar steels. Almen blocks should be mounted in locations where verification of impact energy is crucial. Actual intensity is verified and recorded prior to processing the tool or die. This verifies the complete peening operation is set up and run according to the approved engineered process. After the tool has been processed, intensity verification is repeated to ensure the processing parameters have not changed. For multiple die sets, intensity verifications will be performed throughout the processing as required.

Saturation (Intensity Verification) – Initial verification in the case of new process development requires the establishment of a saturation curve. Saturation is defined as the earliest point on the curve where doubling the exposure time produces no more than a 10% increase in arc height. The saturation curve is developed by peening a series of Almen strips in fixed machine settings and determining when the doubling occurs. The generated curves show that doubling of the time (2T) from the initial exposure time (T) results in less than a 10% increase in Almen arc height.

This would mean that the process reaches saturation at time = T. Saturation establishes the actual intensity of the shot stream at a given location for a particular machine setup. It is important to not confuse saturation with coverage and texture with compression as other "just like us" die treatment processes often do. Coverage is described in the next section and deals with the percentage of surface area covered with peening dimples. Saturation is used to verify the time to establish intensity. Saturation and coverage will not necessarily occur at the same time interval. This is because coverage is determined on the actual part surface, which can range from relatively soft to extremely hard. Saturation is determined using Almen strips that are SAE1070 spring steel hardened to 44-50 HRC.

Coverage Control

Complete coverage of a shot-peened surface is crucial in performing high quality tooling shot peening. Coverage is the measure of original surface area that has been obliterated by shot peening micro-dimples. Coverage should never be less than 100% as fatigue and stress corrosion cracks can develop in the non-peened area that is not encased in residual compressive stress. The adjacent pictures demonstrate complete (Figure 17) and incomplete coverage (Figure 17a).

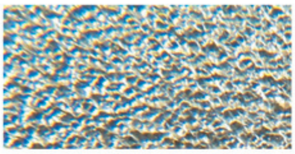


Figure 17 Complete Shot Peening Coverage

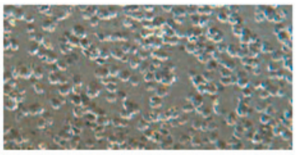


Figure 17a Incomplete Shot Peening Coverage

If coverage is specified at greater than 100% (i.e. 150%, 200%) this means that the processing time to achieve 100% has been increased by that factor. A coverage of 200% time would have twice the shot peening exposure time as 100% coverage. This minimum coverage should be a minimum of 200% or more depending on the process used.

PEENSCAN® (Coverage Verification) – Determination of shot peening coverage can be fairly easy when non-tool steels or softer materials have been peened because dimples are quite visible. A 10-power (10X) magnifying glass is more than adequate for these conditions. For applications involving higher hardness tool steels (38-65Rc), however, determination of coverage is more difficult. Also, internal holes, welded areas, tight radii, extremely hard materials and large surface areas present additional challenges in determining coverage.

The patented PEENSCAN® process, utilizing DYESCAN® fluorescent tracer dyes, is ideal for measuring uniformity and extent of coverage for difficult conditions. The whitish-green dye is not visible under normal lighting conditions and must be viewed under a UV (black) light. The coating can be applied by dipping, brushing or spraying the part under analysis. As the coated surface is impacted with peening media, the impacts remove the elastic fluorescent coating at a rate proportional to the actual coverage rate. When the part is viewed again under a black light, non-uniform coverage is visibly evident. The peening process parameters can then be adjusted as necessary until the procedure verifies complete obliteration of the area of concern.

Figure 18 demonstrates this concept. The figures are computer simulations of a core slide with the green representing the whitish-green dye and blue representing the base material under black light conditions. As the (green) dye is removed from peening impacts, the (blue) base material is exposed, indicating complete coverage. The inspection process has been found, in tool processing, to be superior to using a 10-power glass. For tool steels that exhibit higher Rockwell hardness, this is the only means to determine and assure that the surface has complete coverage without destructive evaluation.

Residual Stress Modeling

When engineering a proper callout for processing or developing a new specification criteria, one important consideration is predicting or modeling the residual compressive stress profile after processing. The following are some die factors that influence the resultant residual stress profile:

- Material, heat treatment and hardness
- Part geometry and accessibility

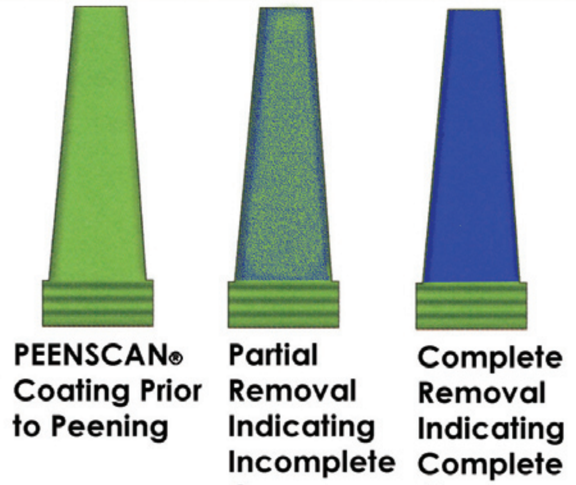


Figure 18

- Shot (size, material, hardness, saturation and intensity)
- Single peen, dual peen, tri-peen or other multiple combinations

Badger Metal has more than 25 years of experience and can utilize an internally developed software package called Peenstress^{SM} to select the proper peening parameters, for optimizing and predicting shot peening results. The software has included a multitude of materials, hardness and heat treatment conditions. Once the appropriate material (and heat treat condition) is selected, the following shot peening parameters can be modeled and correctly chosen:

- Shot size
- Shot material and hardness
- Shot intensity (coverage and saturation)

The software graphically plots the theoretical compressive curve based on the software modeling values. By altering these shot peening parameters, the shot peening callout can be optimized to achieve desired results. The software also encompasses a large database of x-ray diffraction data that can verify the resultant theoretical modeled curves.

Laser Technology

Badger Metal Tech is also doing studies and working through Livermore Labs regarding the next generation of new peening technology — Laser peening or Laserlife. Due to increased benefits but higher cost, this new technology is currently only being used commercially in the medical, aerospace, military and/or other industries where the now higher cost can be justified.

The future use of lasers for all types of perishable tooling is being further evaluated with some initial testing conducted by Case Western University.

The process uses a unique Nd:glass, high-output, high-repetition laser in conjunction with precision robotic manipulation of the part to be laser peened. During the laser peening process, the laser is fired at the surface of a metal part to generate pressure pulses of one million pounds-per-square-inch, which send shock waves through the part. Multiple firings of the laser are what creates the predefined surface pattern (Figure 19) and impart a layer of compressive stress on the surface that is four times deeper than that attainable from current mechanical treatments. The primary benefit of laser peening is a very deep compressive layer with minimal cold working, which increases the component's resistance to failure mechanisms such as fatigue, thermal shock fatigue and heat checking.

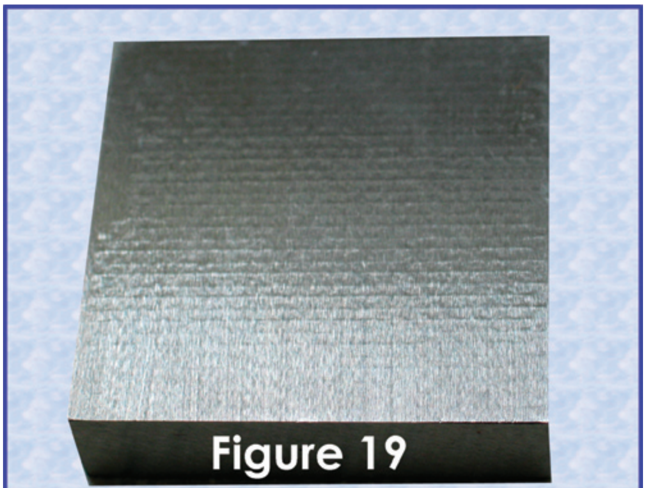


Figure 19
waffle overlap from fired laser

Case Western University has measured the compressive levels using their traditional dip tank specimen and found the depth of the laser-induced compressive stress layer to be up to 0.060 inches (1.5 mm) on H-13 steels vs. 0.015 to 0.020 inches (.38mm to .50mm) for standard Metallife® peening. A secondary benefit is that thermal relaxation of the residual stresses of a laser-peened surface is less than a shot-peened surface due to the reduced cold work involved with the process. The benefits of an exceptionally deep residual compressive layer are shown in Figure 20. The testing consisted of unpeened, mechanically shot-peened and laser-peened specimens. Normal laser peening involves one additional step to flatten the curve and induce higher surface compression values. To establish baseline data, this was not done for the initial test at Case Western. The parent laser peening facilities in the U.S. were used for this test.

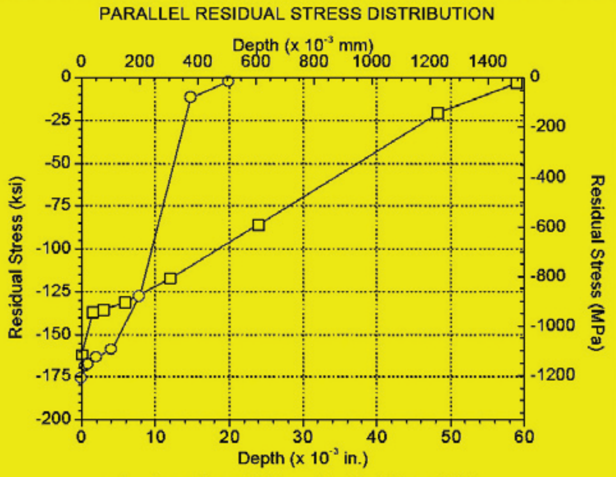


Figure 20

Historical Case Study

Companies have been using this process to extend the life and improve the performance of various types of perishable industrial tooling.

The following is a case study conducted from a die caster in Canada along with some other results that correlate and validate the benefits discussed earlier. Because of the sensitive nature of non-disclosure, only an internal tracking number is shown for each of the field result reports:

The Canadian die caster experienced a savings of $76,000 by performing the process on a repeat basis when the tool was new and at regular 50,000 shot intervals (Figure 21). Normally, two tools would have to be built for a total cost of $300,000 ($150K each tool) to obtain the 300,000 shots.

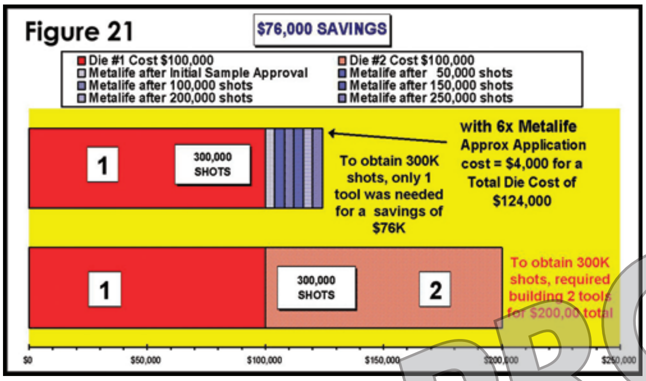


Figure 21

Six applications were applied during this case study, resulting in a 25% cost savings. Two photos of castings are shown from different dies making the same part. Figure 22 was never treated. Figure 22a was treated when new and again at 50,000 shots. The p/n are blocked at the customer's request.

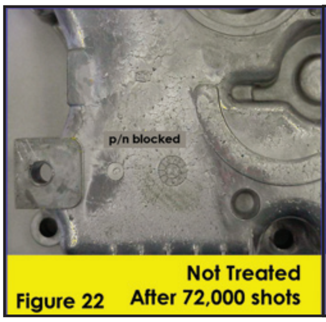


Figure 22 Not Treated After 72,000 shots


Figure 22a Processed NEW & at 50K After 120,000 shots

Conclusion and Summary

As long ago as the 11th Century, residual stress was being countered by inducing compressive stress. Not many individuals today are aware of the concept, yet in our everyday lives, we are using equipment or products that would not perform without the use of the technology. Today, it is a commonly used method to correct manufacturing effects in any industry that produces metal parts. In 1983, Badger Metal Tech adopted and focused its proprietary Metallife® ambient applied technology for use on hot and cold work tool steel and other perishable tooling.

Although the concept in theory is straight forward, the number of controlling parameters must be known, addressed and maintained to ensure getting the desired repeatable results. Besides countering residual stresses, there are many other benefits derived from applying the process to perishable tooling and die steels.

In addition to the Metallife® compressive stress benefits, the surface enhancement creates additional benefits:

- Elimination and reduction of cavitation pitting/break out at the gate or runner area of the casting.
- Hide surface defects on casting surfaces by reducing or preventing thermal heat checking fatigue.
- Flow effect to prevent lamination or cold shot effect as encountered in magnesium die casting.
- Reduction and redistribution of porosity to encourage homogeneous fill characteristics.
- Better paint adhesion especially when a powder paint system is used on the casting.
- Lower temperature gradient since the actual surface area is increased as a non-linear component.
- Lube retention in critical areas to prevent soldering.
- Lower coefficient of friction between sliding tool surfaces due to peak to peak interaction area.

Although it is not a panacea for all the modes of tooling failure, it is a big step in the right direction to preventing or reducing breakout, heat checking, fatigue, lamination and soldering. These contribute to extended tool life and improved performance providing better castings at a lower cost. Best results are obtained by applying when the tool is *new* before sampling and then again at normal half life or designated multiple points in the tooling's normal life.

New technology for countering residual stress four to six times better is under development using a special laser process. The current high cost confines its use commercially, at present, to the aerospace, military and medical industry.

About the Author

Jerald (Jerry) V. Skoff started Badger Metal Tech, Inc. in 1983, and since that time more than 100,000 tools have passed through their facility in Menomonee Falls, WI. He has written numerous articles for the die casting industry including congress white papers for die casting expositions. His most recent was an article on the recent advances in FNC, which appeared in the May 2003 issue of Die Casting Engineer magazine. He is considered as an authority on die casting die residual stress and chaired a task force for NADCA's Die Materials Committee that worked to establish baseline stress parameters for die cast tooling.

References

http://www.badgermetal.com
http://www.knightsedge.com
http://www.metalfinishing.com
http://www.aws.org
http://www.protoxrd.org
http://www.shotpeener.com
http://www.curtisswright.com
http://www.drgears.com
http://www.shotpeening.org