Shot Peening

Understanding Residual Stress Effects and Corrective Action for Die Casting Tools – Part 1

Jerald V. Skoff, President
Badger Metal Tech Inc.
Menomonee Falls, Wisconsin

Introduction and History

Recently, NADCA prepared and is publishing a User Guide on Relieving Stress in Die Casting Dies. The guide discusses two means to accomplish 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 an unknown proven quantity for many die casters. This is the first article of a two-part series to explain some facts surrounding this type of mechanically induced compressive stress, along with the controls used to assure obtaining the maximum benefits from Badger Metal Tech's proprietary Metallife® process.

Part 1 will cover general peening's history, definition, stress curves, depth and manufacturing effects that shorten life and performance on a far too significant number of die casting dies. Part 2 will discuss Metallife®'s numerous benefits, special controls that must be followed for maximizing those benefits, new technologies in the field and some case studies.

During the 11th Century, a special brand of European swords were produced that had improved performance along with resistance to breakage. Most swords at the time were thick and heavy to keep them from breaking. A broken sword in battle meant permanent downtime and probable doom to the user. These heavy swords, however, took more physical energy and strength to swing, which slowed down the user's reaction time…also not a good thing.

If you had the money or were a king, you could go to Toledo, Spain, and buy the newest technology in swords. The cunning Toledo blacksmiths had developed a thinner, lightweight, well-balanced weapon that would hold a sharp edge and could be bent almost double, over and over, without breaking. No other sword makers could produce such an indestructible battle weapon, which made the Toledo swords famous to this day. Their art was never revealed, even after swords gave way to firearms. Even metallurgists who examined the blade's steel composition, heat treatment and finishing were unable to find the secret to these break resistant weapons.

In the 1970s, science again delved into the mystery of the Toledo blades. This time they re-examined them using modern X-ray diffraction methods for measuring compressive stress. To their surprise, they found that the blades had been peened, not with shot as is done today, but with ball peen hammers. Who would have figured that in the 11th century these smart blacksmiths were using a basic technology that today is used in many products and industries but is not as well accredited, as it should be, especially in die casting?

Many centuries after the Toledo sword was no longer of importance, peening was rediscovered and used extensively in the U.S. automotive industry, but only after repeated fatigue tests showed unexplained reasons for extended life of automotive components. Prior to this time, sand was being used to descale large steel leaf springs after heat treatment, but this process was a dirty and dusty operation which could cause serious or fatal lung illness to anyone working in the silicon blasting environment. Hence, sand blasting was replaced by steel shot (1/16″ dia. or less) to de-scale the springs. General Motors noted that these peened springs were lasting longer and had fewer breakage problems. Upon examination, they found that the tiny balls of steel bombarding the surface of the springs were cold working the material and creating a permanent compressive zone. From this experience, shot peening was born. Today, its use is so extensive and necessary that airplanes and helicopters cannot fly without it; automobile engines, drive trains and transmissions depend on it and nuclear reactors are made safer by it. Even the artificial heart would only exist on the drawing board without it. The components for these products, like die cast tooling, all have the same goal — extended life, improved performance and resistance to breakage.

With this in mind, in 1983, Badger Metal Tech took the peening life extension technology to a new level. They developed a proprietary process for peening the tools that make the parts.

In this article, some of the particulars will be revealed that make this process possible. The process was conceived in 1983 and designed exclusively for the perishable tooling industry. Successful products are often imitated but not duplicated. Although others may make similar claims, there are no substitutes. Since 1983, more than 100,000 die casting dies, as well as tens of thousands of other perishable tools, have passed through the doors of Wisconsin's Badger Metal Tech. Although it is not a panacea for all the modes of tooling failure, it is a big step in the right direction to preventing early fatigue and extending tool life and performance.

Generic Definition

Shot peening is a cold working process in which the surface of a part is bombarded with small spherical media called shot. Each piece of shot striking the metal acts as a tiny peening hammer, imparting a small indentation or dimple on the surface. In order for the dimple to be created, the surface layer of the metal must yield in tension (Figure 1). Below the surface, the compressed grains try to restore the surface to its original shape, producing a hemisphere of cold-worked metal highly stressed in compression (Figure 2). Overlapping dimples develop a uniform layer of residual compressive stress.

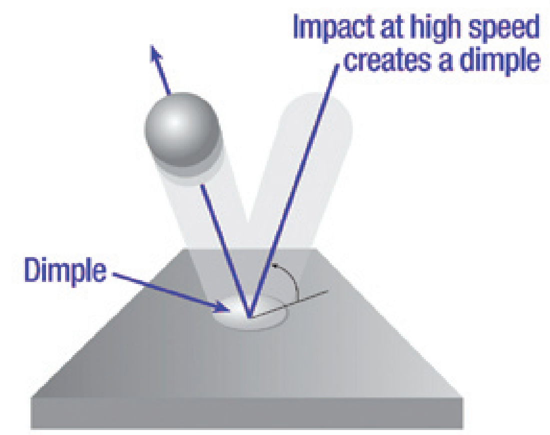


Figure 1 *Mechanical Yielding at Point of Impact*

Figure 2 *Compression Resists Fatigue Cracking*

It is well known by metallurgists and an axiom of physics that cracks will not initiate nor propagate in a compressively stressed zone. Because nearly all fatigue and stress corrosion failures originate at or near the surface of a part, compressive stresses induced by shot peening provide significant increases in part life. The magnitude of residual compressive stress produced by shot peening is at least as great as half the tensile strength of the material being peened.

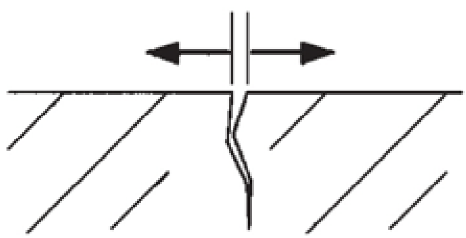
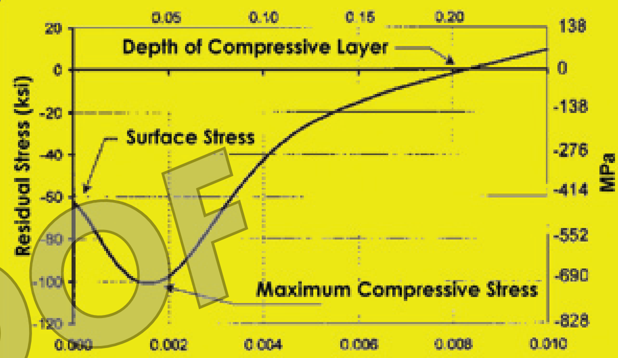


Figure 3 *Crack Initiation and Growth Through Tensile Stress*

In most modes of long-term failure, the common denominator is tensile stress. These stresses can result from externally applied loads or residual stresses from manufacturing processes such as thermal shock, welding, grinding or machining. Tensile stresses attempt to stretch or pull the surface apart and may eventually lead to crack initiation (Figure 3). Compressive stress squeezes the surface grain boundaries together and will significantly delay the initiation of fatigue cracking. Because crack growth is slowed significantly in a compressive layer, increasing the depth of this layer increases crack resistance. Shot peening is the most economical and practical method of ensuring both surface, residual and deep compressive stresses.

Residual Stress Curves & How They Affect Die Cast Tool Life

The residual stress generated by the treatment is of a compressive nature. This compressive stress offsets or lowers applied tensile stress. Quite simply, less (tensile) stress equates to longer tool life. A typical stress profile is depicted in Figure 4. Special tool steel curves were developed in conjunction with the process to assure repeatability and consistency. The amount of texture to the surface does not guarantee a proper curve structure or adequate saturation. These are some of the factors that must be taken into consideration and can only be measured by X-ray diffraction (destructive sampling) and Almen strips (work piece simulation expectations) to be covered in Part 2.



Typical Shot Peening Residual Stress Profile

Figure 4

Maximum Compressive Stress – The maximum value of compressive stress induced. It is normally just below the surface. As the magnitude of the maximum compressive stress increases, so does the resistance to die fatigue cracking.

Depth of Compressive Layer – The depth of the compressive layer resisting crack growth. The layer depth can be increased by increasing the impact energy. A deeper layer is generally desired for crack growth resistance and propagation.

Surface Stress – This magnitude is usually less than the Maximum Compressive Stress and before the curve knee.

When a die is peened and subjected to an applied load, the surface of the component experiences the net stress from the applied load and shot peening residual stress. Figure 5 depicts a bar with a three-point load that creates a bending stress at the surface. The diagonal dashed line is the tensile stress created from the bending load. The curved dashed line is the (residual) compressive stress from generic peening. The solid line is the summation of the two showing a significant reduction of tensile stress at the surface. The process is highly advantageous for stress risers (radii, notches, cross holes, grooves or ribs, sharp corners, etc.) and high strength materials. Peening induces a high magnitude of localized compressive stress to offset the stress concentration factor created from these geometric changes. Peening is ideal for hot work and cold work tool steels. Compressive stress is directly correlated to a material's tensile strength. The higher the tensile strength, the more compressive stress that can be induced. Higher strength materials have a more rigid crystal structure. This crystal lattice can withstand greater degrees of strain and consequently can store more residual stress.

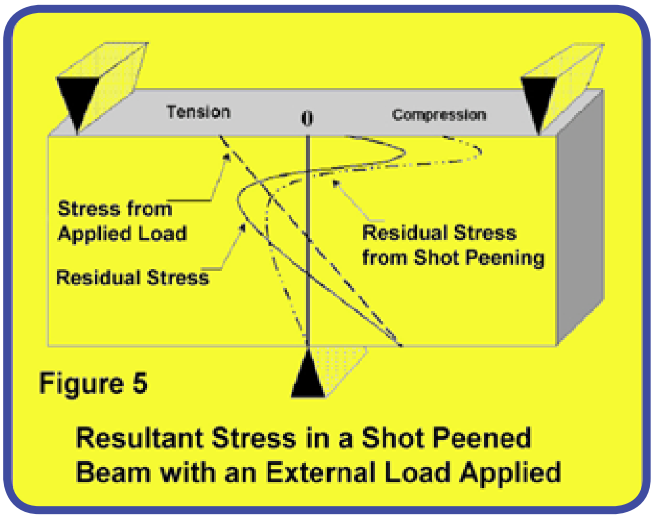


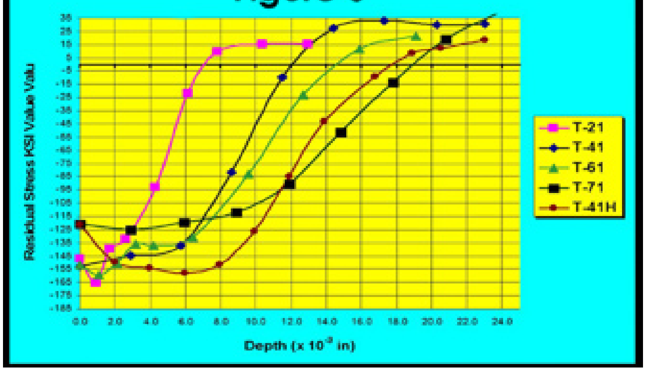
Figure 5

Resultant Stress in a Shot Peened Beam with an External Load Applied

Depth of Residual Stress Considerations

The depth of the compressive layer is influenced by variations in peening parameters and material hardness. Figure 6 shows the relationship between these effects on the depth of the compressive layer and the resultant curves. Shown are the intensity curve values for five of the 10 different processing parameters that were developed, then depth/value measured by X-ray diffraction at Proto in Windsor Ontario and Lambda Labs in Ohio.

Figure 6



Media

The media most commonly used for shot peening consists of small spheres of cast steel, conditioned cut wire (both carbon and stainless steel), ceramic or glass materials. Most often, cast or wrought carbon steel is employed. Stainless steel media is used in applications where iron contamination on the part surface is of concern. Carbon steel cut wire, conditioned into near round shapes, is specified more frequently due to its uniformity. Glass beads are also used where iron contamination is of concern. They are generally smaller and lighter than other media and can also be used to peen into sharp radii of threads and on delicate parts where very low intensities are required.

Effect of Shot Hardness

The hardness of the shot will influence the magnitude of compressive stress (Figure 7). The peening media should be at least as hard or harder than the tools being treated unless surface finish is a critical factor. The proprietary process encompasses various hardness parameters for the needed and desired results. Commonly used 45-52 HRC, while effective, is not as good at developing the critical compression curve needed for tool steels. For these, one must use a special higher hardness media (curve not shown), even though more costly, to assure maximum depth and high compression values for its higher intensity "T" processes.

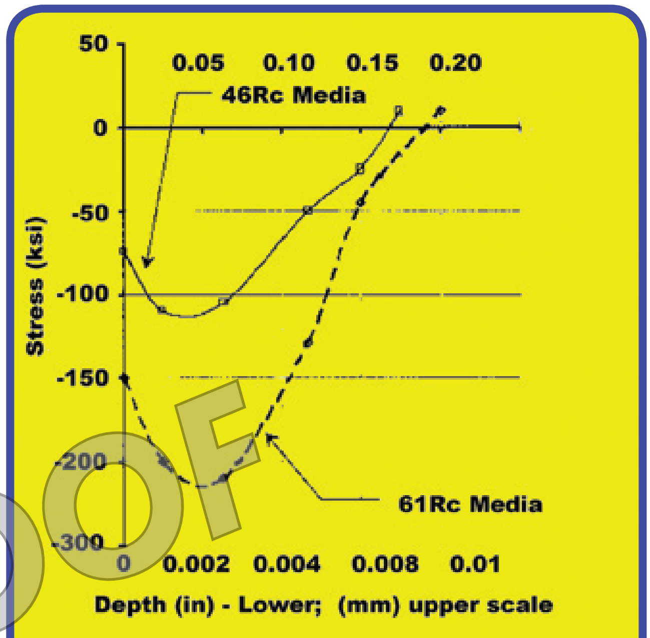


Figure 7

Carburized Steels

Harder media is also essential when processing nitrided or nitro-carburized die steels. When properly applied, these high hardness diffused surfaces that are commonly 65-70 HRC benefit in the following ways:

- High magnitudes of compressive stress of ~200 ksi (1379 MPa) or greater offer excellent fatigue benefits.
- Carburizing anomalies resulting from surface intergranular oxidation are reduced.
- They retard initial fatigue cracking and slow existing crack propagation.

Effect of Manufacturing Processes on Fatigue Life

Manufacturing processes have profound effect – detrimental or beneficial – on the fatigue properties of die and tool steels. Detrimental processes include welding, grinding, abusive EDM processing, thermal shock, improper heat treatment, steel selection, etc. These choices leave or generate high surface residual tension. The summation of residual tensile stress and applied loading stress accelerates fatigue failure.

Beneficial manufacturing processes include surface hardening by nitriding, ferritic nitro carburizing and coatings, all of which induce some residual compressive stress into the surface. Honing, polishing and burnishing the surface are enhancing processes that remove defects and stress raisers from manufacturing operations along with small compressive stress effect. Surface rolling induces compressive stress but is primarily limited to cylindrical geometries.

Welding

The residual tensile stress from welding is created because the weld consumable is applied in its molten state — its hottest, most expanded state. It then bonds to the base material, which is much cooler. The weld cools rapidly and attempts to shrink during the cooling. Because it has already bonded to the cooler, stronger base material, it is unable to shrink. The net result is a weld that is essentially being "stretched" by the base material. The heat-affected zone is usually most affected by the residual stress and, hence, where failure will most likely occur. Inconsistency in the weld filler material, chemistry, weld geometry, porosity, etc., acts as a stress riser for residual and applied tensile stress to initiate fatigue failure. Tensile stresses generated from welding are additive with applied load stresses.

The combined stress will accelerate failure at welded connections. The peening process, in combination with stress tempering after welding, is extremely beneficial in reversing the residual tensile stresses that tend to cause failure in the heat-affected zone. Various methods and combinations are possible: tempering alone (most common), peening alone or tempering + peening to the welded die insert. The effect of these steps are shown (Figure 8) for various combinations. This treatment, in combination with stress temper, is the most effective. When the die cast weld is stress tempered at 1000˚F (620˚C) for one hour per inch of thickness, the tensile stress is sometimes reduced to nearly zero along with a normalizing and softening of the weld to a hardness closer to the base material. As a result, a deeper layer of compressive stress is then possible. By reducing the weld tensile stress fatigue properties, significant resistance is imparted to future fatigue crack initiation and propagation in the weld area.

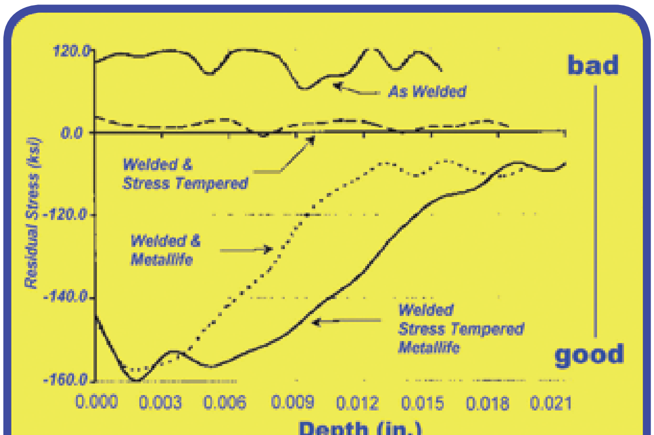


Figure 8 Residual Stresses from Welding

The American Welding Society (AWS) Handbook cautions readers to consider residual tensile stresses from welding if the fabrication is subject to fatigue loading as described in the following statement: *"Localized stresses within a structure may result entirely from external loading, or there may be a combination of applied and residual stresses. Residual stresses are not cyclic, but they may augment or detract from applied stresses depending on their respective sign. For this reason, it may be advantageous to induce compressive residual stress in critical areas of the weldment where cyclic applied stresses are expected."*

The use of a shot peening process to improve resistance to fatigue, as well as stress corrosion cracking in welded components, is recognized by:

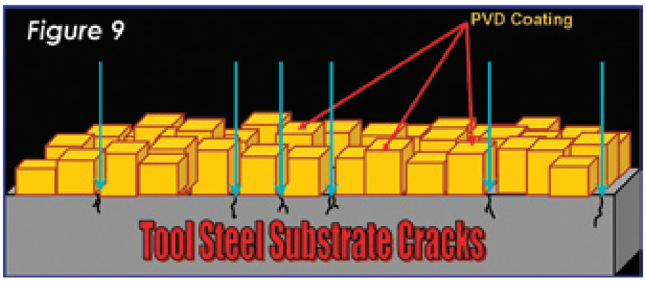
- American Society of Mechanical Engineers
- American Bureau of Shipping
- American Petroleum Institute
- National Association of Corrosion Engineers

Grinding

Typically, grinding induces residual tensile stress as a result of localized heat generated during the process. The metal in contact with the abrasive medium heats locally and attempts to expand. The heated material is weaker than the surrounding metal and yields in compression. Upon cooling, the yielded metal attempts to contract. This contraction is resisted by the surrounding metal resulting in residual tensile stress. Residual tensile stress of any magnitude will have a negative effect on fatigue life and resistance to thermal fatigue cracking. The expansion and contraction cycle of a die's surface by molten metal and die lube generates these same types of stresses which may lead to premature thermal cracking or heat checking. Proper application of shot peening to form the correct compression curve will reverse the resultant residual stress state from tensile to compressive. The beneficial stress reversal is similar to that from shot peening welded regions in a state of tension.

Coatings

Although coatings prove beneficial to improving tool life, many PVD coatings are deposited in a columnar fashion, leaving clear paths to the substrate material. Proper substrate preparation should include a compressive layer. Peening accomplishes this and, at the same time, removes grain boundary inclusions affecting the coating's integrity. Fatigue deficits may also occur if there is micro-cracking in the coating's brittle surface. Under fatigue loading, the micro-cracks in the coating can propagate into the base metal and lead to fatigue failure. When the base metal is shot peened, the potential for fatigue crack propagation into the base metal from the plating is dramatically reduced.



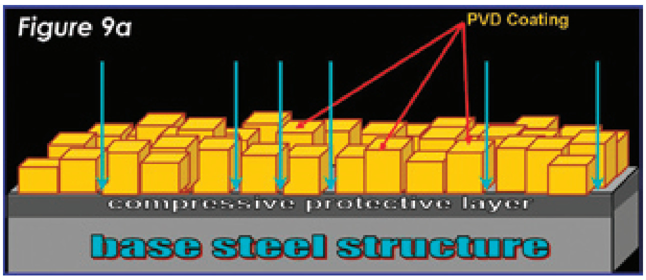


Figure 9 depicts micro-cracking propagating into the base material. After processing, Figure 9a shows the compressive layer preventing the micro-cracking from propagating into the base material. Processing prior to coating is recommended on cyclically loaded parts to enhance fatigue properties.

Electro-Discharge Machining (EDM)

EDM is essentially a "force-free" spark erosion process. The heat generated to discharge molten metal results in a solidified recast layer on the base material. This layer, which should be properly removed, can be very brittle and exhibits tensile stresses similar to those generated during the welding process. The treatment for hot work tool steel applications is beneficial in restoring the fatigue debits created by EDM.

Galling and Soldering

Galling is an advanced form of adhesive wear that can occur on materials in sliding contact with no or only boundary lubrication. In its early stages, it is sometimes referred to as scuffing. The adhesive forces involved cause plastic deformation and cold welding of opposing asperities. There is usually detachment of metal particles and gross transfer of fragments between surfaces, which often leads to mechanical seizure.

The treatment can be beneficial for surfaces that gall. The cold worked surface also contains dimples that act as lubricant reservoirs. These reservoirs, by retaining lubricant, also slow or stop the interaction of aluminum (Al) atoms in the molten cast metal and the iron (Fe) atoms in the tool steel from forming covalent bonds resulting in soldering. As the soldering increases beyond a purely mechanical phase, there is an actual interaction or intermetallic bonding effect. At this stage, removal is difficult without compromising the tool steel itself. It is very important that some type of barrier be active between the two metals to prevent this interaction. Lubricant retention is the most common method for accomplishing this; however, extended spraying cycles cause increased temperature and cycle swings both on the steel's surface to as much as 0.08″ below. The cycle extremes shorten tool life and lead to premature accelerated fatigue cracking. When lube can be retained and not added to the surface, a lower thermal gradient is produced. Often, nitro carburizing and peening are used in conjunction to create this needed barrier.

Thermal Fatigue

Thermal fatigue refers to metal failures brought on by uneven heating and cooling during cyclic thermal loading. Rapid heating and cooling of metal induces large thermal gradients throughout the cross-section, resulting in uneven expansion and contraction. Measurements have been taken that show that the transition to these high tensile stresses occur quickly on baseline polished H13. Enough stress can be generated to yield the metal when one location attempts to expand and is resisted by a thicker, cooler section of the tool.

Thermal fatigue differs from elevated temperature fatigue, caused by cyclic mechanical stresses at high temperatures. Often, both occur simultaneously because many parts experience both temperature excursions and cyclic loads.

Conclusion and Summary

The history of peening dates back to the 11th Century where residual stresses were being countered by inducing compressive stress in swords and then again in the industrial age when the automotive industry discovered its benefits. Still today, not many individuals are aware of the concept, yet in our everyday lives, equipment or products are being used that would not perform without the use of the technology. Today, it is a commonly used method to correct manufacturing effects on OEM parts in any industry that produces metal parts. In 1983, Badger Metal Tech adopted and focused the ambient applied Metallife® technology for specific use on tool steel and other perishable tooling.

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

Although it is not a panacea for all the modes of die cast and tooling failure, it is a big "catch up" step in the right direction to preventing early fatigue and extending tool life and performance.

Part 2 of this article will continue discussing the Metallife® peening benefits, special controls to follow for maximizing its benefits, new technologies in the field and some case studies.

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 Expos. His latest was an article on the recent advances in FNC, which appeared in the May 2003 issue of Die Casting Engineer magazine. He is considered an authority on die casting die residual stress and chaired a task force for the Die Materials Committee, which worked to establish baseline stress parameters for die cast tooling.

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

Jerald V. Skoff, President
Badger Metal Tech Inc.
Menomonee Falls, Wisconsin

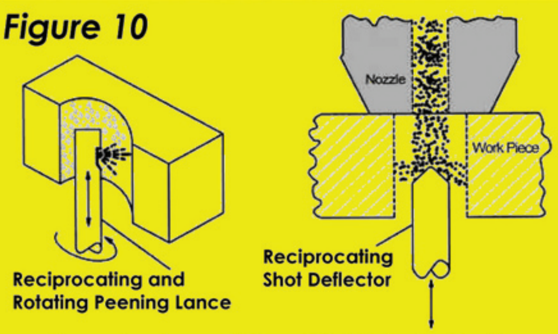
Introduction

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, this processing method must be used with 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. Figures 11 and 11a show the surface finishes from the single and multiple peening at 30X magnification.

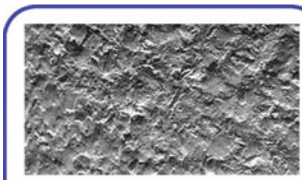


Figure 11 SEM Photo of Single Peen Surface Finish

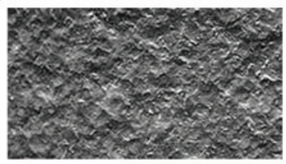


Figure 11a SEM Photo of Dual Peen Surface Finish

Controlling the Process

Controlling the process is different from most standard manufacturing processes in that there is not a non-destructive method to confirm that the operation was performed to the desired specifications. 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

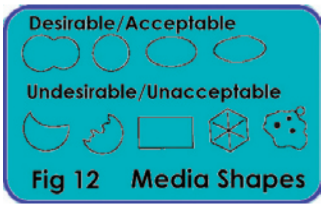
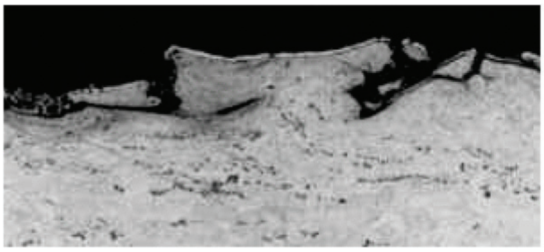


Fig 12 Media Shapes

Peening media must be predominantly round. Figure 12 depicts 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

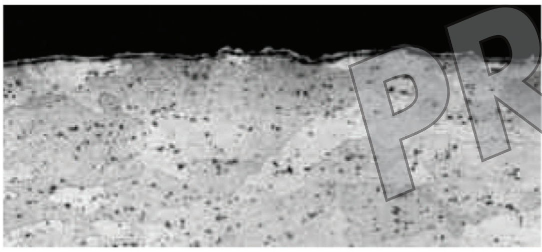
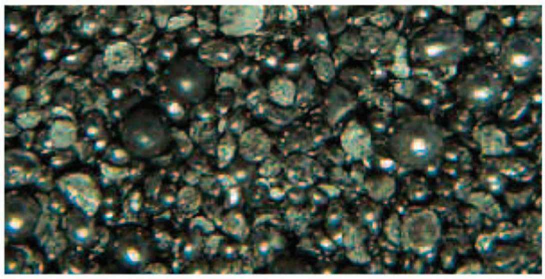


Figure 13 Surface from Proper Media

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

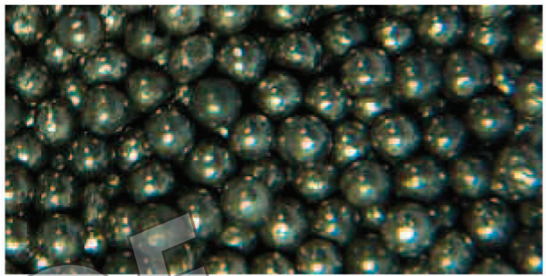


Figure 14 High Quality Shot Peening Media

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 strip system. An Almen strip consists strip of a bar of SAE1070 spring steel hardened to 44-50Rc which is then peened on only one side.


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 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).

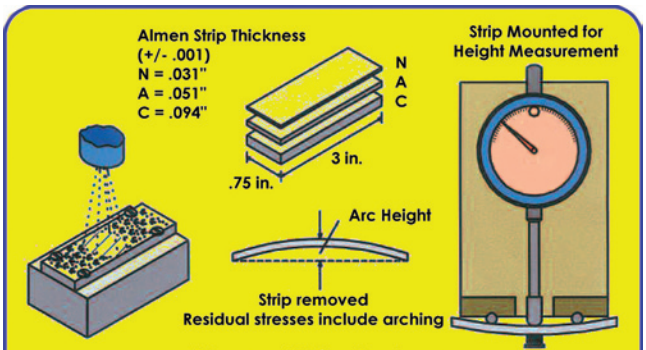


Figure 16 Almen Strip System

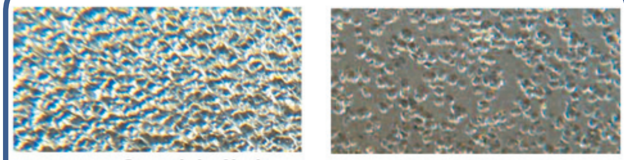


Figure 17 Complete Shot Peening Coverage *Figure 17a* Incomplete Shot Peening Coverage

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 also 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 (100X) demonstrate complete (Figure 17) and incomplete coverage (Figure 17a).

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. The 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 that is 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 just 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
  - Shot (size, material, hardness, saturation and intensity)
  - Single peen, dual peen, tri-peen or other multiple combinations

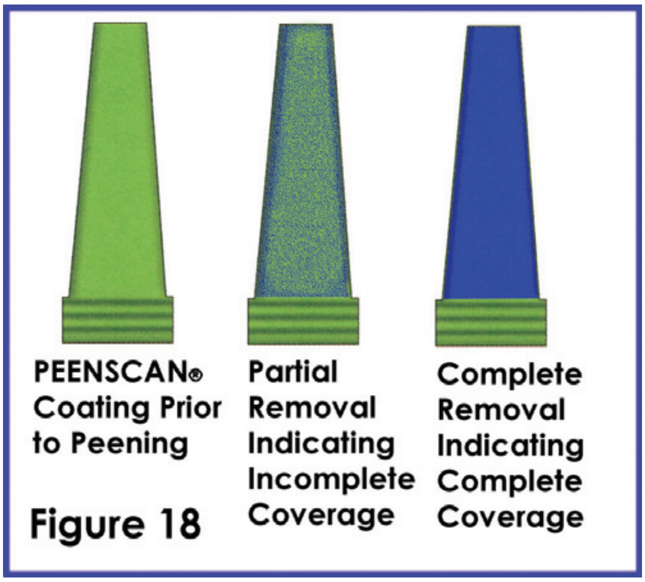


Figure 18


Figure 19
waffle overlap from fired laser

Badger Metal has more than 25 years of experience and can utilize an internally developed software package called Peenstress℠ 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.

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 facility in the U.S. was used for this test. More information can be found at http://www.badgermetal.com/laserlife/laserlife.htm.

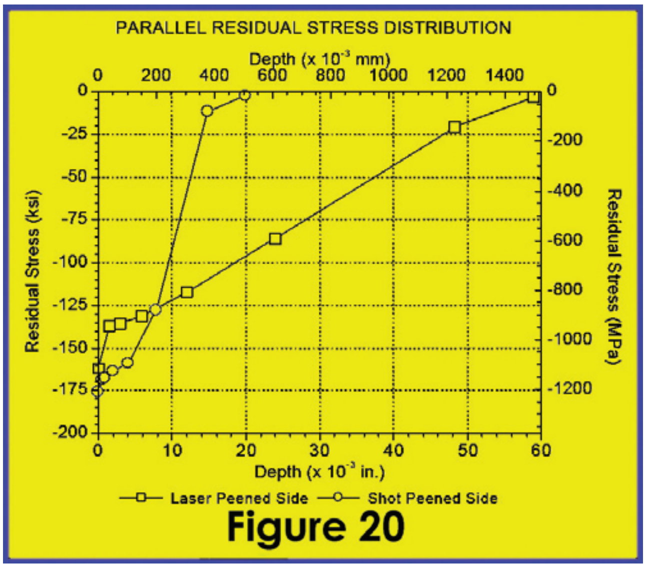


Figure 20

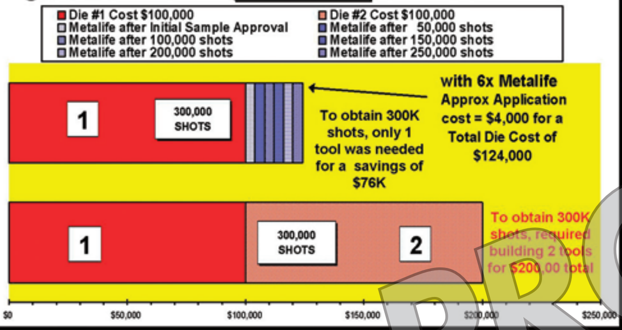
Historical Case Study

Customers for more than 25 years have been using the proces 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, available at http://www.badgermetal.com/field-ml.htm.

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 (#834). 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.

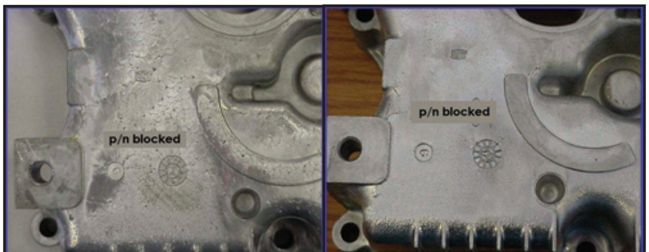


Figure 22 Not Treated After 72,000 shots

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.

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