Users' Guide
for
Relieving Stresses in Die Casting Dies

Produced by
Badger Metal Tech, Inc.
&
The North American Die Casting Association

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Relieving Stresses in Die Casting Dies

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Relieving Stresses in Die Casting Dies

I. Introduction

The die casting industry depends upon expensive steel dies to produce components for its customers. Especially when used for the production of aluminum components, the life of the die casting die is a critical cost factor. Many times the cost of the die can be 10-20% of the cost of each part. For example, a die for a large automotive die casting may cost as much as $800,000. If the life of the die is 200,000 shots, then the die cost is $4 per shot. The total cost of the component may be around $25, in which case the die cost is 16% of the total cost for each part. Anything that can be done to extend the useful life of the die reduces the cost for every piece produced. Accordingly, the industry has invested significant resources into extending the life of dies over the past 20 years.

There are many variables involved in the production of die casting dies. The technical investigations that have been conducted over recent years have focused on identifying the keys to maximize die life. The key areas identified are:

- Die steel composition and processing.
- Die construction procedures.
- Casting production practices.
- Die maintenance techniques.

<u>Die steel composition and processing</u> have been evaluated and prescribed in the form of NADCA Publication #229, "Special Quality Die Steel & Heat Treatment Acceptance Criteria for Die Casting Dies." This publication identifies proper composition, heat treatment, quenching rates and hardness for die casting dies. Adherence to this procedure insures the capability of the steel to achieve acceptable die life. Poor practice in die construction, casting production, or die maintenance may still reduce the die life actually achieved, but without proper steel composition and processing poor die life will result.

Die construction procedures also affect the life of the die. Electro Discharge Machining (EDM) treatments can especially damage the surface of the die and reduce its useful life unless special precautions are taken and the die is properly treated after EDM processing. Welding is another process that is very detrimental to die life. Special die welding procedures are identified in NADCA Publication #229 mentioned previously. Other construction procedures such as rough machining and grinding can also adversely affect the life of the die. Careful and complete polishing the die surface has been found to be beneficial to the life of the die.

Die casting production practices have been found to reduce the life of die casting dies. Injecting molten metal into a die at room temperature shocks the surface of the die. Preheating the die surface to between 300°F and 600°F is recommended and the use of hot oil die pre-heating and cooling has a good record of extending die life. The overuse of die spray to cool the die surface is also detrimental to die life. Die cooling should be provided as much as possible by internal cooling lines to minimize the surface cooling during operations. The constant need to increase production by minimizing casting cycle times may result in reduced die life if the thermal characteristics of the process are not considered.

Die maintenance techniques are also important factors in die life. Unfortunately, the lack of die maintenance often adversely affects the life of the die. Dies are seen as consumable tools in the production process and sometimes little effort is expended to maximize the life of this large investment. Maintenance techniques that can enhance the life of die casting dies include surface treatments and methods to reduce the stress concentrations on the surface of the die. Surface treatments utilized include oxide films, gas nitriding, salt bath nitriding, and ion nitriding. Different steels possess different nitriding properties, depending on their chemical composition. Methods used to reduce the stress concentrations on the surface of the die include thermal stress tempering and proprietary shot peening (**MetaLife**®). These methods are the primary topic of this NADCA Users' Guide.

It is important that the readers of this ***Users' Guide for Relieving Stresses in Die Casting Dies*** understand the technical information and recommendations of this document in their proper context. Reducing surface stresses in die casting dies can help to improve die life, but such a practice is not a miracle cure after using poor die steel composition and processing, poor die construction techniques, or poor operating practices. Reducing the surface stresses of a die is another tool the die caster can utilize to extend the life of dies and further reduce the cost of the die castings being produced.

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II. Executive Summary

The die casting industry utilizes highly engineered steel dies to produce products for its customers. These dies are very costly and make up a significant portion of the cost of a die cast component. The industry is constantly looking for ways to make these dies last longer before requiring replacement. In recent years, industry sponsored research has been conducted to identify the key factors in maximizing the life of die casting dies. The key factors identified are: die steel composition and processing, die construction procedures, die casting production practices, and die maintenance techniques. The North American Die Casting Association (NADCA) has developed publications, procedures, and checklists on these topics to help the industry improve the life of dies.

One of the primary failure modes for die casting dies is thermal fatigue or heat checking. Die maintenance methods used to minimize heat checking include thermal stress relieving and proprietary shot peening (**MetaL* ife®**). The technically correct term for stress relieving a die during its productive life is stress tempering, but stress relieving is often the term used by the industry. NADCA has developed this Users' Guide to assist the industry in utilizing stress tempering and **MetaL*ife®** to enhance die life.

The thermal cycling of die casting dies during production creates tensile stresses on the surface of the die. These tensile stresses can occur in as few as 10 shots on a die that was essentially without surface stress in the beginning. When these tensile stresses exceed the hot strength of the die material they initiate small cracks at stress risers on the surface of the die caused by surface imperfections or even material grain boundaries. As the die continues the thermal cycling in production, the tensile stresses cause the cracks to grow. A significant amount of research has been conducted utilizing X-ray diffraction methods to identify the causes of heat checking. The research results have confirmed that these surface tensile stresses are the cause of heat checking. The research has also shown that a die surface with pre-existing tensile stresses reaches higher levels of tensile stress during operation and a die surface with pre-existing compressive stresses reaches a much lower level of tensile stress during operation when compared to a die surface with zero stress.

Feedback from the die casting industry that was solicited during the compilation of this guide varied widely. Some operations seemed committed to the practice of stress tempering dies regularly and others utilized **MetaL*ife®** to reduce heat checking and provide other process enhancements. Some die casters followed the NADCA recommendation of proprietary shot peening and stress tempering dies on a scheduled basis. However, some die casters had not been able to verify the benefits of stress tempering or shot peening and did not do either. The research results and the industry comments strongly suggest that each die caster should evaluate the cost effectiveness of stress tempering and the nature of the shot peening for dies used in their particular operation.

Taking into consideration the research results referenced in this guide, the NADCA recommendations for maintenance of dies, and the industry comments relative to stress tempering and shot peening the following recommendations are offered:

1. Stress tempering should be performed on die casting dies after the initial die sampling and then on a scheduled basis, depending on the severity of heat checking experienced. This stress tempering should be carried out at a temperature about 50°F below the highest tempering temperature which has previously been used during heat treatment of the die. The purpose of this tempering is to reduce the surface stress of the die to near zero.
2. Dies should be stress tempered after any EDM work on the die.
3. Dies should be stress tempered both before and after any weld repair to a finished die.

4. Specific application shot peening should be utilized following stress tempering to create a compressive stress on the die surface, which further reduces the tendency of the die to heat check and can delay the growth of existing surface cracks. In order to maximize the compressive stress, dies should be reprocessed after each stress temper to renew the compressive stress on the die surface. Some die casters using the **MetaL*ife®** process have been successful with reapplication after every second stress temper.
5. The technical knowledge and experience of those providing stress tempering services and especially shot peening services is critical to the successful use of these techniques. Diligence must be exercised to confirm the technical competence of potential suppliers along with verification of the resultant compression curves.
6. Die life compressive stress relieving, by definition, removes compressive protection and should not be confused with **MetaL*ife®**.

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III. Heat Checking in Die Casting Dies – A Technical Overview

This section will present a technical discussion about why die casting dies experience thermal fatigue or heat checking. The results of research projects to determine how heat checking occurs and what procedures can be used to mitigate die failures are also presented.

Stress and Die Casting Dies

Thermal fatigue is one of the most common and most expensive problems encountered in the die casting industry.[1] This type of failure is a result of repeated, rapid, non-uniform heating and cooling of dies, and the thermal-mechanical loadings that result. The initial onset of fatigue failure is characterized by heat checking on the die cavity surface. Further development of heat checking often results in stuck or defective castings. An example of heat checking on a casting surface is shown in Figure 1.

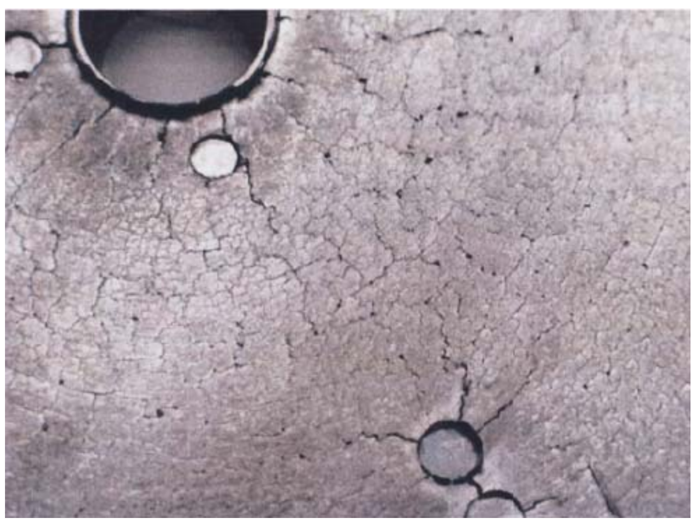

Figure 1. Heat Checking on Casting Surface

Die casting dies are subjected to cyclic mechanical and thermal loading. Each machine cycle subjects the die to the mechanical loads of the machine locking force and the cavity pressure, as well as the thermal loads due to cooling and solidification of the casting alloy and external and internal cooling. Each of these forces affects the time-varying stress-strain field within the die. The extent to which the forces affect the stress-strain behavior and cyclic life of the die is largely determined by their magnitude and the areas upon which they act.

On a properly adjusted machine, the locking force is supported evenly by the holder block-supported contact area of the die faces. Even though the locking force on a large machine may be thousands of tons, the force per unit area on the die is relatively small because of the large surface areas of the die faces.

Cavity pressures are more significant to the problem of fatigue than are pressures due to machine locking force for two reasons. First, they are greater than locking force pressures. Second, they are exerted on the same surfaces that see maximum thermal loading. Positive cavity pressures during intensification also may create compressive strains at the die cavity surface.

The largest thermal loads experienced by the die occur during cooling and solidification of the casting alloy and during spray cooling of the die. These loads, and their effects on the die surface, are shown in Figure 2 below, and described in the paragraphs that follow.

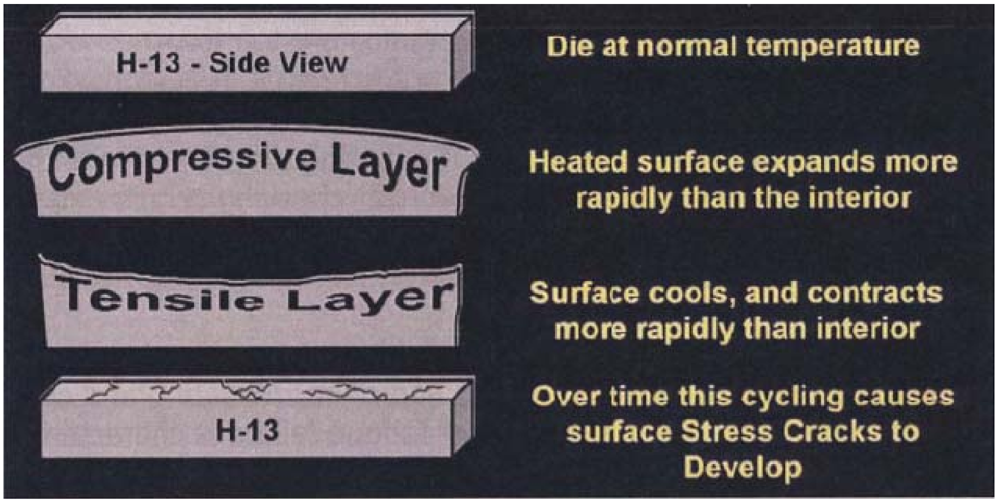

Figure 2. Thermal Cycling of the Die Surface

As molten metal is injected into the die cavity, the cavity surface is rapidly heated. The surface temperature rises as heat is transferred from the molten metal to the die surface. The rate and amount of heat transfer depends upon, among other things, the temperature difference between the molten metal and die surface, and the heat transfer coefficient governing the boundary of the molten metal and the die material. To facilitate quick solidification and to prevent soldering, die cavity surface temperatures prior to injection of molten metal are typically kept several hundred degrees (Fahrenheit) less than the temperature of the molten alloy being cast. Thus, during injection, there is a rapid, non-uniform heating of the die that induces compressive stresses near the die cavity surface, as the expansion of the surface is constrained by cooler adjacent steel.

While there is only one source of heat to the die, the metal being cast, die cooling is the result of heat transfer to several locations. While the die is closed, small amounts of heat are transferred to the platens via conduction and from the die to the surrounding air via radiation. In a die equipped with cooling lines, the largest amount of heat is removed via conduction to the cooling lines.

While the die is open, heat transfer to the cooling lines continues, as does heat transfer to the platens and the ambient air. As the die is opened, the amount of heat lost to the surrounding air increases as the die surface area in contact with the air increases. After ejection of the part, the die cavity surface is exposed to the ambient air, and heat is lost from the hot die cavity surface to the air. Because production schedules often necessitate short cycle times, surface-to-air cooling of the die cavity surface is often supplemented with a relatively cold liquid lubricant die spray. During die cavity surface cooling, tensile stresses are created near the die surface as the contraction of the cooler surface is restricted by adjacent material at higher temperatures. Because spraying increases the rate of heat removal, it increases the magnitude of the spatial temperature gradient near the die surface, thereby increasing the magnitude of the tensile stresses. This thermal cycling of the die surface between compressive and tensile stresses causes cracks to initiate at the die surface. Further thermal cycling creates the necessary stress for the cracks to grow.

Research Results

Research has been conducted to quantify the stresses experienced in a die casting die and provide insight into how these stresses affect the service life of the die.[2] One study was conducted by researchers from Pacific Northwest National Laboratory, Oak Ridge National Laboratory, and Ford Motor Company. A Ford wiper motor insert was used as a test part for modeling the effects of residual stress on the transient stresses and strains that develop during the course of cyclic operation. X-ray diffraction was used to measure the surface residual stresses in the die casting die at the beginning of life, and after being in service for 25,000 shots.

Analysis of the die insert indicated that the thermally induced stresses shifted from compression to tension at about five seconds into the casting cycle. Typical hoop stress, temperature, and plastic strain profiles in the outer layer of the die are shown in Figure 3.

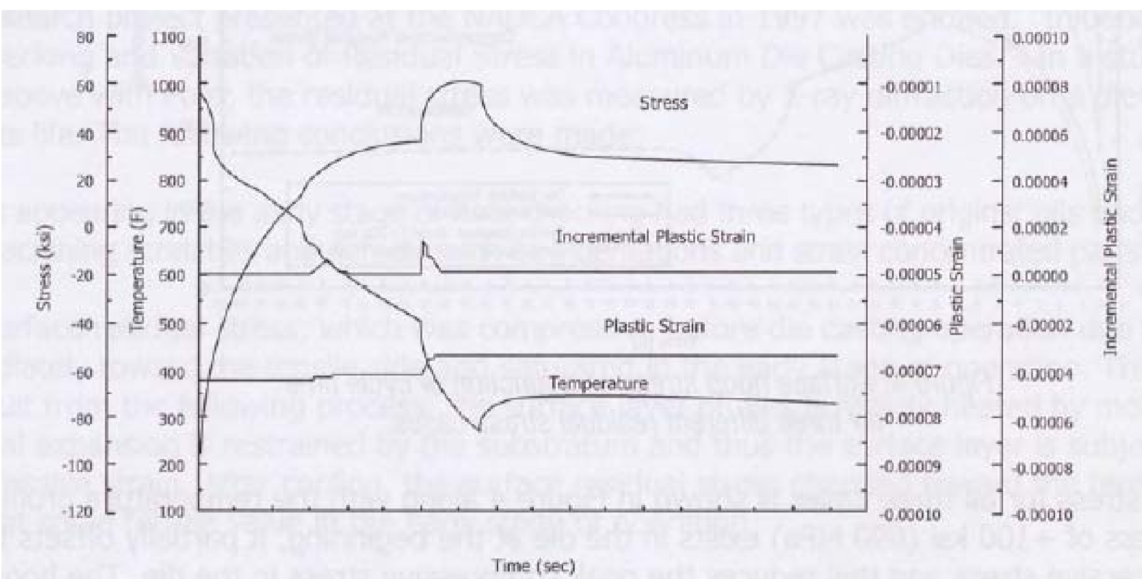

Figure 3. Hoop stress, temperature and plastic strain profiles on the die surface during the course of one casting cycle for a Ford Wiper Motor die.

The initial rapid increase in temperature of the die as it comes in contact with the molten aluminum introduces a very high compressive stress as the outer layers try to expand, but are constrained by the much cooler interior. The hot die surface is plastically deformed by the high level of stress, which exceeds the yield point of the H13 steel at elevated temperatures. The maximum temperature and the maximum stress are actually achieved within the first 0.1 seconds. The stress then reverses almost immediately as the outer layer of the die begins to cool rapidly, and is again constrained. At seven seconds into the cycle, the part was removed from the die. The cooling rate of the now-exposed die surface increases and there is a corresponding jump in tensile stress. This step is accompanied by a small incremental plastic strain as the very outer layer of the die is still hot enough to deform plastically. At about 14 seconds into the cycle, water is sprayed onto the surface. This causes a much larger increase in the cooling rate and sudden large increase in tensile stress. The surface of the die is still at a high enough temperature so that additional incremental plastic strain is incurred. As the temperature continues to decrease, the strength of the steel increases to a level above the thermally imposed stresses and further plastic deformation is halted.

When the water spray cooling portion of the cycle is terminated at about 19 seconds into the cycle, the outer layers heat up slightly driven by the now warmer interior and the stress decays to it final level. At the end of the cycle, the cumulative plastic strain that has been introduced into the die during the course of the cycle is compressive and this is balanced by a tensile stress of about 30 ksi (207 MPa). When the analysis is continued for an additional 10 cycles, the residual tensile stress at the end of the cycle increased by a very small amount.

A second part of the study was to model how changes in the residual stress level in a die at the beginning of service would affect the subsequent development of thermally induced residual stresses during operation. Both tensile and compressive residual stress levels were artificially imposed on the die prior to the start of the casting cycle. These two conditions were then compared against a baseline case with zero initial residual stress. The latter condition would also be representative of a die that had been stress relief annealed.

The calculated hoop stress for all three cases is shown in Figure 4 along with the

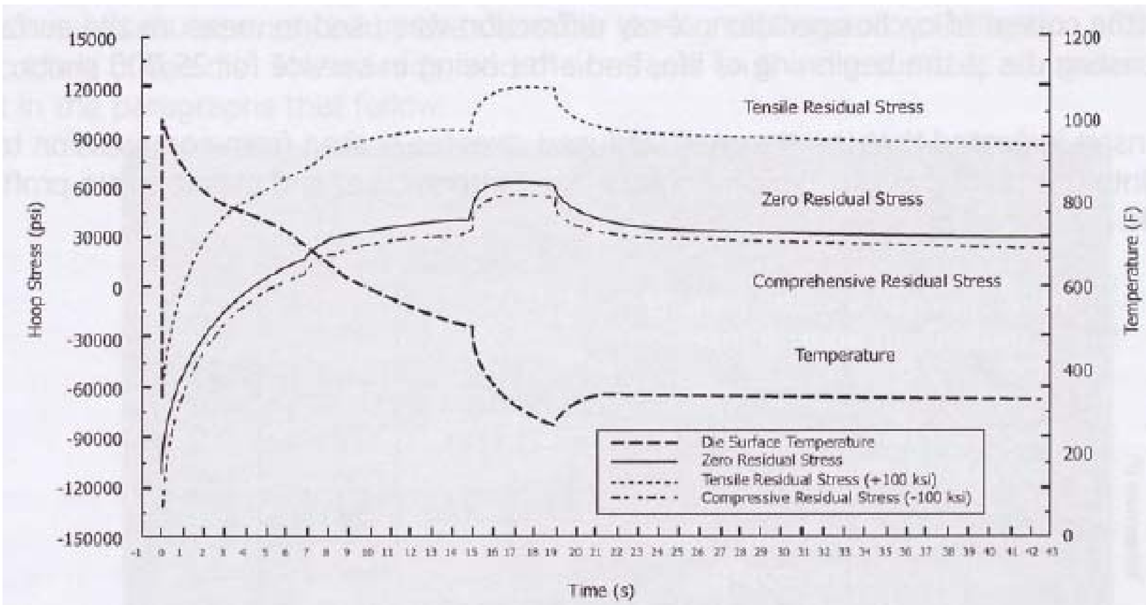

Figure 4. Surface hoop stress as a function of cycle time for three different residual stress cases.

temperature profile. When a tensile residual stress of +100ksi (690 MPa) exists in the die at the beginning, it partially offsets the thermally imposed compressive stress and this reduces the peak compressive stress in the die. The hoop stress in the outer layer declines from about -115 ksi (-793 MPa), for the zero stress case to about -65 ksi (-448 MPa). These stresses occur shortly after injection of molten aluminum, when the die is very hot, so plastic deformation occurs. The amount of plastic compressive strain that is induced is actually much higher, compared to the zero stress case, because it is superimposed on top of the initial residual plastic compressive strain already in the die. When the die begins to cool and the stresses reverse, the tensile stresses resulting from the die cycle become much larger, and even exceed the initial 100 ksi (690 MPa) value. This result is highly undesirable since large tensile stresses will promote crack nucleation and crack growth, thereby exacerbating the heat-checking problem.

If the residual stress is initially -100 ksi (-690 MPa) compressive, then the induced compressive stresses become quite large during the injection part of the cycle and approach -140 ksi (-965 MPa). However, the amount of compressive plastic deformation that occurs at the surface of the die is actually less than in either the tensile or zero stress conditions. A smaller amount of compressive plastic strain develops because the large residual plastic tensile strains that are in the die initially must be reversed. An additional benefit is the much slower reversal in stress which diminishes, significantly, the cyclic plastic strain. The peak tensile stress, following the quench cycle, is also less than even the zero stress case. Thus, the driving force for crack growth has been diminished.

It is generally believe that aluminum die casting dies develop residual tensile stresses in service as a result of the plastic compressive strains induced during initial heat-up. If the die begins operation with a residual compressive stress of -100 ksi (690 MPa), the amount of cumulative plastic compressive strain developed after the 10 cycles of operation is of the order 0.0007. The stress actually increases a little after the first cycle and then approaches a steady-state condition after several cycles. These calculations imply that tensile residual stresses actually develop during the first cycle of operation. Strain hardening then dampens the cumulative plastic strain and the plastic strain amplitude slightly with successive cycles.

The summary of the project on the Ford die reported that in general, it is better to have dies in an initial state of residual compression. It also reported that the commonly used industry practice of bench polishing die surfaces to remove the EDM white layer is adequate for the purpose of placing some compressive stress on the surface. However, if the white layer is not removed and tensile stresses remain, die life could be significantly reduced.

Tensile residual stresses develop in most dies during the initial casting cycle. These stresses will remain constant or perhaps increase slightly with cycle time during early life. It would generally not be beneficial to anneal out these stresses, because they will immediately reform during the next casting cycle. If annealing is performed, it would be desirable to re-introduce surface compressive stresses by re-polishing or shot peening the surface.

Another research project presented at the NADCA Congress in 1997 was entitled, "Initiation and Propagation of Heat Checking and Variation of Residual Stress in Aluminum Die Casting Dies."[3] In a study similar to the one discussed above with Ford, the residual stress was measured by X-ray diffraction on a die casting die at various stages of its life. The following conclusions were made:

1. Cracks appearing in the early stage of heat checking had three types of origins: pits and wavy patterns, various machining scratches and defects such as indentations and strain concentrated parts of the die surface.
2. The surface residual stress, which was compressive before die casting operation due to polishing, changed immediately toward the tensile side and saturated in the early stage of operation. This fact is considered to result from the following process: the surface layer of dies is rapidly heated by molten aluminum, the thermal expansion is restrained by the substratum and thus the surface layer is subjected plastically to compressive strain. After cooling, the surface residual stress changed toward the tensile side and saturated at some tensile value in the early stage of operation.
3. On the gate side of the cavity, in which the saturated tensile residual stress was large, micro cracks initiated in the saturated period. On the position opposite from the gate, in which the saturated tensile residual stress was small, the residual stress did not decrease and micro cracks did not initiate at the end of the die service life.

4. In the later stage of crack propagation on the gate side of the die cavity, heat checking was observed by the naked eye and the tensile residual stress decreased to zero.

In summary, research over many years has confirmed that heat checking of die casting dies is caused by excessive tensile stresses on the surface of the dies which initiate cracks. These same stresses over subsequent casting cycles cause these cracks to grow. This heat checking can be minimized by proper selection and processing of the steel used for the die. It is also minimized by reducing the temperature differential existing on the die surface during the casting cycle and by minimizing the temperature differences from one part of the die to another. Without proper selection and processing of the steel and minimizing the temperature profiles in the die, the heat checking will grow to be much worse.

In spite of all the precautions that can be taken to reduce the tensile stresses that build up on the surface of die casting dies during operation, they cannot be eliminated. The question remains of how to best manage those stresses and how to reduce the stresses before they cause damage to the die. These questions are addressed in the remainder of this guide.

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IV. Methods to Improve Die Life

The discussion in the previous section sought to explain why dies crack and fail prior to the end of their normal useful life. The most common causes of die failure are catastrophic cracking and heat checking. Previous research[4] has shown that catastrophic cracking (gross cracking) is primarily the result of poor steel chemistry or poor processing of the steel used to make the die casting die. The cooling rate of the steel from the austenitizing temperature is especially important in this regard. This research has been summarized by NADCA in Publication #229, available from NADCA at www.diecasting.org, and will not be repeated here. Proper steel chemistry and processing also improve the resistance of the die surface to heat checking but cannot eliminate it. Methods used by the industry to further reduce the impact of heat checking, both thermal stress relieving and shot peening, are presented in this section.

Thermal Stress Relieving

It should be pointed out at the onset of this discussion that what is normally called "thermal stress relieving" by the industry when attempting to reduce or eliminate the tensile stresses present on the surface of a die after it has been in production for a period of time is more appropriately called "stress tempering." *Stress relieving* is only done on dies in the soft condition (annealed) at a temperature of around 1250°F. This might be done on a die that has major welding due to a machining error or a design change. Its purpose is to prevent quench cracking in the welded areas. A second reason for stress relieving would be for a very complex die where distortion of the die is of great concern.

Stress tempering is done on dies that have been hardened at a temperature of around 1000°F, or 50°F below the highest tempering temperature which has previously been used during heat treatment of the die. This stress tempering is performed in the following cases:

- After any EDM work (mandatory).

- After final machining (mandatory).
- After weld repair of a finished die (mandatory).
- Prior to weld repair of a finished die (desired).
- After the die has been in service for a predetermined number shots (desired).

It is this scheduled stress tempering that serves to relieve the tensile stresses that build up on the surface of a die during its use in production. This process is also commonly referred to as stress relieving throughout the industry. However, it is important to know the difference in practice. If stress tempering was actually done when stress relieving was the correct process, it would not be a fatal mistake. The opposite mistake, in which a finished, hardened die is stress relieved (1250°F) will most likely cause the die to be much too soft for a normal die life.

During die casting, the surface of the die is subjected to thermal strains derived from the variations in temperature. This repeated straining results in residual stresses being generated in the surface of the die, as discussed in detail in the previous section. In most cases, such residual stresses will be tensile in nature and thereby assist the initiation of heat checking cracks. Stress tempering the die will reduce the level of residual tensile stress and thereby enhance die life. Generally, it is recommended that stress tempering be performed after the running-in period of the die and then after 1000-2000 and 5,000-10,000 shots. The procedure is then repeated for each additional 10,000-20,000 shots, so long as the die exhibits only minor amounts of heat checking. However, there is little point in stress tempering a heat checked die because the formation of surface cracks in itself reduces the level of residual stress, unless compressive induced (not compressive relieving) is to be performed on the die.

Stress tempering is best carried out at temperature about 50°F below the highest tempering temperature which has previously been used during heat treatment of the die. Normally, two hours holding time at temperature should be sufficient. Several companies that provide stress tempering services for the die casting industry contributed to the development of this guide. They are listed below and can be contacted for additional technical information.

- Century Sun Metal Treating, Traverse City, Michigan.
- Paulo Products Company, St. Louis, Missouri.
- Schmolz-Bickenbach, Chicago, Illinois.
- Therm-Tech of Waukesha, Waukesha, Wisconsin.

Generic Shot Peening

Shot peening of steel can be traced to the 11th century when a special brand of European sword was peened to give it extended life and improved performance, along with resistance to breakage. Most swords were manufactured thick and heavy to keep them from breaking, but it took a great deal of strength and energy to use one in battle. If you were wealthy, however, you could go to Toledo, Spain, and buy the latest 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. Their art was never revealed even after swords gave way to firearms as the primary weapon of war.

In the 1970's some engineers again delved into the mystery of the Toledo blades. This time they re-examined them using modern X-ray diffraction methods. To their surprise they found that the blades had been peened, not with shot as is done today, but with ball peen hammers. Many centuries after the Toledo sword was no longer of importance, peening was rediscovered and used extensively in the U.S. automotive industry. Up to that time, sand was being used to de-scale large steel leaf springs after they were heat treated, but the process was dirty and dusty and created a poor environment for workers. To improve the environmental conditions, steel shot (1/16" diameter or less) replaced the sand 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 it is used in critical parts for airplanes, helicopters, automobile engines and transmissions, nuclear reactors, and even artificial hearts.

Generic shot peening is a cold working process in which the surface of the die 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. This is shown in Figure 5.

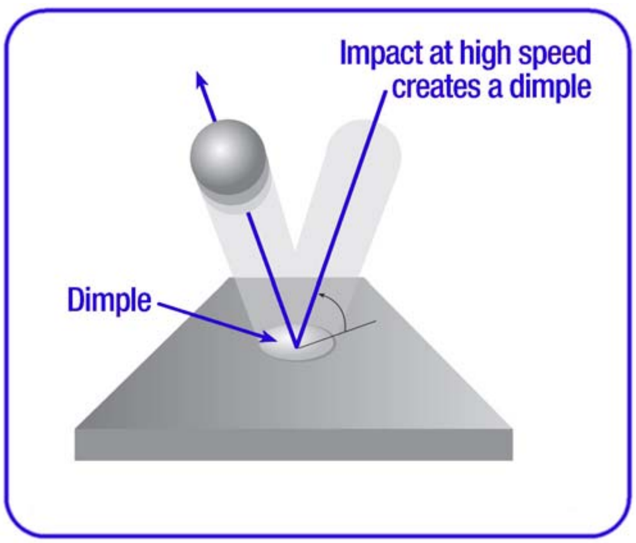

Figure 5. Mechanical Yielding at Point of Impact

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. This can be seen in Figure 6. Overlapping dimples develop a uniform layer of residual compressive stress.

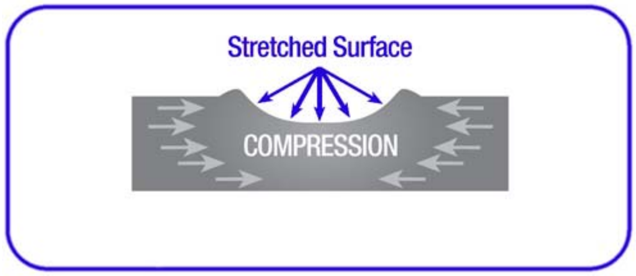

Figure 6. Compression Resulting from Impact

It is well known by metallurgists 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 die casting die, compressive stresses induced by shot peening can provide significant increases in die life. The magnitude of residual compressive stress produced by shot peening can be as great as half the tensile strength of the material being peened.

In most modes of long term failure of die casting dies the common denominator is tensile stress. Tensile stresses attempt to stretch or pull the surface apart and may eventually lead to crack initiation. This can be seen in Figure 7.

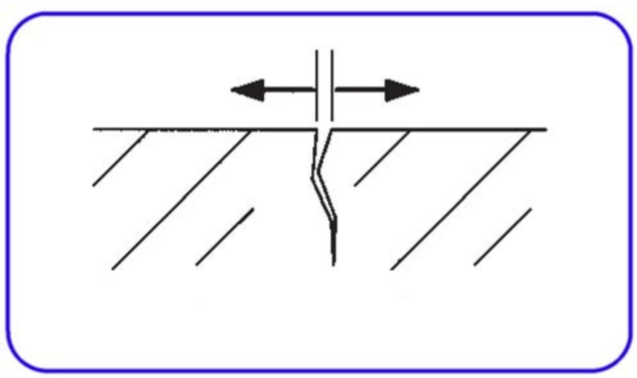

Figure 7. Crack Initiation and Growth
Through Tensile Stress

Compressive stress squeezes the surface grain boundaries together and will delay the initiation of fatigue cracking. Because crack growth is slowed in a compressive layer, increasing the depth of this layer increases the crack resistance. Shot peening is a very economical and practical method of ensuring that die surfaces have residual compressive stresses. In the remainder of this section, several aspects of shot peening for die casting dies are presented. These include considerations for the depth of the residual stress, control of the peening process, and future peening technologies.

The *depth of the residual compressive stress* imparted to a steel die is influenced by variations in peening parameters and the peen material hardness. The media most commonly used for shot peening consists of small spheres of cast steel, conditioned cut wire (both carbon and stainless steel), and ceramic or glass materials. Most often cast or wrought carbon steel is employed. Stainless steel media is used in applications where iron contamination is of concern. Carbon steel cut wire, conditioned into near round shapes, is being 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 be used to peen into sharp radii of threads and on delicate parts where very low intensities are required.

The hardness of the shot will also influence the magnitude of the compressive stresses. This can be seen in Figure 8. The peening media should be at least as hard as or harder than the tools being peened, unless surface finish is a critical factor.

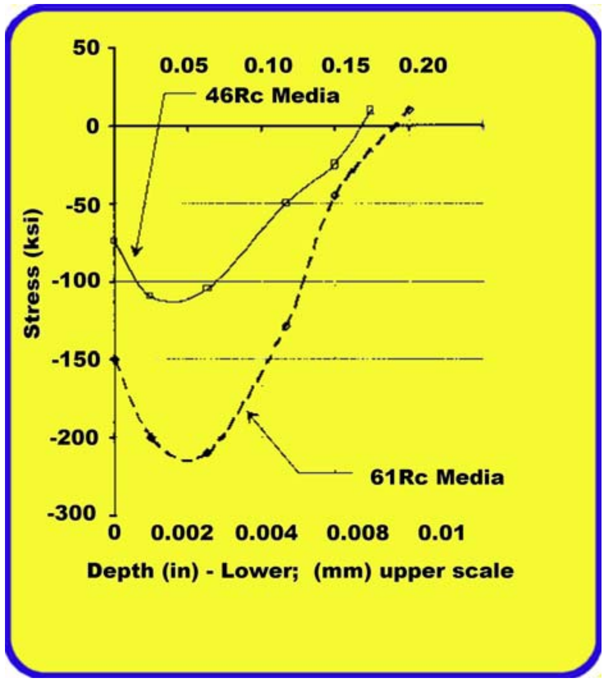

Figure 8. Effect of 46Rc and 61Rc Media on
Compressive Stress Imparted to Die by **MetalLife®**

Media of 45-52 HRC is commonly used and is effective, but is not as good at developing the required compressive stress as higher hardness material in the 55-62 HRC range. While higher hardness material is more expensive, it can be used to assure the maximum depth and high compression values needed. The harder media is essential when processing nitrided or nitro carburized die steels.

The control of the peening process is an important part of successfully imparting the required compressive stress to the surface of the die. Peening is a line-of-sight process and access to the surface is important. When the depth of an internal blind bore is greater than the diameter of the hole it cannot be effectively processed by external methods. Special internal lances have been developed, however, that eliminate this limitation when used under closely controlled conditions. This equipment makes it possible to peen holes as small as 0.096 inches (2.4 mm) in diameter.

Another consideration in shot peening is that controlling the process is different from many manufacturing processes in that there is no nondestructive method to confirm that it has been performed to the proper specification. Techniques such as X-ray diffraction require that a part be sacrificed to generate a full compressive depth profile analysis. It is important that the following variables be maintained to ensure repeatable peening specifications.

First, the peening media integrity must be maintained. The media must be predominantly round and when media breaks down from usage; the broken media must be immediately removed to prevent surface damage. Also, the peening media must be of a uniform diameter. If a mixed size batch of media is used for peening the larger media will drive a deeper residual compressive layer, resulting in a non-uniform stress layer. Special classification equipment is needed to assure meeting these criteria.

Second, the shot peening intensity must be consistent. In order to accomplish this, metal strips of various thicknesses are processed along with the part. The compressive stress on the metal strip causes the strip to bend. The intensity of the peening can then be measured by the deflection of the metal strip. Such process controls are necessary to insure consistency each time a die or insert is processed. Verification of the coverage of the peening over the entire part must also be made. This is done using a special fluorescent dye on the part surface. After the part has been processed, inspection under a UV (black) light permits verification that the entire surface has been peened in accordance with specifications. Special patents apply to inspection of coverage by this method.

Finally, the future of shot peening is likely to be laser peening. Development projects at Livermore Labs have resulted in initial commercial applications in medical, aerospace, and military applications. 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 sends shock waves through the part. Multiple firings of the laser is what creates the pre-defined surface pattern and imparts a layer of compressive stress on the surface that is four times deeper than that attainable from current peening technology. 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 a fatigue, thermal shock fatigue, and heat checking.

For more information on shot peening of die casting dies to reduce heat checking, please contact Badger Metal Tech Incorporated in Menomonee Falls, Wisconsin, which provided technical assistance in the preparation of this guide or use their website as a reference (http://www.badgermetal.com/).

Die life compressive stress relieving, by definition, removes compressive protection and should not be confused with **MetaLife®**.

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V. NADCA Recommendations

The North American Die Casting Association has produced a publication (#E-501) entitled “Care and Maintenance of Die Casting Dies – Manual and Checklist” for use by the die casting industry in maximizing the useful life of dies. The publication was created by members of the NADCA Die Materials Committee in cooperation with Professors J. Wallace and D. Schwam of Case Western Reserve University. This publication was intended to be used as a foundation upon which to build a more extensive die care maintenance program.

In the Care and Maintenance of Die Casting Dies publication it is recommended that dies be stress relieved (stress tempered) every 25,000 shots. Other times to stress relieve (temper) are after initial sampling and after any die repair or change that includes welding, EDM, heavy grinding, or polishing. At the first sign of heat checking, the die should be polished out and then stress relieved (tempered) at 950°F. After final sample approval, the die surface can be treated with a nitro-carburizing treatment to improve its surface behavior if desired.

The publication goes on to recommend that after final sample approval, micro-precision shot peening should be considered. This process places the die surface in a highly compressive state and favorable results have been reported from the field for a reduction in thermal fatigue cracking (heat checking). The micro-precision peening should be repeated at the normal untreated half-life of the tool. For example, if the die normally would get 120,000 shots, the half-life would be at 60,000 shots. Applications may need to be more frequent depending on the tendency for heat checking of the surface of the die. If applied correctly, stress tempering, nitro-carburizing, and shot peening may be used together.

The recommendations provided by NADCA are consistent with research results and were developed by experts in the die casting field. Die casting companies could benefit significantly by incorporating the recommendations into die design, die construction and die maintenance procedures.

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VI. Feedback from Die Casting Companies

During the development of this guide, suppliers and die casters were solicited for their comments on the use of thermal stress relieving and shot peening to extend the life of die casting dies and minimize the degree of heat checking experienced on dies in production. In this section, those comments are presented for the benefit of those utilizing this guide.

It was surprising during the accumulation of these comments that some die casters religiously utilize thermal stress relieving or **MetaL*ife®** because of the benefits derived, while others claimed that they had seen no benefit from the use of these technologies. Such is the nature of die casting. There is no magic formula that applies to every die caster. The success of these techniques is dependent on many variables, such as the types of castings produced, the alloys being cast, the volume of parts being produced, the surface conditions required for the castings produced, the cost structure of the particular die caster, and the technical resources available to the company.

The comments are divided into three categories. The first group is from those companies, both die casters and die shops, who utilize thermal stress relieving as a part of their tooling maintenance programs. The second group of comments is from die casters who utilize shot peening to extend the life of their dies. The third group of comments is from die casters who claim that neither stress relieving nor shot peening has proved cost effective for them. None of the companies are identified, but their comments are mostly quoted verbatim and may be of interest to the readers of this guide.

<u>Comments from Users of Thermal Stress Tempering</u>

- "We utilize stress tempering after any machining of hardened dies. We also stress temper both before and after welding on a hardened die. We haven't always tempered both before and after welding, but the welds often failed in service, sometimes big cracks and sometimes only spider cracks. Since adopting this practice we haven't had a problem in years."

- A die caster reported that they had been diligently stress relieving for 15 years. They stress relieve at a minimum of every 50,000 shots on zinc tools and every 5,000 shots on aluminum parts with large cross sections and deep heat-sink ribs. Thinner cross sectioned aluminum parts with shallow impressions are stress relieved every 10,000-15,000 shots. New tools are stress relieved after the first sample, after the second sample, and after the first 5,000 production shots. All stress relieving is done at 1000°F in their own furnace. The furnace is calibrated every quarter. For zinc parts they have been running for 22 years, die life has been improved from 200,000-300,000 shots to 1.2-1.4 million shots.
- "We stress temper any tool with a volume of over 50,000 a year on a quarterly basis. On some higher volume tools it is more like every other month. We have furnace capabilities in house so we generally stick to the schedule. We generally bring the block to 950 degrees F +/- 50 degrees and hold the block there for one hour per inch of thickness and then air cool. This serves two purposes: one, it re-oxidizes the surface of the steel and two, we get the stress temper benefit."

Comments from Users of **MetaL*ife®**

- "We are very pleased with the performance of tooling for our parking meter castings after application of **MetaL*ife®**. The dies no longer stick, solder, or drag. We also noticed that the heat checking on the older tools is considerably reduced with much better casting appearance. Flow is also improved."
- "After applying **MetaL*ife®** to a small barber utility tool, we were notified by our polisher that the casting from this tool was taking less time to buff which we attribute to improved surface characteristics, a reduction in

hidden porosity and better casting fill. The cosmetic requirement of this tool was such that the slightest imperfection in the surface would show after painting which was unacceptable."

- "We have set up a schedule to do **MetaL*ife®** on all of our big runner dies every 30,000 shots. We are seeing considerable benefit in our casting appearance by incorporating peening as a scheduled maintenance procedure."
- "We have been using **MetaL*ife®** since 1996 to retard heat checking and extend our tool life. We have also noted better paint adhesion due to the textured surface. We use a powder paint system that causes our paint to grab the surface better after peening. The powder paint also has a more even appearance. The texturing also helps casting fill characteristics."
- "We have several parts that we do a periodic **MetaL*ife®** to and this does seem to give us a longer life. All tools that we do a peening process to get stress tempered at the same time so I can not tell you if the shot peening alone is helping us or the stress temper or both."

<u>Comments of Die Casters Not Using Stress Relieving or generic shot peening</u>

- "We played with these techniques several years ago, and did not see any significant improvement in the die life results. At this point all new inserts are stress-relieved at the die shops when they are shipped to our plant. No other treatments are given after they are put on the machines. Our dies are averaging about 300,000 shots, and some of them are showing over 400,000 shots. We achieve this by having good quality steel, fast quench rate, and consistent cycle time on the machine. All of our dies are designed to have a lot of internal cooling passages to minimize the amount of spray. I think this also contributes to our long die life. We do not see a need for these treatments because most of the failure modes we have are related to parting line crashing and slide wear, and not much to heat checking, to which these treatments may be beneficial. We are proud of the die life we get on our dies."

- "We did a two year study of die life and failure on continuous running dies. Our experience is that die life can certainly hide heat checks and may provide some aesthetic value but no significant die life improvement was noted. We applied to several dies after sampling and in every case we got in trouble because of damage to the cavity detail. I would strongly urge that if this process is used it should be done prior to the customer receiving castings. The stress relief of dies is a much more difficult issue. The research done by Professor Schwam has shown significant benefit in this practice, yet we tried hard and could not realize the results in our practice. We did not measure or quantify crack length, rather used the visual criteria mandated by our customer. We did not see any significant difference; hence we have since halted the practice."

It is difficult to draw any precise conclusions from these comments. Some users seem committed to the practice of stress relieving dies regularly and others utilize shot peening to reduce heat checking and provide other process enhancements. Some die casters seem to follow the NADCA recommendation of shot peening and stress tempering dies on a scheduled basis. However, the research results and the comments above strongly suggest that each die caster should evaluate the cost effectiveness of these techniques for their operation. Certainly, the cost of disassembling and reassembling a die may be prohibitive for some die casters. However, others may do this routinely for other purposes. Each die caster must evaluate the costs and benefits of using these techniques to reduce heat checking and extend the life of dies.

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VII. Summary and Recommendations

The previous sections of this guide have provided comprehensive information on the practice of stress tempering die casting dies to improve their life, as well as the utilization of shot peening to accomplish the same purpose. Technical reports on research activities in these areas have been referenced and in some cases quoted directly. Information has been gathered from both vendors and die casters on the usefulness of stress tempering and shot peening of die casting dies. Some users strongly recommend both processes while others have been unable to see the benefits. In some cases, research results have strongly supported the technologies, but the experience of production die casters has not validated the research results. In this section, the technical information is summarized and general recommendations are provided.

Summary

Research results and technical studies seem to agree that the cause of heat checking in die casting dies is thermal cycling on the surface of the die, which results in tensile stresses being established on the die surface. These tensile stresses can occur in as few as 10 shots on a die that was essentially without surface stress in the beginning. When these tensile stresses exceed the hot strength of the die material they initiate small cracks at stress risers on the surface of the die caused by surface imperfections or even material grain boundaries. Once the cracks appear the tensile stresses are relieved. As the die continues the thermal cycling, the tensile stresses appear once again and the cracks continue to grow over time.

One technical paper reviewed during the preparation of this guide provided the following conclusions[5]:

- The basic material properties affecting heat checking resistance favorably are high hardness, high hot yield strength, high temper resistance, good ductility and high thermal conductivity.

- EDM machine surfaces examined in this investigation have not significantly different heat checking properties than a conventionally grinded surface.
- Nitrided and especially CVD-coated surfaces have an excellent resistance against crack initiation. However, as soon as initiation occurs, crack propagation is very rapid.
- Heavily shot peened or milled surfaces both show a high resistance to heat checking. An increase of the surface hardness due to cold working may be one explanation to the results.
- Stress tempering at regular intervals lowers the tensile stresses and has a beneficial effect on the heat checking resistance.

The study summarized above also determined that the size and hardness of the steel shot used for shot peening and the intensity of the peening greatly affected the reduction in heat checking. In the study, the hardest steel shot with a medium level of intensity produced significantly better heat checking resistance that the other combinations tested. This result points to the importance of the technical expertise and experience required by the vendor that provides shot peening services to die casting dies.

Recommendations

The development of specific recommendations for a general audience of unknown circumstances and experience is difficult, if not an unreasonable expectation. In order to be useful to the industry, however, some general recommendations need to be provided. The following recommendations are given in an effort to provide direction for those interested in minimizing the effects of heat checking on their dies. They are supported by the technical evidence provided in this guide and are practiced by a number of die casting companies in the industry. They may not provide sufficient advantage for all die casters in all markets or in all situations, but should be evaluated thoroughly to determine their cost effectiveness.

1. Dies should be stress relieved (stress tempered) after any EDM work on the die.
2. Dies should be stress tempered both before and after any weld repair of a finished die.
3. Stress tempering should be performed on die casting dies after the initial die sampling and then on a scheduled basis, depending on the severity and importance of heat checking on each die. This stress tempering should be carried out at a temperature about 50°F below the highest tempering temperature which has previously been used during heat treatment of the die. The purpose of this tempering is to reduce the surface stress of the die to near zero.
4. Shot peening, when applied effectively, should be utilized following stress tempering to create a compressive stress on the die surface, which further reduces the tendency of the die to heat check and can delay the growth of existing surface cracks. In order to maximize the compressive stress, dies should be shot peened after each stress temper to renew the compressive stress on the die surface. Some die casters have been successful by shot peening only after every second stress temper.
5. The technical knowledge and experience of those providing stress tempering services and especially shot peening services is critical to the successful use of these techniques. Both processes are highly technical and diligence must be exercised to confirm the technical competence of potential suppliers.

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