Improving Tool Life for Aluminum Die Casting Dies

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The dies employed in aluminum die casting are a very important and significant cost factor in the process. The steel dies currently account for about 10% of the cost of producing die castings, if a normal die life of approximately 100,000 shots per die set is attained. When problems are encountered with the dies and premature die failure results, the cost can greatly exceed this 10% value. In addition, the lost production time when replacing and/or repairing dies can add considerably to these costs. Die casting shipments in North America are estimated at $8.7 billion; accordingly, the annual cost of dies is estimated to be at least $1 billion. Improvement in die life constitutes a worthwhile objective to enhance the competitive advantage of this industry.

Die Failure

A number of different mechanisms act to reduce the life of die casting dies. These include heat checking (also termed fire cracking or thermal fatigue failure); gross cleavage fracture across the die segments; erosion damage, or washing of the die surface by molten metal flow; and chemical attack or corrosion. Thermal fatigue cracking is the most frequent cause of die failure. It is caused by the fluctuation of the surface temperature of the die between the casting and lubricant application periods in the cycle. These fluctuations produce dimensional changes and mechanical stresses at the die surface.

Gross cracking, although it usually starts at the die surface, is not primarily a die surface problem but relates to the ability of the die material to resist the propagation of cracks in the presence of tensile stresses. The primary cause is the stresses produced by marked temperature differences within the body of the die.

Erosion of the die surface is produced primarily near the ingates into the die cavity where the die metal is worn away . . . or damaged, at times, by cavitation produced by the collapse of gas bubbles entrained in the entering metal streams. Solution of the die material in the molten casting alloy also can contribute to this wear or may produce soldering of the casting to the die. Corrosion and chemical attack result from the oxidation of the die surface by its environment. This produces oxides that fill and expand the thermal fatigue cracks and decarburize and weaken steel die surfaces. The die lubricant employed should not be corrosive to the die material; damage from the oxygen of the atmosphere is unavoidable.

Die Materials

Modern diemaking technology employs premium grade H-13 steel as the primary die building material. The wide usage of this steel is based on its generally satisfactory performance under the relatively widespread types of environments to which dies are subjected. Some use of other materials—such as maraging steels, tungsten, molybdenum and copper alloys—occurs, but H-13 steel is now the primary material for aluminum die casting dies. Extensive studies conducted at Case Western Reserve University (CWRU) under the direction of the NADCA Die Material Committee, has optimized the characteristics of H-13 steel that are preferred for dies.

This steel—known as premium grade H-13—is described in a detailed specification published by NADCA. Comparing it with commercial H-13 steel, it has closer chemical analysis requirements and a low maximum permissible sulfur content. This low sulfur has been determined to be essential for the combination of thermal fatigue resistance and resistance to gross cracking. Although the specification does not require that this premium grade H-13 steel be produced by VAR or ESR processes, the other requirements have made these processes a necessary part of the steel manufacture.

Another important feature of this specification is close control of the nonmetallic inclusions to minimize fracture paths through the steel. This clean steel requires not only the low sulfur, but also a low oxygen level in the steel. The specification also assures a sound steel by its ultrasonic requirement, and it tests the capability of the steel for obtaining good toughness levels. Other necessary requirements are a relatively fine grain size, the absence of a poor annealed microstructure, and particularly, the avoidance of massive carbides.

This steel is now available from several tool and die steel producers. The NADCA committee that prepared the specification had representatives of steel companies as well as die casters, assuring the availability of this steel. While premium grade H-13 steel costs somewhat more than the commercial grade, it is well worth the added cost in terms of improved die life.

The cost of a finished die involves finishing costs that are considerably higher than the price of the die steel. By using the premium grade, the percentage increase in die costs is small, and the improvement in die life more than compensates for this added cost. Dies are a relatively expensive part of die casting, but their life, except for prototype dies, is so important, that relatively minor costs in die materials or in shaping the die are secondary considerations.

Measuring Properties of Die Steels

While the ultimate test for a die is how it performs during die casting, the large number of variables—and fluctuation of those variables—make it different and frequently unfeasible to conduct a detailed study on die life using dies, die inserts, or cores produced from different materials and processed in different ways. For this reason, a laboratory type of test that can be conducted under controlled conditions is the best procedure for technical evaluation of die materials. This testing has been conducted using a specially developed thermal fatigue test for determining susceptibility to heat cracking, and a Charpy V-notch test to measure the relative resistance to gross cracking.

A thermal fatigue specimen has been used successfully for 25 years for this evaluation.[1] This test has evaluated a large number of potential metals as die materials for aluminum die castings. The results obtained have accurately predicted the relative behavior of the materials in service.

It is a 2 × 2 × 7-in. rectangular parallelepiped specimen with a 1.5-in. dia. hole in the center for internal water cooling. The test produces considerable constraint and high thermal fluctuations during immersion and removal from a 380 aluminum alloy bath. The temperature at the specimen corners fluctuates from nearly 1000° F to 200° F through this immersion and cooling cycle. The four corners have a constant 0.010-in. radius that intensifies the predominantly uniaxial stress at this location.

The outer surface of the specimen is sprayed with a commercial water-base lubricant just before it enters the molten aluminum bath. Water flows through the central hole at a constant rate, and the molten bath is maintained at 1350° F. The specimen is immersed for a constant period and removed from the bath for another constant period to produce the thermal cycle at the corners. The cracks obtained are measured periodically in a section 3 in. long on the corners equidistant from each end. The more severe the crack pattern, the lower the thermal fatigue resistance of the tested material.

The toughness (resistance to gross cracking) is evaluated by the Charpy V-notch test. This test—conducted at room temperature—has proved to provide an accurate evaluation of this property. In a Ph.D. thesis by Richard Bertolo conducted at CWRU, the results of the Charpy V-notch transition curve were compared with the results of both the compact tension fracture toughness test and the dynamic toughness test conducted with a pre-cracked Charpy test. It was determined that the room temperature Charpy V-notch test results provided a good relative evaluation of the toughness of die steels. Since this is a relatively inexpensive, easily conducted test, it is being used for this relative evaluation.

Optimization of Heat Treatment

While the selection of die steel is important in obtaining long die life, the processing of these steels prior to their use is even more important. The H-13 dies are typically placed into service at about 46 Rockwell C, yet the surface of the die after thermal fatigue failure is eventually softened to the low 30 Rockwell C range. The lower strength at this hardness increases the occurrence of thermal fatigue failure. The softening occurs because of tempering and carbide coalescence during this process. It occurs even though the surface of the die does not reach the tempering temperatures used in heat treatment. The simultaneous exposure of the die surface to elevated temperatures and the presence of surface stresses produce this softening effect.

Observation of the crack paths in failed dies indicates that the paths proceed from one carbide particle to another, or from one hard inclusion to another. Since these carbides are frequently located at the grain boundaries, the thermal fatigue cracks tend to follow grain boundaries. Examination of the failed dies reveals that the presence of large alloy carbides and inclusions lowers thermal fatigue resistance. This behavior leads to the conclusion that die steels should be processed to provide a microstructure as uniform, temper-resistant, hard, and strong as feasible. The hardness of a die is determined by the tempering operation. This value is adjusted to some degree depending on the size of the die and the severity of the application.

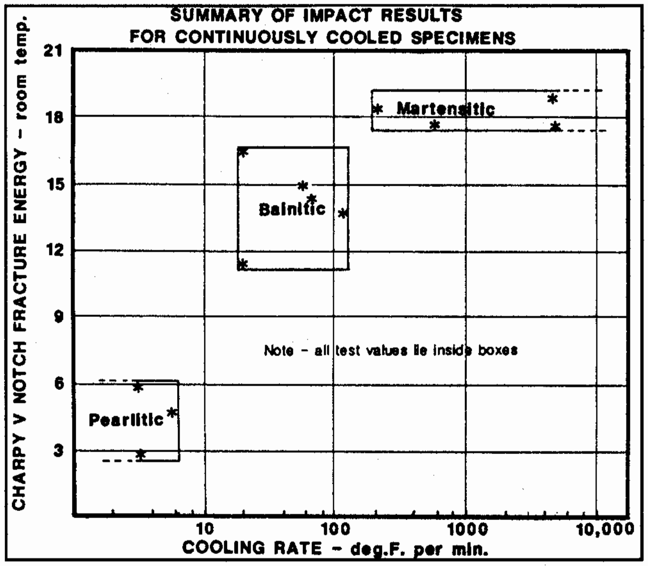


Fig. 1. Summary of impact results for continuously cooled specimens are shown in the graph.

The preferred austenitizing temperature for H-13 has been determined to be 1875-1900° F to provide as much alloy solution as feasible without grain growth. Any significant grain growth sharply reduces the toughness and makes the dies susceptible to gross cracking. Rapid cooling from the austenitizing temperature is important. It should be as rapid as can be tolerated by distortion considerations, but at least 50° F/min from 1750 to 550° F. This heat treatment is designed to quench to martensite and avoid the precipitation of damaging amounts of grain boundary carbides. The details of this structure and the toughness properties are described;[2] Fig. 1 has been taken from this reference.

The value of the fracture energy of the steel at room temperature indicates the relative resistance to crack propagation attained at different rates of cooling from the austenitizing temperature. These steels were all double tempered to 46-47 Rockwell C before testing. The toughness values obtained with cooling rates that produced a bainitic structure were only about 3 ft.lb. below the fracture energy at

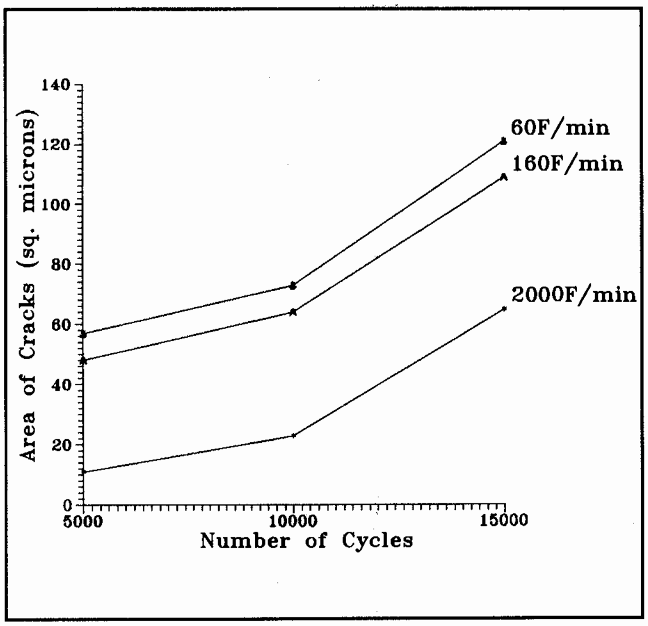


Fig. 2. Effect of cooling rate on thermal fatigue of H-13.

rapid rates of cooling to martensite. Since rapid rates of cooling increase the distortion of the die and can cause cracking, the use of cooling rates of 50° F/min are considered in many quarters to be a reasonable compromise, particularly for the larger dies.

The cooling rate from the austenitizing temperature is also important in determining the thermal fatigue resistance of premium grade H-13 steel. At slower cooling rates, the alloy carbides precipitate at the grain boundaries and provide a path of weakness for thermal fatigue cracking. The effect of cooling rate in ° F/min through the 1750 to 550° F temperature range on the thermal fatigue properties is shown in Fig. 2, as measured with the thermal fatigue specimen discussed previously.

The influence of these same cooling rates on the dynamic fracture toughness transition curve is not as marked, as illustrated in Fig. 3.

It was noted that the area cracked by thermal fatigue in this immersion specimen is some five times higher for 60° F/min cooling rate vs. 2000° F/min cooling rate, whereas the differences in toughness are less.

Another consideration in evaluating die steels for optimum dielife is the presence of alloy segregation or banding in the steel. While some microsegregation has to be expected during solidification of the steel prior to working, severe banding will reduce the thermal fatigue properties considerably . . . and the toughness to a lesser extent. The two elements that segregate to a greater degree are molybdenum and chromium. Both of these are present in H-13 steel. The control of the solidification process obtained in the VAR or ESR processing and homogenization during processing reduces banding and minimizes its effect.

The tempering temperature employed for optimum properties also is a significant consideration. Alloy steels such as H-13 produce significant amounts of retained austenite during quenching; this austenite transforms to untempered martensite in cooling from the first temper. At least a double temper is needed to avoid the brittleness that can result from the untempered martensite. Studies conducted on H13 at CWRU have shown that higher hardnesses after tempering increase thermal fatigue resistance, because a higher yield strength of the steel is obtained at operating temperatures.

However, toughness generally decreases with increasing hardness, and gross cracking can become a serious problem. The usual hardness of H-13 dies before service is 46-47 Rockwell C. Small dies can be placed into service at hardnesses up to 50 Rockwell C—and the largest dies at 43-45 Rockwell C levels—depending on the tendency of the die to be subject to gross cracking. Higher hardnesses also provide greater resistance to erosion. Cooling from tempering temperature can be in air, oil, or water. While temper embrittlement might be a problem, the effect of this cooling rate is very small with the molybdenum present and low phosphorous content of H-13.

The carbon content at the surface of the steel determines the achievable hardness level, and has a marked effect on the thermal fatigue life. Any changes in the local chemistry during heat treatment, either through carburization or decarburization, can affect the thermal fatigue behavior. Decarburization is detrimental and causes premature heat checks because the lower carbon layer has lower strength and lower resistance to thermal fatigue and erosion. The conditions that produce decarburization also can reduce die properties by corrosion. Carburization may also be detrimental; it exhibits lower checking resistance because the surface layer does not have enough toughness. However, slight carburization can increase strength and thermal fatigue life.

Although hardness is a significant factor in die life, as discussed, merely attaining the correct hardness range for an H-13 die does not assure good die life. The hardness level in the entire 42-50 Rockwell C range discussed can be accomplished by several routes without necessarily obtaining the structures required for good die life. This makes it necessary to specify processing of the die through heat treatment, not simply to require a given hardness level.

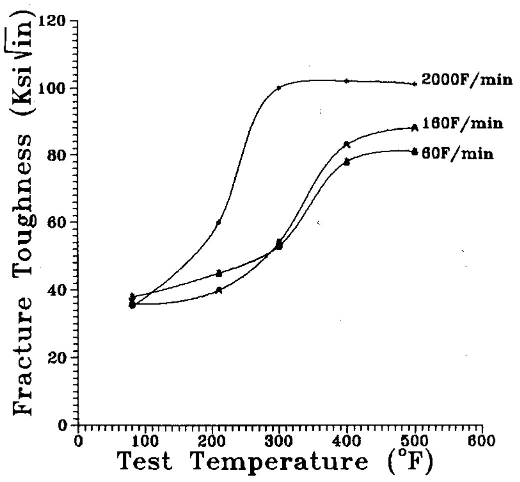


Fig. 3. Effect of cooling rate on the dynamic toughness of H-13 is shown in this graph.

Preheating Dies

Toughness of H-13 is significantly affected by its temperature, as illustrated in Fig. 3. These results demonstrate that a higher toughness is obtained at temperatures of 300° F and higher. The H-13 dies are considerably more susceptible to gross cracking when not preheated to 300° F temperature or higher. In addition, the thermal stresses that are produced in a die surface depend on the temperature difference, normally referred to as delta T, between the die surface and the sub-surface of a die. Proper preheating of a die reduces this delta T and is important in extending die life. While various means are available for accomplishing this preheat, casting a number of preliminary die castings to heat the die is not recommended.

Circulation of hot oil through the die cooling lines is one of the better ways of preheating, but infrared heaters—given sufficient time and capacity—also can provide the needed preheat.

Die Surface Treatments

Considerable work also has been conducted on die coatings to extend die life. This has been successful only when the coating is diffused into the die or core surface. Nitriding and carbonitriding (such as Melonizing) extend die life. A diffused chromium layer also extends die life, but this latter process is expensive, time-consuming, and requires temperature higher than 2000° F. Heat treatment has to follow this exposure. Types of coatings not diffused into the surface have not been effective. The use of shot peening of the die surface—known as the Metalife treatment—also extends die life, because it replaces the residual tensile stresses that develop on the die surface with compressive stresses. The die is shot-peened initially and then periodically (every 10,000 to 20,000 die cycles), thereafter.

Thermal stress relieving the used die at 50° F under the highest tempering temperature also is used. Studies using the thermal fatigue immersion specimen have demonstrated that Metalife and thermal stress relieving have reduced thermal fatigue cracking. The effective use of these shot peening or thermal stress relieving processes is to apply these procedures during the life of the die. The die is removed from service periodically, processed to reduce the tension residual stress at the surface, and returned to use.

The application of die lubricants is necessary to aid in stripping, to reduce soldering, and aid in building up an oxide-degenerate lubricant layer on the die surface. This is particularly necessary in the case of aluminum alloys of low iron composition. These low iron alloys may solder to the die unless the lubricant forms a barrier. The lubricant should not be corrosive to the die surface. The procedure has been to use water-based die lubricants diluted at 10-40 to 1 water-to-lubricant ratios.

The use of graphite or white graphite in the lubricant has been discouraged by environmental considerations, so present lubricants are primary hydrocarbons. The proper lubricant aids in achieving longer die life. It may also be preferable to use an insulating lubricant to reduce heat transfer to the dies. Application of the lubricant, particularly in large quantities, produces an abrupt drop in die surface temperature. If the quantity of lubricant applied is large, this can accentuate thermal fatigue cracking.

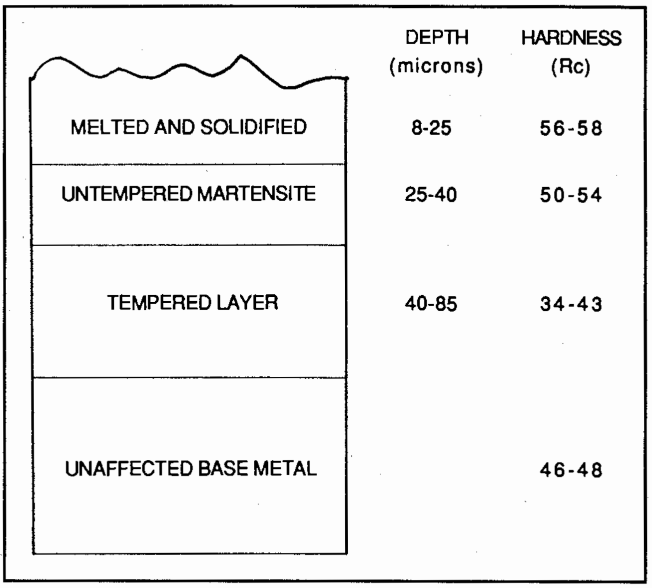
Effect of Electro Discharge Machining

At the present time, two procedures are employed widely for heat treatment of H-13 steel dies for aluminum die castings. The first procedure is to machine the block of die steel close to final dimensions in the annealed condition when the steel is relatively soft (about 26 Rockwell C hardness). Then, the die is heat treated by austenitizing in a vacuum furnace, cooled as rapidly as feasible by nitrogen gas blown into the vacuum furnace at pressures that are several times atmospheric, and then tempered at least twice to the hardness levels previously discussed. The distortion that occurs during this heat treatment is corrected by final machining.

Since these final machining operations are conducted on hardened steel, they are slow and expensive. It is desired to keep these operations to a minimum by predicting and controlling the distortion. The amount and causes of this distortion when heat treating and cooling these dies in a vacuum furnace are being studied in a NADCA/DOE-sponsored investigation currently underway at CWRU. The project is designed to determine the extent of this distortion in various-shaped dies at different rates of gas cooling, including 50° F/min from 1750 to 550° F. This will permit the machining of the die in the annealed state to as close as feasible to final dimensions, thereby reducing final machining operations.

The second method of processing H-13 dies involves the use of EDM. This method is to block out the general dimensions of the die by machining the annealed block of steel. Generous allowances are made to compensate for distortion after heat treatment, since final finishing by EDM can be accomplished by EDM as readily in the hardened as in the annealed state. The blocked-out die can be heat treated to its high hardness level in conventional atmospheric controlled furnaces. Sufficient additional finish has been allowed to remove the dimensional variances from distortion and any changes in surface conditions.

The rough machined die, before EDM finishing, can be cooled considerably faster from the austenitizing temperature than is possible by gas injected into a vacuum furnace. The use of oil quenching also can be employed. The additional finish on the die configuration allows for more distortion to be removed than is feasible with conventional machining procedures employed for dies heat treated in vacuum furnaces. The EDM process, however, does have some effects on metal structure that require consideration and adjustment. This process has been studied at CWRU[3], and in a recent Ph.D. thesis.[4]



	DEPTH (microns)	HARDNESS (Rc)
MELTED AND SOLIDIFIED	8-25	56-58
UNTEMPERED MARTENSITE	25-40	50-54
TEMPERED LAYER	40-85	34-43
UNAFFECTED BASE METAL		46-48

Fig. 4. Various layers in an EDM-machined surface of H-13 steel are described.

The EDM process produces different layers in from the surface, as illustrated in Fig. 4. The melted and solidified layer—also called the white layer—is extremely hard and cracked. It has to be removed by surface grinding or polishing, since it leads to rapid surface cracking and deterioration. However, it is usually only about 0.0004-in. deep and can be readily removed. A tempered martensite layer about 0.0012-in. thick underlies the white layer. This layer also is hard and brittle, so it has to be tempered by thermal treatments before die service. This leaves a significant deeper layer about 0.0025 in. thick that has been softened by the heat produced in the EDM process to 42 Rockwell C from the original 47 Rockwell C. This layer cannot be altered before die service.

In order to avoid reducing die life by thermal fatigue, mechanical removal of the white layer and tempering of the martensitic layer are necessary. Also, subsequent surface hardening treatments are desirable to overcome the effects of the remaining layers.[4]

Summary

This article has presented the present state of knowledge in obtaining good die life for aluminum die casting dies. Recommendations for selection of the die steel, heat treating procedure, die surface treatments, and vacuum treatment or EDM processing of the die are considered. This area is one of advancing technology, however, and it is hoped that further improvements in all aspects will be attained in the future, to further extend die life.

For the present, it is suggested that die casters compare their procedures with those described, and evaluate whether their methods utilize present technology.

References

1. J.C. Benedyk, D. J. Moracz, and J. F. Wallace, "Thermal Fatigue Behavior of Die Materials of Aluminum Die Casting," 1970 SDCE Transactions, paper 111
2. J. F. Wallace, W. Roberts, and E. Hakalinin, "Influence of Cooling Rate on Microstructure and Toughness of Premium Grade H-13 Die Steels," 1989 NADCA Transactions, paper G-T89-013
3. L.L. Centa and J.F. Wallace, "Effect of Electro-Discharge Machining on Surface and Subsurface Microstructure of H-13 Steel," 1989 NADCA Transactions, paper G-T89-032
4. H.J. Kim, Ph.D. thesis, CWRU, "Analysis of Mitigation of the Influence of EDM on the Thermal Fatigue Properties of H-13 Die Steels," 1991