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Experimental and Numerical Investigation of the Effect of Process Parameters on the Erosive Wear of Die Casting Dies

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This study investigates the causes and the mechanism of erosive wear in die casting dies, which are commonly made of H-13 die steel, by controlled experiments and computer simulations. Experiments were carried out under actual production conditions for a range of process and geometrical conditions with the accelerated erosive wear of core pins being used as a surrogate measure of die erosive wear. This paper reports the results of an investigation of the effect of metal velocity, inlet melt temperature, and the angle of metal impact on erosive wear in die casting dies. The study shows that in die casting, the erosive wear profile exhibits a strong correlation with the impact velocity profile, the erosive wear rate increases with a decrease in the inlet melt temperature, and the maximum erosive wear takes place at a metal impact angle of 72°. This indicates that the primary driver of erosion in die casting is the impact of partially solidified metal or solid particles at high velocities, with diffusion effects not being as critical.

Keywords
die casting, erosion, aluminum alloys

1. Introduction

DIE CASTING is a high volume production process, which produces geometrically complex parts of nonferrous metals with excellent surface finishes and low scrap rate. Production rates of 200 parts per hour and production batches of 300,000 parts are common.

These die castings are generally produced by using two steel die halves called the cover and ejector die halves. Each of the die halves usually contain a portion of the die cavity. The process sequences are : (a) Die closing. The die halves are closed and locked by the die casting machine. The required clamping force during the process may be hundreds of tons. (b) Cavity filling. The molten metal is injected into the die cavity under very high pressures and velocity for low cycle times. Typical filling times are measured in milliseconds with typical flow velocities of approximately 40 m/s (132 ft/s). (c) Casting solidification. The molten metal rapidly solidifies in the die cavity. (d) Parts ejection. After the casting has solidified, the die halves are opened, and the part is ejected. (e) Lubrication. The open die halves are sprayed with water-based lubricants and antisolder compounds.

Die wear and failure is a significant issue in die castings due to the high cost of dies. The reason for die wear is that the die casting process inherently requires multiple reuse of the die (typically more than 100,000 castings are produced per die campaign with production rates of 2,500 shots per 24-h day). Low cycle times in die casting therefore dictate that molten metal be introduced into the die cavity at high flow velocities and that the molten metal rapidly solidify (large thermal gradients) to the part shape. Flow velocities of 40 m/s (132 ft/s) and die temperature gradients as high as 1000 °C/cm (4500 °F/in.) are common. While these severe conditions are mandated to achieve these high production rates, they also limit the die materials that can be used and their respective production campaign. Wear phenomena are widely observed in H-13 die steel, the most commonly used die material due to this severe mechanical and thermal loading. The major wear mechanisms leading to premature die failure are:

- *Erosion or washout:* This is a result of the high velocities with which the molten metal impinges parts of the die cavity causing steel to be washed away with the melt. Most die casting dies have complicated geometrical features, such as cores, pins, ribs, and corners, which are especially prone to erosive wear. This erosive wear reduces the ability of the die to maintain dimensional tolerances and often requires rebuilding of regions of the die that have suffered extensive washout.
- *Heat checking (thermal cracking):* This is caused by the thermal fatigue due to the alternate heating and cooling of the die surface during die casting. The large thermal gradients created cause the die surface to be in compression during heating and tension during cooling of the die. This results in thermal cracking, which appears as cracks called heat checks on the die surface, degrades part surface finish, and ultimately leads to die failure.
- *Soldering and corrosion:* This is caused by the chemical interaction of the casting alloy and the die material during filling and solidification. This results in parts of the molten metal sticking to the die surface (soldering), which obviously produces defective castings or corrodes part of the die surface.

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After extensive technical market research, Malm and Tidlund (Ref 1) concluded that die erosion and heat checking were the two most important factors that limit the life of die steels in die castings. At the Ohio State University (OSU), an ongoing study is investigating the wear and failure mechanisms by controlled experiments and computer simulations (Ref 2-13). One of the objectives of this study is to investigate erosive wear on die surfaces where high molten metal flow velocities exist and to develop erosive wear models that quantify the effect of process parameters on erosive wear in die casting dies. This paper outlines the details and discusses preliminary results of this experimental-numerical investigation of the effect of process parameters on erosive wear in die casting.

1.1 *Prior Work in Wear Modeling of Die Casting*

A few publications have outlined the likely causes of erosion in die casting dies from empirical observations. Barton (Ref 14), for example, classified erosive wear in die casting dies as being of four significant types:

- *Gate erosion:* After a die has been in service for a long time, a gate is larger than it was initially. As expected, this change is most noticeable with castings that have long shallow gates. Barton attributed gate erosion to the repeated abrasion and regeneration of the amorphous oxide film, which is created on the die whenever it is in contact with the molten metal. This action takes place only at the gate because it is only here that the metal velocity is sufficient to allow fluid metal to flow in contact with the die surface.
- *Washout:* This most common type of erosion occurs when a metal stream or jet impinges directly on the cavity surface (e.g. a core or pin) at a short distance from the gate. Barton surmised that washout was primarily caused by the localized heating that occurs due to impinging jets. This causes severe localized thermal stresses, which result in a shearing of the oxide layer on the die thereby causing erosion. Washout is the most common type of die erosion and also the most significant in relation to die performance.
- *Cavitation erosion:* At high speeds common in die casting, cavitation bubbles are generated in the flow (Ref 15, 16). When they collapse at the die surface, large forces are generated and produce die erosion. Davis and Murray (Ref 17) reported that cavitation was a common cause of erosion in the die casting of zinc alloys because of the high gate velocities (40 to 60 m/s) required to produce high quality castings. It is, however, not as significant in aluminum casting because of lower velocities.
- *Erosion caused by flow separation:* Another cause of erosive wear, reported by Smith (Ref 18), was by flow separation at some point where due to a change in direction the molten metal separates from the die surface. This type of erosion does not, however, appear to be very common although different theories have been suggested to explain the mechanisms involved (Ref 14, 18).

While the published works on the types of die erosion are primarily based on empirical observations of the wear in production dies, a review of the literature shows no studies that have attempted to quantify the effect of process parameters on erosive wear in die casting. However a few different dip tests were developed over the years to evaluate the effect of steel grade, heat treatment, surface treatment (coatings), and melt composition on corrosive wear and/or heat checking. These wear tests typically involve dipping of pins in molten zinc (Ref 1) or molten aluminum alloy (Ref 11-13) in order to simulate the corrosive wear or heat checking (Ref 19) mechanisms seen in actual die casting dies during production. From these dip tests, some of the following conclusions were drawn:

- Melt alloying composition significantly affects the corrosive wear phenomena with pure metals likely to be more prone to corrosion than alloys (Ref 1, 11, 12, 19). One possible explanation for this is that the die casting metals have a limited solubility of iron, which may be diffused from the die (possibly H-13) steel. Diffusion of iron into a pure metal melt is therefore more likely than an alloy that has a certain composition of iron already dissolved in it.
- The corrosion attacks generally decrease with decreasing melt temperature (Ref 1, 11). This is not surprising as hardness is typically reduced and diffusion rates typically increase at higher temperatures. This finding, though intuitively obvious, is contrary to the results reported in this paper, and the reasons for this divergence are explained in a later section.
- Malm and Tidlund (Ref 1) reported that hardened and tempered samples generally show smaller loss than soft annealed samples This report certainly agrees with current industrial knowledge and practice. However in the corrosive wear studies conducted at OSU (Ref 11, 12), Yu and Shivpuri report that metal hardness is relatively insignificant in resisting the diffusive attack of molten aluminum. These tests, however, do not take the effect of high velocity metal impact, which is the main driver for erosive wear.
- If metallic contact between the tool steel and the melt can be avoided, such as with an oxide film, the risk of severe erosion attack decreases significantly (Ref 1). This observation is similar to that of Barton (Ref 14), who suggested that one of the mechanisms of gate erosion and washout was the abrasion and regeneration of the oxide film, which is created on the die surface. This certainly suggests that coatings would provide a mechanical barrier to reduce wear in die casting dies.

The corrosive dip tests are, however, merely simulative tests that consider the effect of reaction between the molten metal and the die material and do not measure the effects of physical parameters like metal velocity and angle of metal impact under real production conditions, which are more critical to the erosive wear in die casting dies. Since these physical parameters are the primary drivers of erosion and washout in die casting, any test that attempts to study erosive wear must consider the effects of these process parameters. These dip tests are, however, excellent screen tests to evaluate coatings and surface treatments under laboratory conditions.

To avoid the deficiencies of the dip tests described above, an erosive wear test procedure was developed to evaluate coatings and surface treatments under actual production conditions at OSU (Ref 2, 3, 5-7). The tests were carried out on a commercial

250 ton Buhler die casting machine (Buhler Inc., Minneapolis, MN) and an accelerated procedure was developed to obtain meaningful wear results in a reasonable amount of time. While empirical determination of potential coatings and surface treatments to reduce diffusive or corrosive attack is important, it is also necessary to understand the mechanisms and types of erosive wear, a subject that does not appear to be widely investigated in die casting. Therefore, the same test procedure was also used to evaluate the effect of physical process parameters on erosive wear under actual production conditions. This paper outlines the preliminary work conducted in this area.

1.2 *Effect of Process Parameters on Erosive Wear for Other Applications*

The key parameters that influence the erosion process as listed by Springer (Ref 20) include: liquid density, viscosity, shape and size distribution of spray droplets, impact velocity, impact angle, solid density, solid endurance limit, fracture toughness, hardness, grain size, and surface roughness. Although these parameters are likely to influence erosive wear, the relative influence of these parameters in causing die erosive wear in die casting has not been investigated. While only a few studies have attempted to determine the effect of process parameters on erosive wear in die castings, several empirical or theoretical studies have evaluated the effect of process parameters on erosive wear for other applications. A brief overview of some of these studies primarily used to develop erosive wear models in turbine and rain erosion applications is presented below.

In order to select materials capable of withstanding erosion damage, various investigators have used primarily empirical simulative techniques to study the response of materials to repeated impingement. These experiments can be classified as single impact studies, rotating arm tests, rocket sled tests, and ballistic tests by Brunton and Rochester (Ref 21).

While studying the deformation of solids due to single impact, Bowden and Brunton (Ref 22) fired a short jet or slug of liquid at the stationary solid specimen. The jet was produced by compressing a small volume of liquid in a chamber using a fast acting piston fired from a gas gun and then allowing the compressed liquid to escape through a nozzle.

Rotating arm tests yield data that are more readily applicable to practical situations. When the disk rotates, the specimens impact against steady jets or sprays directed across the path of the specimen in a direction parallel to the axis of rotation. Impact velocities of 800 m/s have been obtained by this approach according to Honneger (Ref 23) and Gardner (Ref 24).

Higher velocities may be obtained in a rocket sled test where the specimens travel on a sled propelled by a rocket through artificial rain or by ballistic tests where the specimens are fired from a gun (Ref 21).

A number of erosive wear models have been obtained from these simulative erosive wear experiments. Experiments of Honneger (Ref 23) indicate that erosion does not proceed at a constant rate. There is an initial period, the incubation period, during which there is no appreciable weight loss. This is followed by a period during which material is removed at a maximum rate as the pits formed by material link up and cover the impact area. After a time, the erosion rate begins to decrease, becoming a lower and approximately constant rate.

Other studies report that the erosion rate (E) during the second stage of the erosion-time curve may be expressed either as:

$$E \alpha (V-V_c)^{n_1}$$

where V is the velocity with which the liquid impacts the surface, V_c is the threshold velocity below which no mass loss occurs and n_1 is dependent on the process and material, or by the expression:

$$E \alpha V^{n_2}$$

where n_2 is also dependent on the process and material. Honneger (Ref 23) obtained a value of 2 for n_1 with a constant V_c =125 m/s (the impact velocity below which mass loss is zero).

Investigating the effect of impact angle, Fyall et al. (Ref 25) found that the erosion rate during the early stages of erosion was given by the expression:

$$E \alpha (V\cos\theta - V_c)^n$$

where θ is the angle between the normal to the surface and the direction of the impact velocity. They observed that the angle of impact had little effect on erosion in the later stages, and they surmised that this happened because the damage was then caused by outward flow under the drops striking the rims of pits in the surface.

In their test on a chrome steel, Baker et al. (Ref 26) proposed the equation:

$$E \alpha (V\cos\theta - V_c)^n \sec\theta$$

where secθ was introduced to account for the effect of tangential velocity components on erosion. Unlike smooth hard materials where the normal component of velocity determines the damage potential of the drop, the tangential component is believed to make a significant contribution to the erosion of low shear strength materials, such as soft polymers.

Brandenburger and de Haller (Ref 27) carried out systematic tests on the effect of drop size. The results appeared to show a strong increase in erosion with drop diameter. The threshold velocity, V_c, below which no damage occurs has also been found to depend inversely on the drop size (Ref 28).

The shape of the impact surface is also reported to be critical to die erosion. It was observed by de Haller (Ref 29) that the erosion rate increased when the impact surface was made concave. Vater (Ref 30) observed that plane surfaces were more rapidly eroded than convex ones and that natural defects in the surface were more affected than artificial ones. This is because the duration of the maximum impact pressure and the area over which it acts increases with the concavity of the solid surface (Ref 21).

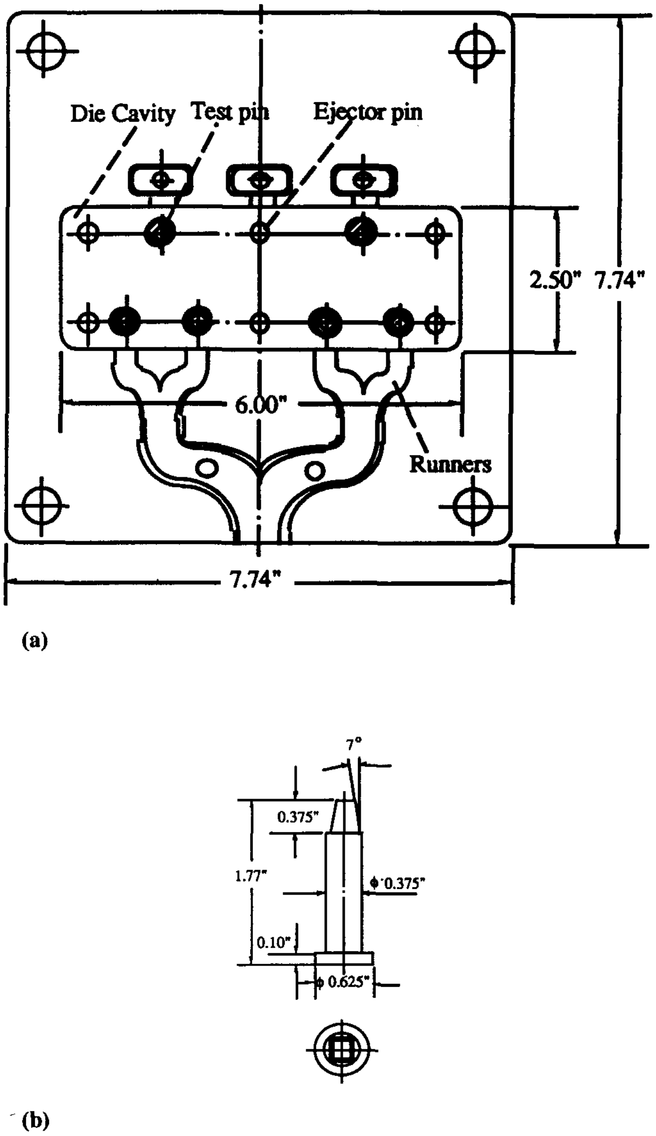

Fig. 1 Dimensioned drawing of the multiple pin die

Hancox and Brunton (Ref 31) examined the problem of the effect of surface roughness on erosion. It was found that erosion was reduced as the surface roughness decreased, but surface finish had no effect on erosion when the surface roughness was greater than 12 microns.

Many attempts have also been made to relate erosion resistance to a single mechanical property of the material. Heymann (Ref 34) found that erosion resistance varied, on the average, with about 8/3 the power of hardness. Thiruvengadam (Ref 32) suggested that strain energy to fracture in a tensile test may be a good measure of the erosion resistance of a material. Thiruvengadam and Waring (Ref 33) plotted cavitation damage against strain energy to fracture for a number of materials, found that the points were scattered in a straight line, and thereby concluded that “the damage decreased as the strain energy to fracture increased.”

Studying the effect of liquid properties on erosion, Hancox and Brunton (Ref 31) showed that carbon tetrachloride erodes metal at about twice the rate of water. They suggested that this was primarily due to the greater energy density in the outflowing liquid. They also reported that erosion decreased with temperature. This was attributed to an increase in the viscosity of the liquid. As viscosity increases, the velocity of the outward flowing liquid increases, and more shear damage is done to the surface of the solid.

Analytical theories on the cause of erosion due to the impact of liquid droplets on a solid surface have also been provided by among others, Springer (Ref 20), Thiruvengadam (Ref 32), Heymann (Ref 34, 35), and Springer and Baxi (Ref 36). A comprehensive review of the empirical and theoretical models is available in a review publication of Gahr (Ref 37).

The erosive wear models developed from these erosive wear tests thus give an indication of the relative importance of various process parameters on erosive wear. However these models are not directly applicable to die erosion in the die casting operation as they have been developed using simulative tests (such as single impact or rotating arm tests) and do not consider diffusion effects, corrosion effects, temperature effects, material interactions, and the partially solidified state of the eroding metal.

Therefore to adequately evaluate the erosive wear of a die casting die, a proper testing procedure needed to be developed that would consider material interactions (like the dip tests, which evaluate diffusive or corrosive wear), physical interactions (like the droplet impact studies described), and the combination of both effects that occur in die casting. Ideally a test should be designed for a production scale die in an actual die casting environment. However due to system complexity and variability, parametric evaluation of important factors affecting wear by experiments on production scale equipment would require a large number of expensive trials. Thus a simple, inexpensive laboratory test procedure was designed to closely reflect real production conditions while allowing sufficient flexibility for parametric evaluations as well as accurate and quick wear measurements. A 250 ton Buhler die casting machine was used in these experiments, and the experimental procedure is explained below.

2. Accelerated Erosive Wear Test Procedure

Industrial experience reported in the past has indicated that core pins or die inserts exposed to the liquid metal attack in front of the gates exhibit the highest level of erosive wear (washout) and soldering. Consequently, the wear of core pin surfaces was chosen to represent accelerated wear of the die surface exposed to high flow velocities.

In order to evaluate different materials or surface coatings, “a multiple-pin flat plate die” with six test pins was designed and fabricated for these experiments as shown in Fig. 1. Only the top edge of the pin shown in Fig. 1(b) is within the die cavity and is exposed to the molten metal. One of the reasons for choosing the multiple-pin design was the ease of assembly, disassembly, and measurement. In addition, a multiple-pin design allows the testing of several pins simultaneously thus providing multiple test sites for comparative evaluations. The flat cav-

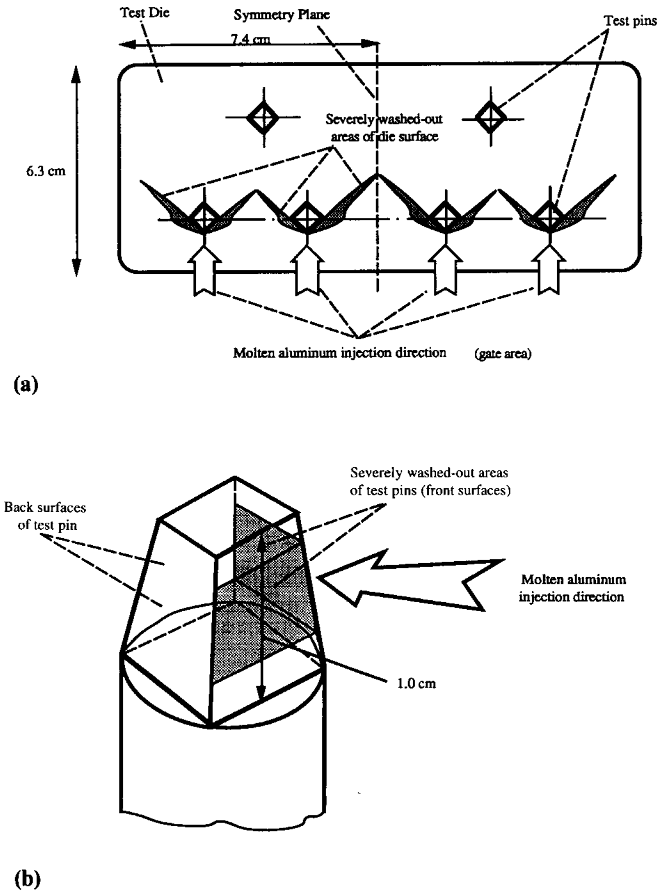

Fig. 2 Schematic of a cross section of the die geometry of the original pin layout indicating regions of the pin (Fig. 2b) most prone to washout. The symmetry plane is used for numerical simulations.

ity (plate) design also allows for the study of the effect of filling and solidification on die wear because of its geometrical simplicity. In addition, the test pins can be rotated or their shape changed, permitting the study of the effect of the angle of attack and surface geometry on wear. Each test batch contained one control pin to check the repeatability of each campaign.

Because wear is a gradual loss of material, tests could be very long term (>100,000 shots) and costly. In order to accelerate the wear effects and to allow for quantifiable erosive wear in a reasonable number of shots, an operating procedure was developed to provide an extreme environment on the test pin so that quantifiable wear loss can occur in a reasonable number of shots. One of the operating conditions chosen to accelerate the erosive wear rate is the use of a pyramidal test pin design with sharp corners (Fig. 1). These sharp pin corners will easily erode, solder, and exhibit heat checking along the edge within a reasonable time frame. An additional advantage of this design is that the wear of a straight edge is comparatively easy to measure. To further accelerate the erosive wear, a hypereutectic aluminum alloy, A390, with a high silicon content was used for the tests. Relatively speaking, the primary silicon particles in partially solidified melt are bigger and have irregular shapes and sharp corners. Furthermore, because the silicon is very hard, A390 is more aggressive than other aluminum die casting alloys, which results in a higher abrasive wear rate for the die surface.

After designing an accelerated wear test procedure, it was important to conduct pilot tests to verify this experimental design (Ref 2, 4, 5). These pilot tests indicate that the weight loss in the pins after 1000 shots is statistically significant in evaluating erosive wear, and four identical front row pins (made of H-13) have statistically identical wear rates, indicating that each pin location can be used as an independent test site.

Two major performance measurements selected for wear quantification were the pin weight loss and the edge profile change. The profiles of the pin edges facing the gate were measured by a comparator using 20× magnification and are used in this study to quantify the effects of process parameters.

Two basic orientations of the test pins in the die were tested. Initially (Ref 2, 8, 9, 10), the orientation of the test pins chosen was as shown in Fig. 1. In this design, the pin orientation is such that the molten metal from the gate first strikes the edge of the pin. This is clear in Fig. 2, which shows a schematic of this pin layout in the die cavity and the pin geometry, indicating regions of the pin most prone to washout. This pin arrangement is henceforth called the "original pin layout."

To evaluate the effect of die geometrical features (specifically the effect of angle of attack of the molten metal) on die erosive wear, Chu and Shivpuri (Ref 4) and Venkatesan and Shivpuri (Ref 10) used a modified design and layout of pins in the six pin erosive test die. Figure 3(a) shows a schematic of this pin layout while Fig. 3(b) shows the orientation of the tested pins to the injection direction of molten aluminum. Unlike the original pin layout, the side of the pin (instead of an edge) is directly in front of the molten metal from the gate. Such a layout is obtained by rotating the pins in the original pin layout by 45 degrees. The front edge, however, was cut at different angles to the vertical (angle α in Fig. 3b) in order to evaluate the effect of angle of attack of the incoming molten metal jet on the erosive wear. The front edge angles for which experiments have been performed at present are 83, 75, 70, and 65 degrees as shown in Fig. 3(a). Thus the angle at which the molten metal impinges on the pin is different for each pin thereby providing a means to evaluate the effect of angle of attack under similar experimental conditions. This pin layout and orientation henceforth will be referred to as the "angle of attack pin layout."

3. Correlation of Experimentally Obtained Wear Data with Process Parameters

Wear models can be developed from experimental data obtained from these erosive wear tests if the values of important process parameters at the erosive wear pins and different locations in the die cavity are known during the filling and solidification stages for different choices of process conditions. These values of flow and thermal parameters are very difficult to measure during a die casting operation. Therefore, a strategy was implemented in which the process parameters at different

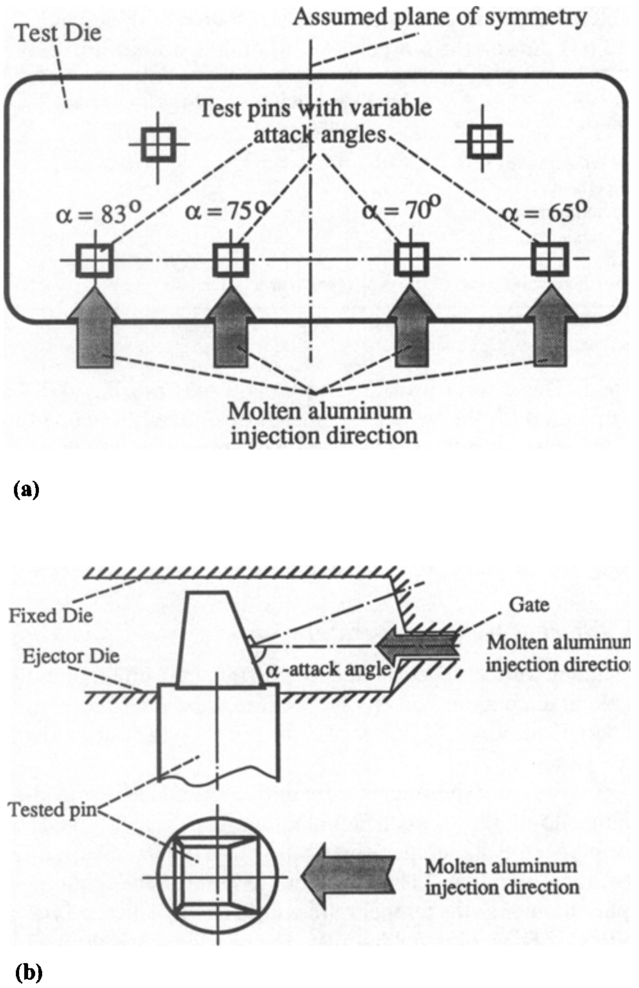

Fig. 3 Schematic of the orientation of test pins in the test die for the angle of attack layout. The location of pins with differing front edge angle α in the die is shown in Fig. 3(a).

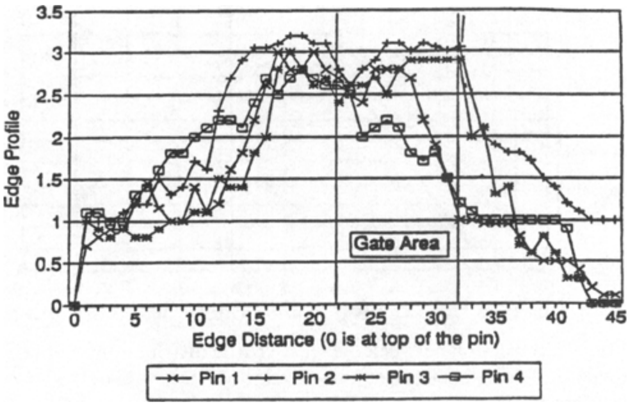

Fig. 4 Edge profiles of the front row pins of the original pin layout wear tests

locations in the cavity are determined by numerical simulations of the filling and solidification stages of the process.

Because erosive wear takes place primarily during the filling stage, the most important requirement of a die casting process simulation model for this study is the fluid flow modeling during mold filling. The modeling of the filling of a mold cavity in die casting is, however, very difficult. This is because fluid flow during this stage is highly transient, inertia dominated, and often turbulent with Reynolds numbers in excess of 10,000 due to flow of high velocity metal through rapidly changing geometry in the runner-gate system or in the casting cavity. Therefore, common simplifications used for modeling less taxing flow problems in sand casting and injection molding, such as the assumption of laminar and viscosity dominated flow, are no longer valid. Thus any model used for evaluation of the effect of process parameters must be capable of handling momentum dominated flow, jetting, and the complex free surfaces commonly seen in die casting.

The numerical model was therefore developed from FLOW-3D (FlowScience Inc., Los Alamos, NM) (Ref 38), a three-dimensional finite difference software with an excellent free surface modeler and the capability of handling the complex momentum driven flows common in die casting (Ref 8-10). Verification of filling patterns obtained from this numerical model were carried out by comparison of filling patterns with those obtained from water analogy studies in the literature (Ref 39).

3.1 *Effect of Metal Velocity*

In order to quantify the effects of process parameters on erosive wear, the edge profiles of the "original pin layout pins" were used as a quantitative measure of erosive wear. The profiles of the pin edges facing the gate were measured by a comparator using 20× magnification. The profiles were drawn before and after the experiment, and a square grid was placed along the pin edge traced before the experiment. Wear was then measured in terms of the length of grids. The wear profile for four front row pins (H-13) is shown in Fig. 4.

Using the FLOW-3D based numerical model, a numerical simulation of the filling of the original pin layout was obtained (Ref 10). Velocity profiles of different pins from these original pin layout simulations were obtained and correlated with the experimentally obtained edge wear profile. This was done by plotting the component of the velocity normal to the pin obtained from these simulations, as a function of the distance along the pin edge that is directly in front of the molten metal. The height of the pin is 10 mm (0.375 in.), and there are ten uniform cells in the thickness direction. The gate extends from 5 mm (0.2 in.) downwards to 7 mm (0.275 in.). Figure 5 shows a typical correlation. The wear ratio is plotted against the velocity ratio at the nodal points where the velocities are obtained. The ratios at different locations are evaluated by dividing the value at the location by the highest value along the pin edge. The value of the wear profiles along the pins is the average of four identical (H-13) front row pins (Fig. 4). As shown, a positive correlation exists between wear and velocity distribution along the pin edge thereby indicating that the metal velocity is a primary mechanism of erosive wear. This correlation between velocity and erosive wear along the length of the pin was obtained for a particular velocity. Experiments are currently being conducted to evaluate the erosive wear for a range of inlet gate velocities. Since the impact velocities on the surface of the pin

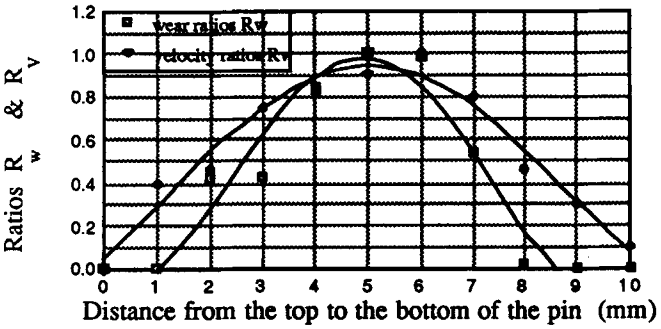

Fig. 5 Correlation between die wear profile distributions and velocity profile distributions along an edge of a wear pin of the original pin layout (Fig. 2). The wear and velocity ratios indicate the ratio of the wear and velocity at a location to the maximum

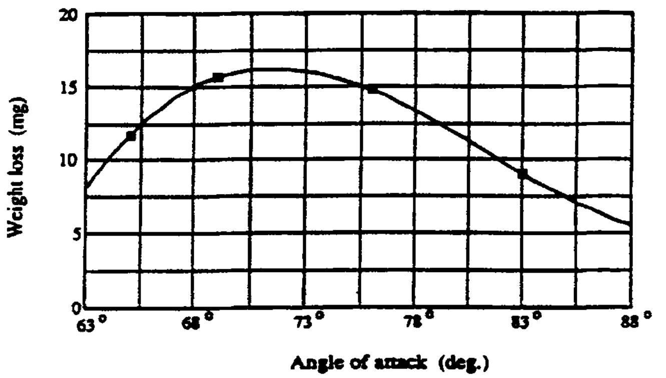

Fig. 6 Dependence of erosive wear rate of test pins on attack angles of molten aluminum alloy. The weight loss of the pins is measured after 1000 shots.

are likely to be very similar to the gate velocity because of jetting, the experiments will provide a further quantification of the effect of impact velocity on erosive wear in die casting. Preliminary results indicate that the wear profiles on pins for different velocities are similar to those reported in this paper.

3.2 *Effect of Angle of Metal Impact*

Preliminary results of the effect of the attack angle of molten metal on the erosive wear rate of die pins is shown in Fig. 6. The erosive wear rate defined by the weight loss of the pins after 1000 shots is plotted against the attack angle of the molten metal (angle α in Fig. 3). As shown, the maximum wear rate occurs at an impact angle of approximately 72°. Previous studies have indicated that for impact of pure liquid, the impact angle at which maximum wear occurs is 90° (Ref 21). For solid impact, the tangential component contributes to erosive wear, and the impact angle at which maximum wear takes place is 45° (Ref 40). These results indicate that the aluminum metal is not completely molten, but is partially solidified. This is typical of die casting operations where large heat losses in the ladle, sleeve, and runner-gate system result in partially solidified melt during filling.

Experimental determination of the wear profiles of the pin face for the angle of attack pin layout are also being determined. These wear profiles and weight loss profiles will be compared with the velocity distributions already obtained to study further the effect of the "angle of metal impact" and molten metal velocity at impact on die erosive wear. These experiments will be repeated for a range of velocities and temperatures to study further the effect of the "angle of metal attack" for different process conditions.

Table 1 Dependence of erosive wear rate of nitrided and H13 test pins on the temperature of molten aluminum alloy

Material	H-13 weight loss, mg/g	Nitriding weight loss, mg/g
Low temperature (50 °C superheat)	0.519	0.658
High temperature (150 °C superheat)	0.306	0.294

Note: The weight loss of the pins is measured after 1000 shots.

3.3 *Effect of Metal Temperature*

Studies were also conducted to determine the effect of molten metal temperature on erosive wear of wear pins under production conditions. Preliminary results of this study are shown here.

Erosive wear experiments were initially conducted with aluminum alloy A390 at two different temperatures: 150 °C and 50 °C superheat. Both temperatures fall within typical die casting operational windows. The temperature controller for the gas furnace maintains the temperature within 20 °C. The edge wear profiles of H-13 pins for both the temperatures are shown in Fig. 7. As shown, the wear profiles, although qualitatively similar, are quantitatively quite different. The wear seen at the lower temperature is much greater than that seen at a higher temperature. Figure 8 shows a similar pattern in the wear profiles of nitrided pin used in the same experiment. Although the erosive wear is reduced in the nitrided pins as compared with the H-13 pins, again the wear at the lower temperature is much greater than that at the higher temperature.

Table 1 shows the ratio of the total weight loss to the initial weight of pins for both the H-13 and nitrided pins at these temperatures. The erosive wear rate is much higher at the lower temperature for both sets of pins. Although it would appear that the percentage weight loss is small, remember that only a small part of the pin is exposed to the erosive wear action of molten metal.

This is contrary to the results reported by Malm and Tidlund (Ref 1) and Yu and Shivpuri (Ref 12) as described earlier. These authors observed an increase in the wear with an increase in the temperature. These dip tests, however, consider merely the effect of metal diffusion or corrosion and do not take into account the effect of physical impact and high velocities. As the temperature decreases, the solid fraction and consequently the amount of solid particles in the melt increases. The impact of more solid particles on the pins at the same velocity thus causes greater wear at the lower temperature. Although the die is likely to be cooler at a lower temperature thereby reducing metal diffusion, the increased wear due to the impact of more solid particles appears to be more significant to the overall wear. These

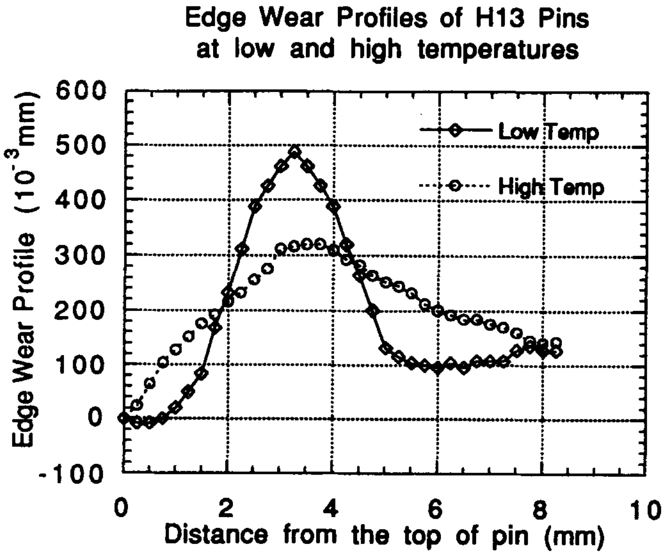

Fig. 7 Dependence of edge wear profiles of H-13 test pins on the temperature of molten aluminum alloy. The edge wear profiles of the pins are measured after 1000 shots.

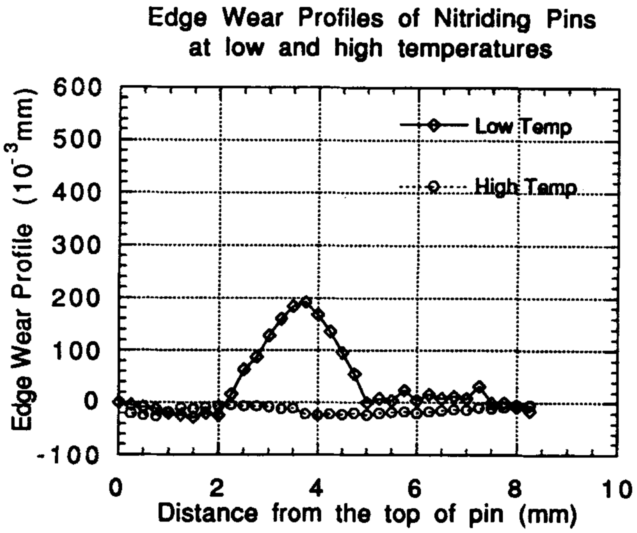

Fig. 8 Dependence of edge wear profiles of nitrided test pins on the temperature of molten aluminum alloy. The edge profiles of the pins are measured after 1000 shots.

results thus show that the most significant driver of die erosion is the impact of high velocity solid particles on the die.

Experiments are currently being conducted for more temperatures to quantify further the effect of temperature on erosive wear.

As shown, the metal temperature, metal velocity, and angle of metal impact have a significant impact on die erosive wear. The results reported here are preliminary. A series of experiments is currently being conducted based on a "design of experiments" approach to complete this study of the effect of process parameters on erosive wear in die casting. The metal velocity, metal temperature, angle of metal impact, die material hardness, and pin shapes will all be varied in each set of experiments to obtain comprehensive wear models for a range of conditions. The ultimate aim of such a wear model is to predict the erosive wear in an actual die casting die, given the process conditions, using numerical simulations to obtain the values of parameters, such as velocity, temperature, etc. at various locations of the die.

4. Conclusions and Future Work

An accelerated erosive wear test procedure was developed to evaluate erosive wear in die casting dies under production conditions. The procedure involved the use of pyramidal test pins as a surrogate measure of die wear and avoided the drawbacks of prior studies of erosive and corrosive wear in die casting. Even though the erosive wear is accelerated, the one significant drawback of this experimental approach is the large time frame required to obtain meaningful results.

This test procedure was used to evaluate the effect of process parameters, such as metal velocity, angle of metal impact, and metal temperature, on die erosive wear. Numerical simulations of the filling and solidification stages were carried out to obtain the values of process parameters at various locations in the die. These process parameters at pin locations were then compared with experimentally obtained wear profiles and pin weight loss to evaluate the effect of process parameters.

These comparisons show that the computed velocity profile at the edge of experimental die pins used for the wear study matches closely with the measured wear profile indicating metal velocity to be a primary mechanism for core pin and, consequently, die washout.

Studies on the effect of the angle of metal impact indicate that maximum wear is obtained at an impact angle of approximately 72°. This indicates that the metal is partially solidified, and erosive wear models developed for pure liquid impact or solid impact cannot be used in die casting. Comparison of velocity profiles with wear profiles for a second orientation of pins to test the effect of the angle of attack of molten metal and die geometrical features is currently being investigated.

Studies on the effect of metal temperature show that the erosive wear increases with decreasing temperature. This is possibly because the impact of larger numbers of larger sized solid particles at lower temperatures causes an increase in the erosive wear of the pin. This indicates that the primary driver of erosion in die casting is the impact of partially solidified metal or solid particles at high velocities, with diffusion effects not being as critical.

A series of experiments re currently being conducted based on a "design of experiments" approach to complete this study of the effect of process parameters on erosive wear in die casting. The metal velocity, metal temperature, angle of metal impact, die material hardness, and pin shapes will all be varied in each set of experiments to obtain comprehensive wear models for a range of conditions.

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