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A Study of Erosion in Die Casting Dies by a Multiple Pin Accelerated Erosion Test

R. Shivpuri, M. Yu, K. Venkatesan, and Y.-L. Chu

An accelerated erosion test was developed to evaluate the erosion resistance of die materials and coatings for die casting application. An acceleration in wear was achieved by selecting pyramid-shaped core pins, hypereutectic aluminum silicon casting alloy, high melt temperatures and high gate velocities. Multiple pin design was selected to enable multiple test sites for comparative evaluation. Apilot run was conducted on a 300 ton commercial die casting machine at various sites (pins) to verify the thermal and flow similarities. Subsequently, campaigns were run on two different 300 ton commercial die casting machines to evaluate H13 die material and different coatings for erosive resistance. Coatings and surface treatments evaluated included surface micropeening, titanium nitride, boron carbide, vanadium carbide, and metallic coatings—tungsten, molybdenum, and platinum. Recent campaigns with different melt temperatures have indicated a possible link between soldering phenomena and erosive wear. This paper presents the details of the test set up and the results of the pilot and evaluation tests.

Keywords
die casting, erosive wear, washout, coatings, surface treatments

1. Introduction

THE DIE CASTING process uses high pressure to inject high-temperature molten metal into a die cavity representing a part geometry. Figure 1 shows a typical horizontal cold chamber die casting operation including the ladle, the die platens (moving and stationary), the die cavity, the shot sleeve, the plunger etc. The die casting process can be divided into the following stages: die closure; molten metal pouring into the shot sleeve; metal injection and cavity filling; solidification and die holding; part ejection; and spray cooling and lubrication.

During the injection process, the molten metal is thrust into the die by a plunger rod through a shot sleeve with an extremely high gate velocity. Typical gate velocities are in the 30 to 60 m/s range, and the molten metal is between 600 to 715 °C. It is easy to see that in a cavity with intricate geometrical features (cores, pins, sharp corners etc.), erosion will occur rapidly. This erosive wear of die cavity surfaces during the filling stage may be due to the following phenomena: solid particle impingement, liquid impingement, and cavitation erosion (Ref 2). Severe erosion often changes the dimensions of the die cavity, and if it is near a critical feature, it may lead to the rejection of the part. The operation has to stop, and the die must be repaired before continuation.

During filling, solidification and the die holding stages, the molten aluminum attacks the die steel surface. Corrosion and diffusion reactions occur especially near the washed out or eroded area due to the lack of protecting oxidation films. These reactions result in soldering of the cast metal to the die surface. A soldered area hinders the ejection of the casting from the die and causes drag marks, which can result in the casting being scrapped because of its appearance. Even worse, the core pin may be bent or broken. The expensive die casting machine has to stop in order to clean the die surface. The soldered material is usually brittle and hard. When the new die casting cycle starts, some of the brittle soldering layer is eroded away from the high velocity molten metal stream. This sequence of alternating erosive and corrosive action continues until the die needs to be polished or fixed.

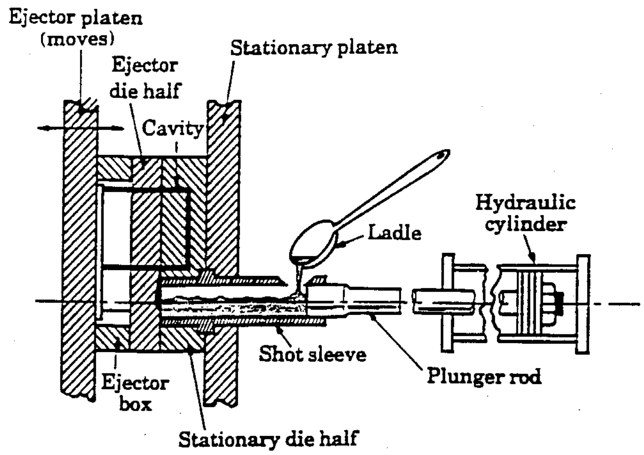

Fig. 1 Schematic of a cold chamber die operation (Ref 1)

The primary objectives of this investigation were to:

- Develop a near production accelerated test for investigating die erosion. This test includes a test die, an experimental design procedure, and production conditions of industrial scale.
- Use this test procedure to evaluate different coatings and surface treatments for possible wear resistant applications in die casting.
- Understand the phenomena of washout (erosive and corrosive attack) of steel die surface due to molten aluminum attack and the effect of different production conditions on the washout rate.

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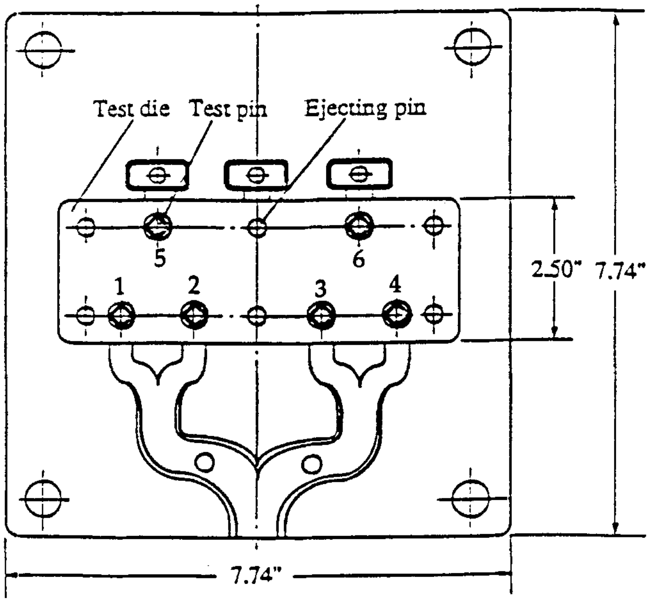
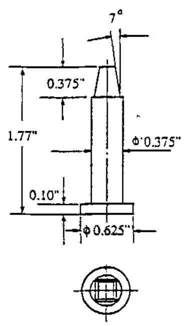


(a)



(b)

Fig. 2 Test die (a) and test pin (b) designs. Dimension in inches

2. Erosive Wear Mechanism in Die Casting

Erosion is a progressive loss of material from a solid surface due to the mechanical interaction between that surface and an impinging fluid stream. The result of erosion is washout of the die surface. The washing action cleans off applied lubricant and scratches and breaks up the protective oxide film. This allows for an intimate contact of the molten metal and the die substrate. Once the protective oxide layer is broken, corrosive attack, such as diffusion, solution, and intermetallic compound formation can occur. Understanding the erosive mechanism, predicting the erosive behavior of different aluminum casting alloys, die materials, and their heat treatment, and accounting for the effects of elevated temperatures and chemically active environments are areas where knowledge of materials response is most needed.

Tukkaram (Ref 2) identified the following variables that affect erosive wear in die casting dies: injection pressure, die temperature, metal temperature, and die design. According to him, mechanical erosion, commonly known as washout, is primarily due to the impingement of solidified metal in the casting metal on the die surfaces under high velocity.

Worby (Ref 3) explained that the degree of erosion is mostly a function of the gating and casting techniques as well as the die material. Malm and Tidlund (Ref 4) listed the following factors that will affect the die erosion: temperature of the casting metal, composition of the casting metal, design of the die, and surface treatment of the die.

Barton (Ref 5) categorized erosion into three types: gate erosion, washout, and cavitation jet erosion. The gate erosion occurs because of the repeated abrasion and regeneration of the oxide film. This takes place in the gate area with high gate velocity. The wash out effect is due to the molten metal stream impinging directly on the cavity surface at a short distance from the gate and is highly localized along the line of the gate. Cavitation jet erosion is due to gas bubbles being carried along in a stream of molten metal. When these bubbles collapse (implode), they produce a local jet with high velocity and pressure, which damages the die surface.

Brunton (Ref 6) also mentioned the cavitation effect of the bubble. From his experiment with air bubbles in water, he found that the damage caused by a bubble collapsing near a surface is similar to that produced by a high velocity impact of jets and droplets. Velocity is a key factor in cavitation erosion.

Based on the reported die casting literature, the possible erosive mechanisms involved in die casting process can be classified as: solid particle impingement, slurry (liquid and solid) erosion, and cavitation erosion.

3. Design of the Test Die

A testing procedure must be developed that accentuates the surface loss due to erosive phenomena to evaluate die erosive wear adequately. Ideally a test should be designed on an actual test die in an actual die casting environment. However, the risk of damaging a costly and complex die, and the cost of interrupting production makes this approach unfeasible. Consequently, one objective was to design a simple laboratory scale test which is near the actual production situation and can get the result in a reasonable period of time.

Industrial experience with die wear indicates 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 surface was chosen to represent the accelerated wear of the die surface exposed to high flow velocities.

For the evaluation of different materials or surface coatings, "a multiple pin flat plate die" with six test pins was designed and fabricated for these experiments (Fig. 2). 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 cavity (plate) design 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 angle of attack and surface geometry on wear loss. Each test batch contained one control pin to check repeatability of each campaign.

The gate area design is based on the Aluminum Die Casting Institute (ADCI) "flow predictor" (Ref 7). This gate design package is based on knowing the pumping rate capability of the die casting machine shot end, then using this information to predict the behavior when a die is put on the machine. The runner design is based on the ADCI "runner design" package (Ref 8). Thermocouples were installed at the center of the die and at 12.7 mm below the die surface in order to sense the temperature at that location and to ensure that the die temperature reaches a steady state before measurements are taken.

4. Test Acceleration

Wear is a gradual loss of material. Wear test can be very long term (>100,000 shots) and expensive. In order to accelerate the wear rate, 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. The operational conditions chosen to accelerate the erosive wear rate are listed below.

4.1 *Pyramidal Design of the Pin*

Die pins are conventionally cylindrical with round cross section. However in the accelerated test design, the areas of the test pins inside the cavity were given a pyramidal shape with the edges of the pyramid facing the molten aluminum jet. The reasons for this are: (a) a sharp edge would erode much faster than a round edge, and (b) it is much easier to measure a sharp edge than a round surface.

4.2 *Aluminum Alloy A390 with a High Silicon Content*

The A390 alloy is a hypereutectic aluminum silicon casting alloy. The advantages of A390 are high fluidity, high thermal conductivity, and superior wear resistance of the casting. Its chemical composition consists of 16 to 17% Si, 4 to 5% Cu, 0.6 to 1.1% Fe, and other elements. (Compositions are in wt%.)The melting point of A390 is approximately 660 °C. Relatively speaking, the primary silicon particles in partially solidified A390 melt are bigger and have irregular shapes and sharp corners. Furthermore the primary silicon particles are very hard, and A390 is more aggressive than other aluminum die casting alloys and will provide higher erosive wear to the die surface.

4.3 *High Gate Velocity*

The average value of gate velocity in an industrial die casting operation is approximately 40 m/s. In early tests on a single pin test die, the gate velocity of over than 65 m/s was used. However, with that high a gate velocity, the gate area seized prematurely because of enhanced soldering problem. Due to gate seize up, the machine had to be shut down and the soldering had to be cleaned. This interrupted the test operation frequently. To avoid this problem in the current test, the gate velocity was lowered to approximately 48 to 55 m/s.

4.4 *High Melt Temperature*

Since erosion and corrosion (two components of surface washout) are temperature dependent phenomena, the melt temperature was raised to accelerate wear. However at significantly high superheats, severe soldering was encountered in the runner and gate regions which did not permit efficient operation of the machine. Therefore, slightly lower superheat, about 50 to 75 °C, was selected for tests.

5. Pilot Test: Test Procedures

5.1 *Experimental Design Methodology*

Before using the multiple pin test die and test pins to evaluate the coatings for erosive wear, the validity of the die design and the test procedure for the erosive test were verified. The experimental design program selected for this goal was called the "pilot test."

One of the major objectives of this research is to compare the erosive wear resistance of different coatings through multiple test sites. Therefore, the multiple pin test die was checked to determine if it fits this requirement. In other words, we have to make sure the die provides equal wear behavior at the six test pin locations (flow and thermal balance) for comparative evaluation.

5.2 *Assumption of Site Location*

Based on the geometric locations of the pins and the gates shown in Fig. 2, pins 1, 2, 3 and 4 are the front-row pins that face the ingate runners directly, and pins 5 and 6 are the rear-row pins. Two assumptions can be made for the multiple pin die design as follows.

First, the "symmetrical location assumption" says that pin positions 1 and 4, 2 and 3, and 5 and 6 experience the same experimental conditions respectively.

Second, the "identical location assumption" says that pin locations 1, 2, 3 and 4 have the same experimental conditions while pin locations 5 and 6 experience identical effects. Note that if the "identical location assumption" holds, then the "symmetrical effect assumption" will also hold.

5.2.1 *Minimum Shots for Quantifiable Wear*

A good experimental design is expected to yield reasonable results in a minimum number of tests. During the die casting machine operation, it is very hard to obtain exact operational conditions. Furthermore, in the measurement of the weight loss of the test pins, instrumentation tolerance and human errors have to be considered. The minimum shots reflect the condition in which significant weight loss can be achieved as that the errors due to operational, measurement, and human factors are only a small fraction.

5.3 *Response and Independent Variables*

A response variable represents the expected outcome of the experimental system being investigated. The surrogate measure for the die wear in this research was chosen to be the weight loss of the test pin because it is easily quantifiable. The other re-

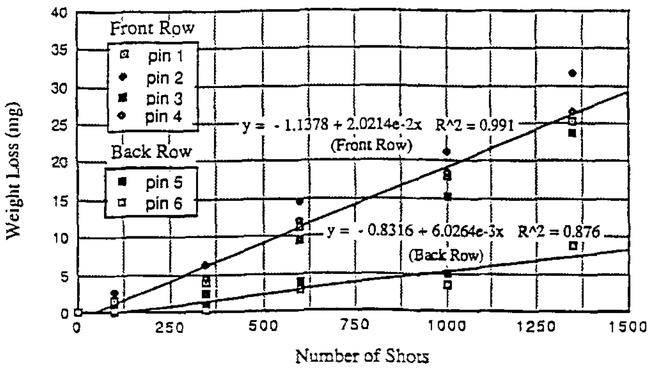


Fig. 3 Weight loss of pins at different stages of the pilot test

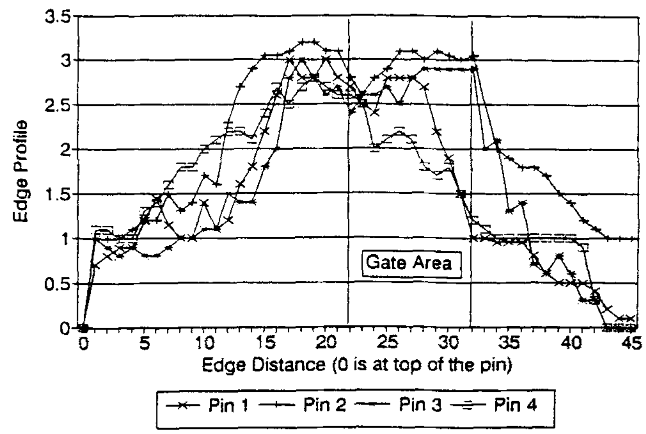


Fig. 4 Edge profiles of the four front-row pins in pilot test after 1350 shots

sponse variable chosen in this test was the shape change in the sharp edge of the test pin facing the ingate (i.e. the surface degradation).

The independent variables are those used to check the response of the experimental system. Since we are mainly checking the erosive wear resistance of different coatings, the major independent variables are the types of coating: the composition and the application technique.

5.3.1 *Operational Conditions*

The pilot run was conducted on a 300 ton Harvill die casting machine (Harvill Machining Inc., Perris, CA). Some subsequent tests were conducted on a 300 ton Buhler machine (Buhler AG, Uzwil, Switzerland). The ranges of process parameters selected were: (a) 700 to 732 °C furnace temperature; (b) 50 m/s gate velocity; (c) 6.895×10^6 psi accumulator pressure; and (d) 3 s spray time.

The plunger speed was monitored by the external monitoring system (shot scope). There were two thermocouples installed in the die to check the steady state behavior of the system. One of the thermocouples was mounted 3.175 mm beneath the center of the cavity and the other, 3.175 mm beneath the biscuit area.

5.3.2 *PerformancMeasurements*

The test pin was measured by: (a) precision balance, 0.0001 g weight accuracy; and (b) optical comparator, 20 to 50 × magnification.

Initially, the pins were measured for weight, hardness, surface roughness, and edge profiles. The measurement error for a typical pin with a mean weight of 29 g was approximately 0.00036 g. The test pin had been heat treated based on ADCI specifications, and the average hardness of the pin surface was measured at 46 HRC. The test pin edge profile was measured by an optical comparator. The surface warping was detected by a surface analysis system.

6. Results and Discussions of the Pilot Test

The weight loss of the pins was the primary measurement for erosion in this study. After a predetermined number of shots

Table 1 Different coatings and surface treatments for erosive wear evaluation

Coatings and treatments	Sources	Application technique
PS200/PS212	NASA	Thermal spray
PS200/PS212	NASA	PVD
PS200/PS212	NASA	Extrude
TAZ 8A	NASA	PVD
TAZ 8A	NASA	Extrude
TiN	CSU	PVD
B_4C	CSU	PVD
VC	Arvin, TD	Salt bath
Fe_3Si	OSU	Pack cementation
Cr	OSU	Pack cementation
Metalife	BM	Shot peening (micro)
Heat treatment	...	Commercial heat treatment
W	UWM	Ion implantation
Mo	UWM	Ion implantation
Pt	UWM	Ion implantation

NASA: NASA Lewis Research Center, Cleveland, OH
OSU: The Ohio State University, Columbus, OH
CSU: The Colorado State University, Boulder, CO
UWM: University of Wisconsin, Madison, WI
PVD: Physical Vapor Deposition
BM: Badger Metals, Menomonee Falls, WI

(measurement interval), the die was dissembled and the pins extracted. After being cleaned with KOH solution, the pins were weighed individually. The dies were then reassembled, and production continued until the next measurement interval was reached. The change in weight of the different pins (weight loss) for the different stages of the pilot test is shown in Fig. 3.

After 600 shots, the measured weight loss for pins 1, 2, 3, and 4 was adequately large to conclude that the H13 pin had eroded. Furthermore, as expected, the weight losses of the front-row pins (1 to 4) were much larger than those of the rear-row pins (5 and 6). Pin 2 had the highest weight loss, and this location was used as the control pin location in subsequent trials.

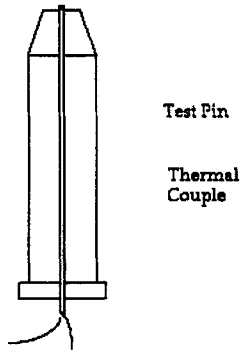


Fig. 5 Diagram of the thermocouple installation in the pin

Table 2 Different test batches for coating evaluations

Batch No.	Coating and surface treatment selection	No. shots	Machine
1	TiN, H13, Metalife, *PS200 (PVD)*	348	Harvill
2	*PS200 (SP)*, H13, VC, B_4C	355	Harvill
3	TiN, H13, Metalife, *PS200 (PVD)*	950	Buhler
4	*PS200* (SP), H13, VC, B_4C	950	Buhler
5	TiN, VC, CrSi, FeSi, H13, *TAZ*	1000	Buhler
6	*PS200 (ext)*, *PS212 (ext)*, H13, nitriding, *TAZ (ext)*	1000	Buhler
7	W, Mo, Pt, H13, *TAZ (ext)*	1000	Buhler

Note: All the coatings given in italics were provided by NASA. Ext is extruded pins.

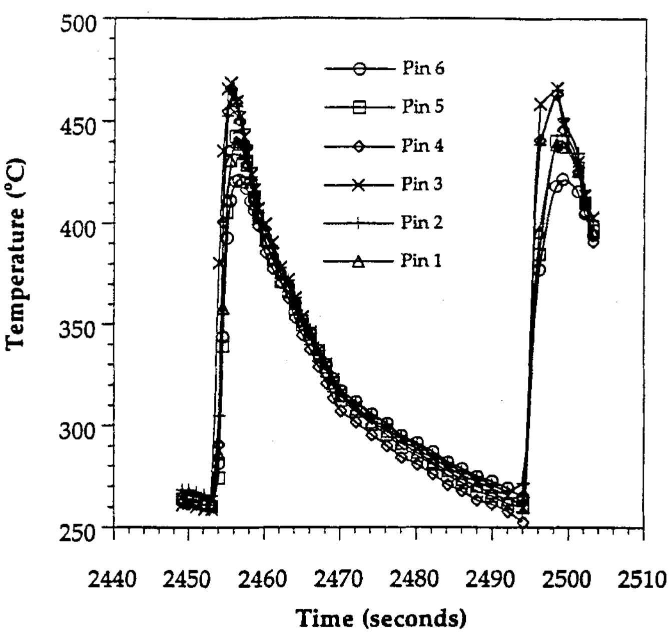


Fig. 6 Temperature profiles of six pin surfaces

From simple calculations, two regression lines can be fitted to the test data to estimate the weight loss rate for the front-row and the back-row pins. The results show that the wear loss rate (slope of curves) of the front-row pins is about 3.4 times larger than that of the rear-row pins. The profiles of the pin edges facing the flow of the molten metal are plotted in Fig. 4. In Fig. 4, the abscissa is the distance from the top edge of the pin (gate area is between 20 and 35 units) and ordinate being the location of the worn out edge (zero ordinate is the original edge). Due to the insignificant changes of rear-row pins 5 and 6, only the edge profiles for the front-row pins (1 to 4) are plotted. The convex profiles represent metal washout amount. The profiles are almost identical for the four pins indicating similar metal flow (magnitude and direction of the velocity vector) at these locations. This validates the flow balance in the pin locations. The largest washout area is at the middle of the pin, which is located in front of the gate that directly faces the jet of the molten metal. Note that as expected, pin 2 has the largest convex area among the front-row pins, which further reinforces our previous finding regarding the pin weight loss.

The temperature at each cavity location was measured by thermocouples inserted in the pins as shown in Fig. 5. Figure 6 shows the results of the measurement after 50 shots of operation when the equilibrium state was reached. The temperature readings at the front four locations are almost identical. These results validate the thermal balance of the locational assumption.

The temperatures at four front-row locations were slightly higher than the two rear-row locations because the filling and solidification processes start at the rear of the cavity, with the gates freezing last.

The following conclusions are based on the results of the pilot runs.

(a) The front-row pins show an approximately equal weight loss rate and similar edge wear profiles. The weight loss in pin location 2 is slightly larger than the rest of the front-row pins. This variance may come from a few sources, such as the variabilities in weight loss measurement or the machining of the die (pin may be slightly closer to the gate). However, the temperatures and flow at these locations during a steady state operational cycle (shot) can be assumed to be the same.

(b) The rear-row pins do not experience as large a weight loss and surface wear as the front-row pins because the impinging jet expands as it travels in the die cavity. This reduces the velocity impingement on the surface of the rear-row pins compared to that of the front-row pins. In addition, the front-row pins maintain a slightly higher temperature.

(c) The minimum number of shots needed for the coated pin experiments for measurable wear is expected to be larger than 300. A statistical analysis indicated that after 300 shots the weight changes can be assumed to be significant for the H13 pins.

7. Evaluation Tests: Coatings and Surface Treatments

Based on the pilot test results, the following strategy was adopted for the evaluation of surface modification techniques. The front-row pin locations were primarily used to evaluate the coated pins; the rear row pins were measured only for reference purposes. One possible way of arranging the coated pins was to

Table 3 Results of melt temperature on soldering and erosion of H13 pins

Shots	650 °C First 1000	650 °C Second 1000	700 °C First 1000	700 °C Second 1000
Initial pin weight, g	24.46865	24.46063	24.50659	24.49908
Soldering pickup, g	1.00×10^{-4}	2.00×10^{-5}	1.74×10^{-3}	1.20×10^{-4}
Soldering pickup, ratio, %	4.09×10^{-4}	0.82×10^{-4}	7.1×10^{-3}	4.9×10^{-3}
Weight loss, g	1.27×10^{-2}	4.61×10^{-3}	7.51×10^{-3}	3.99×10^{-3}
Weight loss, ratio, %	5.19×10^{-2}	1.88×10^{-2}	3.06×10^{-2}	1.63×10^{-2}

put three different surface treated pins and one H13 control pin in the front row. The uncoated pin in the front row serves as the control pin so that results of different campaigns can be correlated. Pin location 2 was chosen to be the location for the control pin (uncoated H13 die steel pin), because the highest wear loss rate was obtained there during the pilot test.

7.1 *Coating and Surface Treatment Selection*

Many factors that affect the selection of the coatings and surface treatment, such as the functional requirements, level of adhesion, coefficient of thermal expansion, heat transfer capability, market availability, etc. Most of the wear-resistant hard coatings are ceramics. Some of the commonly used metallic ceramics for wear resistance include the families: carbides, nitrides, borides, and silicides. Basically, our objective was to cover all the commercial coatings and surface treatments by including the most promising candidates from each family. Furthermore, some coatings developed by NASA Lewis Research Center for high-temperature application and commercial surface treatments, such as Metalife (micropeening), were also included. Pins extruded from high-temperature materials were also tried. The coatings and surface treatment evaluated in the accelerated tests are listed in Table 1.

The PS200/212 coating has been tested successfully as a cylinder liner coating in an external combustion Stirling engine (Stirling Thermal Motors, Inc., Ann Arbor, MI) for lubrication and for wear resistance. This coating consists of chromium carbide for wear resistance, silver and calcium fluoride, barium fluoride, and eutectic for lubrication. This coating can be coated by either PVD (about 10 mm) or sputtering processes (600 mm). Sputtering provides a very thick coating.

TAZ 8A is a nickel-based, high-temperature alloy coating, which consists of 70% nickel, 6% chromium, 4% tungsten, 4% molybdenum, and 6% aluminum. Some tungsten base (Aniviloy 1150) and molybdenum base (Mo-TZM) alloys have been used in the die casting industry because of their high thermal conductivity and very high resistance to thermal shock. This coating was applied by the PVD process, and the coating thickness was also in the 10 mm range. The compositions are in wt%.

Boron carbide is the hardest carbide known; however, B_4C has the lowest density and thermal expansion coefficients among the carbides (Ref 9). The coating was applied by the PVD process under 200 °C, and the coating thickness was below 2.5 mm.

Titanium nitride has very low affinity for metals; it is widely used in cutting tools and high wear applications. The coating was applied by the PVD process under 260 °C and the coating thickness was below 2.5 mm (Ref 9).

VC coating has been used in Japan since 1970. It is applied via a salt bath process; the coating thickness is usually in the 5 to 10 mm range. The temperature of this salt bath process is approximately 1000 to 1050 °C, and the dipping time is about 5 to 8 h for obtaining 5 to 10 mm thickness. According to the document published by Toyota Research Center (Ref 10), this coating has very good resistance to erosion attack, soldering and heat checking.

Fe_3Si and Cr-Si coatings have been applied by using a pack cementation method. Pack cementation is a kind of CVD (chemical vapor diffusion) process which gives a diffused coating. Both these coatings were applied at temperature approximately 1000 °C for 16 h. The master alloy for Fe_3Si was 73% Fe and 27% Si compound and pure silicon. The master alloy for the chromium coating was 90% Cr and 10% Si. The diffusion thickness after 16 h was 200 mm for Fe_3Si and 250 mm for the chromium coating. The compositions are in wt%.

Metalife is a commercial shot peening process. This process changes the die surface stress state from tensile to compressive. The subsurface penetration is about 0.01 to 0.015 in. The resulting microtexturing of the surface also compliments existing die lubricants by providing better die wetting characteristics, thereby improving the die lubricity and metal flow in the die without causing undesirable changes in dimensional tolerances. This process has been tested successfully for resisting die heat checking and cracking (Ref 11).

Ion implantation and related surface treatments using energetic ion beams are being increasingly employed for wear resistant applications. Three different ion implantation surface treatments (W, Mo, Pt) were applied on the H13 pin surface by plasma surface ion implantation (PSII). Selection of W, Mo, and Pt for coatings was based on the results of an earlierm, heat checking study, which found these three coatings to have the best resistance to heat checking among all metallic coatings.

All the pins were heat treated prior to coating. The heat treatment procedure was according to specification DCRF 01-73-02D. This procedure included stress relieving for two hours at 540 °C, austenitizing under protective atmosphere at 1850 °C for three hours, and quenching. After quench a sequence of three temperings were done to achieve the final hardness to 46 to 48 HRC.

8. Results and Discussions of Evaluation Tests

Seven different batches of the coated test pins were tested; each batch had more than one campaign (Table 2). The average

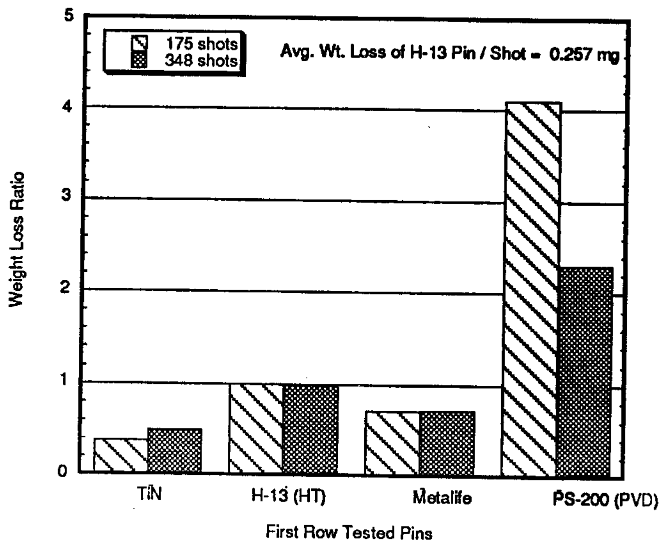


Fig. 7 Weight loss profile of batch 1 test (Harvill test machine)

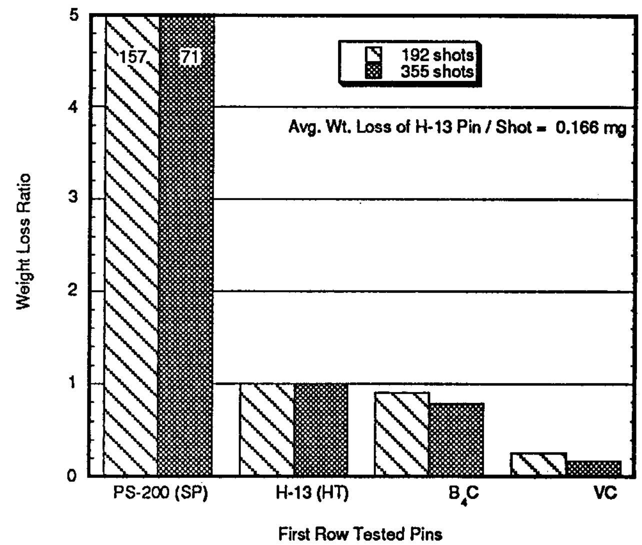


Fig. 8 Weight loss profile of batch 2 test (Harvill test machine)

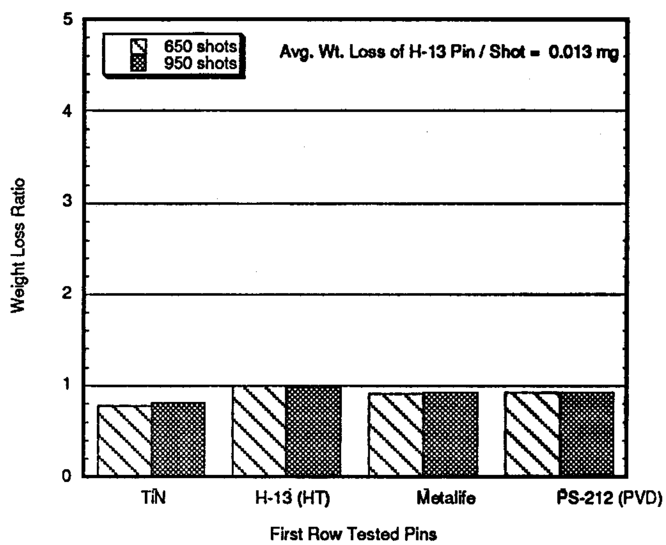


Fig. 9 Weight loss profile of batch 3 test (Buhler test machine)

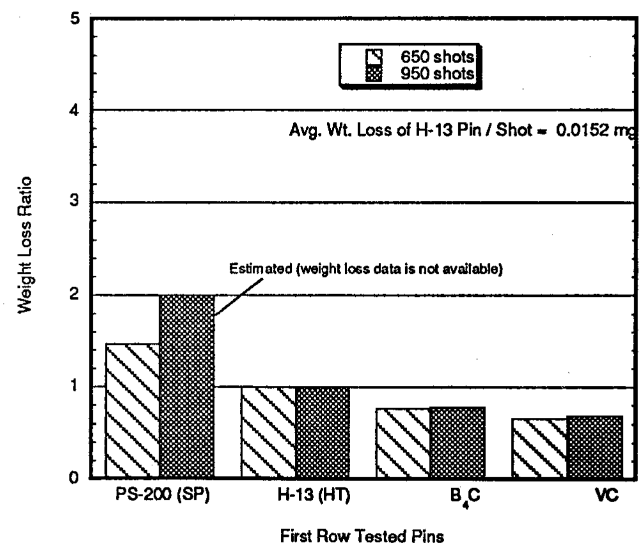


Fig. 10 Weight loss profile of batch 4 test (Buhler test machine)

weight loss per shot and the weight loss ratio (weight loss in coated pin per weight loss in H13 pin) are shown graphically in Fig. 7 to 13.

In batch 1 in Table 2, the TiN coating shows the best resistance to erosive wear, while the PS200(PVD) coating showed the least resistance to erosive wear. The Metalife surface treatment process was very close to the H13 steel in erosive wear behavior. From this data we can roughly estimate that the TiN coating was half of the wear loss of H13 pin.

In batch 2, the VC shows the best results. VC coating shows about ¼ weight loss compared with the H13 blank pin. The PS200 applied by thermal spray is shown to be unsuitable for die casting application. The thermal spray PS200 coating is very porous and was easily washed away under the high gate velocity.

The third batch, Fig. 9, was tested by using the Buhler 300 ton cold chamber die casting machine (replaced the Harvill machine). In this batch, the TiN coating showed the best resistance to the erosive wear. H13, Metalife, and PS200 (PVD) were shown to have very similar weight losses. Because most of the PS200 (PVD) coating was washed away, the virgin H13 substrate was exposed. The Metalife pin basically is the same as H13 pin but with the compressive stress built in on the surface; therefore, the erosive wear result should not be far different from that of the H13 pin. The comparative rankings for this batch are very close to that of batch 1, but the weight loss data

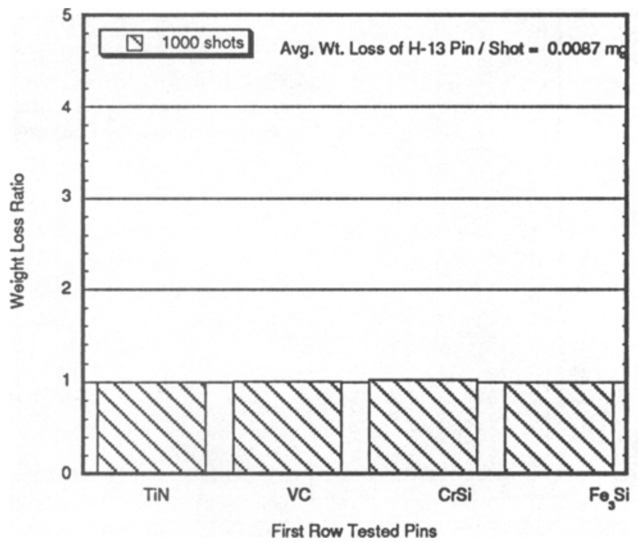


Fig. 11 Weight loss profile of batch 5 test (Buhler test machine)

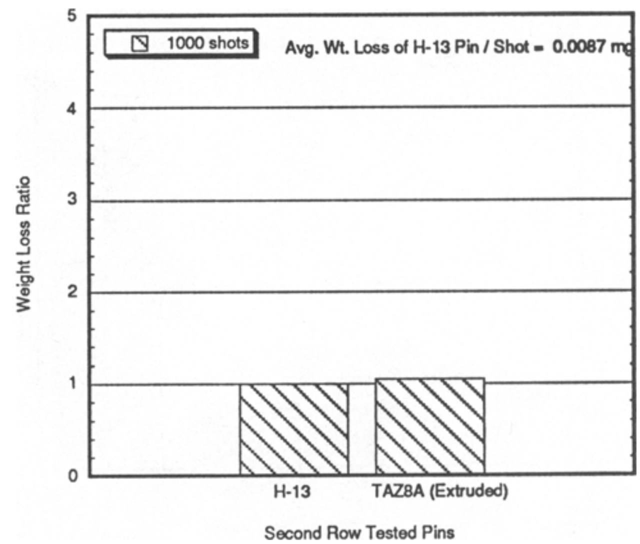


Fig. 12 Weight loss profile of batch 6 test (Buhler test machine)

is slightly different. The main reason for this difference is that the test environment changed. The new Buhler machine operated more consistently and provided better results than the older Harvill machine.

In batch 4 (Fig. 9), the VC showed the best result, but the average weight loss data is not the same as in batch 2. The VC weight loss data started to pick up as the number of shots increased. This may indicate that the VC coating can delay substantially the erosive wear at the beginning. With more shots, the coating surface may degrade or the properties may change so the weight loss increases.

Since the TiN and VC are the two best coatings in the first four test batches, it is hard to say which coating is the best to resist the erosive wear. In the fifth batch, in addition to TiN and VC coatings, two new coatings, Fe_3Si and chromium carbide, were involved. These two new coatings were developed by the Ohio State University for wear applications. The Fe_3Si and chromium carbide coatings were selected based on the results of the corrosive dipping wear tests. The chromium carbide coating showed an excellent capability to resist Al-corrosive wear.

In this batch, it is shown that the VC, TiN, Fe_3Si, and Cr pack coatings all show similar erosive results. The TAZ8A PVD coated pin and H13 uncoated pin did not show good erosive wear resistance. Based on the pilot test, the back-row pins should have less weight loss, but in this batch the back-row pin has the same weight loss range as the front coated pins. This indicated that at low erosive wear rates (coated pins), the corrosive wear mechanism may contributes to the weight loss.

In batch 5, two powder extruded PS212 test pins were put in the same batch with the H13 heat treated and ion nitriding pins. Both of the PS212 powder extruded pins were found broken in the first and second cycles. From the preliminary hardness check, it was found that the extruded pins had hardness of approximately 13 to 14 HRC or 102 to 103 HRB. Since the strength is usually directly proportional to the hardness, the strength of the PS212 extruded pins should be pretty low. Similarly in batch 6, a TAZ 8A extruded pin had been put with the H13 heat treated pin in the back row of the test die. The results were not very promising for TAZ 8A extrusion pin.

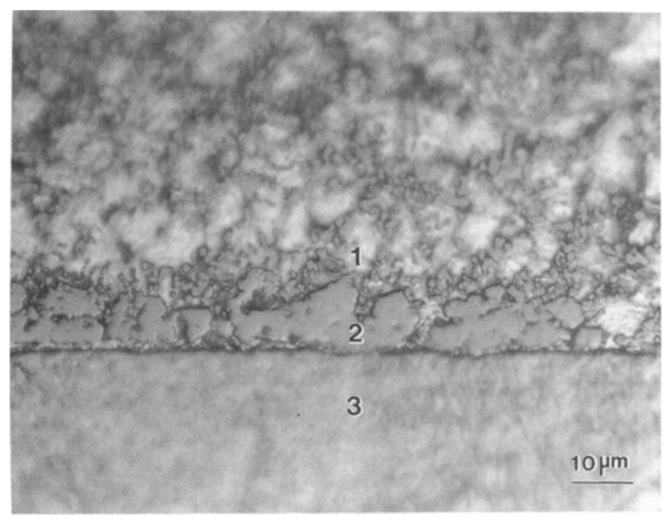


Fig. 13 Cross-sectional micrograph of a typical soldered area after 1000 shots of a die casting campaign. (1) A390. (2) τ_6. (3) H13

9. Mechanism of Washout: Erosion and Soldering

Soldering of aluminum alloy to the H13 die surface is a common phenomenon in the aluminum die casting production. Soldering is an adherence phenomenon. It normally occurs at local spots of the die surface where high temperature or high gate velocity exist. Soldering results in damage to the casting surface and rejection of the castings. In practical production, soldering may quickly worsen and spread once it occurs. A soldered area on the die surface will hinder the ejection of casting from the die and cause drag marks, which result in the casting being scrapped because of its appearance. Figure 13 is the cross-sectional micrograph of a soldered A390 at a H13 test pin after 1000 shots of die casting operation using the accelerated erosion test procedure.

An intermetallic layer between the soldered area and the H13 substrate was formed. This intermetallic composition was analyzed by energy dispersive spectroscopy (EDS) analysis, and an average composition of 55.73 wt.% Al, 15.64 wt.% Si, and 24.35 wt.% Fe was obtained. This composition is close to τ_6 (Al_4SiFe). This τ_6 is a thermodynamically stable phase between 500 and 650 °C according to the ternary Fe-Si-Al diagram. Further EDS analysis of the adjacent area of τ_6 indicated that appreciable amount of Fe exists in the casting alloy. The soldering product may result from both active diffusion of all elements involved, such as Fe, Al, and Si. A 630 Vickers hardness in the intermetallic layer τ_6 was obtained from the microhardness test. Soldering phenomenon is also an indicator for the rapid dissolution of H13 materials as the soldered casting alloy can be readily detached from H13 substrate, and a material loss results.

9.1 *Effects of Melt Temperature*

The melt temperature is an important parameter in a die casting operation. The melt temperature used in aluminum die casting depends on many factors, such as the die and gating design, casting alloy composition, casting quality, and in many cases empirical experience. A study of the effects of melt temperature on the soldering and wear of the die would help in the understanding of the effect of the thermal phenomena at the surface. Table 3 includes the test results of two different melt temperatures, namely 650 and 700 °C, under same gate velocity (50 m/s). The results were obtained from the front-row H13 test pin for 2000 shots. The test H13 pins were unloaded and analyzed after the first 1000 shots and after the next 1000 shots. The amount of soldering was measured after dissolving the test pin with NaOH to removed the soldered aluminum alloy.

The results indicated that the weight loss of H13 pin at low melt temperature (650 °C) is much higher than at higher temperature (700 °C), while the amount of soldering was much larger at the higher temperature. This conclusion holds for both the first 1000 shots and the second 1000 shots.

Therefore, low melt temperature favors soldering resistance of die casting H13 dies because of lower diffusion and chemical reaction rate. However, the erosion resistance of H13 die is poor at low melt temperature because of the presence of an appreciable amount of presolidified casting alloy (solid fraction), which results in enhanced erosive wear.

10. Summary

From the erosion test design and initial test results obtained in this investigation, the following conclusions are drawn:

- The multiple pin accelerated test design is a valid approach to evaluate the erosion resistance of uncoated and surface modified commercial H13 die material. The front four test pin locations have almost identical flow and thermal field, and result in the same erosion characteristics that allow the simultaneous evaluation of different materials and surface modifications.
- The soldering phenomenon occurs readily under the accelerated erosion test procedure. The interdiffusion of Fe and Al and subsequent formation of intermetallic τ_6 was found between the soldered A390 and H13 test pin. This points to a possible link in the erosive and corrosive (soldering) behavior.
- A high-temperature die casting operation yields severe soldering and less erosion due to its enhanced molten aluminum corrosion and less abrasive melt. On the other hand, a low-temperature die casting operation favors soldering resistance while erosion of the die material becomes more severe as partially solidified casting alloy injected into the cavity induces higher erosive wear.
- Thin wear resistant TiN coatings and carbides of vanadium, boron, and chromium improve significantly the erosion resistance of H13 materials.

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