The Effect of Coating Type on Extraction Loads for Steel Core Pins in Aluminum Permanent Mold Castings

Stephen P. Midson
Colorado School of Mines, Golden, Colorado, USA

ABSTRACT

An investigation has been performed to determine if permanent thin-film coatings applied to critical portions of a casting die could be beneficial for aluminum permanent mold casting, thereby enabling the reduction of the need for release coatings or lubricating sprays. A laboratory test has been designed and fabricated to provide a quantitative measurement of the force needed to extract a core pin from solidified aluminum alloys. The test involves pouring molten aluminum alloy A356 into a crucible containing a tapered H13 steel core pin, and once the alloy has cooled to 752F (400C), a tensile testing load cell is used to monitor the load necessary to extract the pin. Five different conditions have been examined, including bare (un-coated) steel pins, sprayed graphite and boron nitride coatings, a silicon-doped diamond-like carbon (DLC), and an AlCrN coating. The measured extraction loads and load-time curves are reviewed, along with the surface condition of the pins after extraction.

Keywords: thin-film permanent coatings, aluminum alloys, soldering, permanent mold casting

INTRODUCTION

Molten aluminum alloys have a high affinity for soldering (welding and sticking) to the die when cast into metal molds.[1,2] This compels casters to use release agents, which have to be applied to the die far more regularly than insulating sprays, sometimes as often as every few castings. For high pressure die casting, organic lubricants are sprayed onto the die, while for permanent mold casting, ceramic coatings and graphite are used. Although the application of these release agents is necessary, they cause various problems, such as reducing the quality of the castings, breaking up the all-important regular molding cadence and the creation of costly housekeeping issues.

Recent research evaluated the use of permanent thin-film coatings, applied to the hot faces of die casting dies, to reduce or eliminate the need for applying organic lubricants.[3-6] A laboratory test has been developed that allowed a semi-quantitative measurement of sticking forces when molten aluminum was allowed to solidify in contact with coated and un-coated steel substrates. Various physical vapor deposition (PVD) thin-film coatings were identified that exhibited zero adhesion strength between the solidified aluminum and the coated substrate (i.e., exhibited non-sticking behavior), and an AlCrN PVD coating was selected for a plant trial, where an entire die was coated with the AlCrN coating. Results from the plant trial[6] showed that the PVD coatings allowed conventional lubricant (die spray) use to be reduced by about 85%, the cycle rate was improved by 12%, and the quality of the castings increased.

The permanent mold casting process takes a slightly different approach to minimize soldering (sticking) of the molten aluminum to steel dies, where ceramic particles bonded with inorganic adhesive coatings are applied to the faces of the die once (or several times) per shift. However, graphite can also be used as a release agent for critical parts of the die, including regions with low draft or cores with deep draws, but graphite creates major housekeeping issues. It is proposed, therefore, that permanent mold casting could also benefit from the use of permanent thin-film coatings applied to the surfaces of steel die components, to minimize the use of conventional release agents. If successful, it is likely that the use of such coatings would improve cast-part quality (both internal and surface), decrease costs, assist with a regular molding cycle, and reduce housekeeping problems.

The approach, therefore, was to perform a preliminary investigation to determine if permanent thin-film coatings applied to critical portions of a casting die could be beneficial for permanent mold casting, thereby enabling the reduction or elimination of the need for conventional lubricants such as graphite. However, the objective of the research described in this paper was reduced in scope by the AFS research board, namely, to demonstrate a laboratory test that can provide reliable and reproducible quantitative measurements of the forces required to extract long cores from aluminum castings. As part of this effort, several different coating conditions were examined, including bare (un-coated) steel pins, sprayed graphite and boron nitride (BN) coatings, a silicon-doped diamond-like carbon (DLC), and an AlCrN coating.

EXPERIMENTAL PROCEDURES

Figure 1 shows schematic drawings of the test apparatus designed and fabricated for this study. Photographs of the actual apparatus are shown in Figure 2, and the following procedure was utilized. The testing apparatus is positioned in a tensile testing machine, which provides a quantitative measurement of the load to extract the core pin from the solidified aluminum. The apparatus consists of a steel crucible approximately 3-inches internal diameter and about six inches tall. An H13 steel core pin is inserted through the bottom of the crucible (Figure 3 shows the core pin), where the 2-inch long drafted section of the pin is inserted into the crucible. Twelve pins were purchased from DME, and the 2º draft was machined by Carley Foundry.

Liquid aluminum alloy A356 was melted in a clay graphite crucible using a small portable electric resistance furnace. Once at about 1337F (725C), the crucible was extracted from the furnace and the molten aluminum alloy poured into the crucible. A type-K thermocouple located within the melt in the crucible was used to measure temperature as the aluminum solidified. Once the cast aluminum cooled to 752F (400C), the tensile testing machine was activated, and the core pin was extracted from the casting at a rate of 1mm/second. A load cell on the tensile testing machine measured and recorded the load required for extraction, allowing the production of load-position curves.

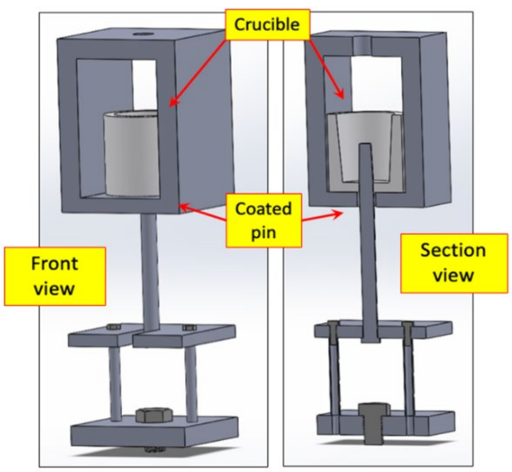

Figure 1. Schematic drawings showing the front view and section of the testing apparatus.

Various coatings were examined in this study, as follows:

- A can of graphite spray was purchased from Grainger and was manually sprayed onto the steel core pin. Both the graphite and BN were sprayed when the pins were at room temperature.
- A can of boron nitride (BN) spray was also purchased from Grainger, and was also hand sprayed on the steel core pin.
- One of the core pins was covered with an AlCrN thin film coating. The AlCrN was produced using physical vapor deposition (PVD) by a commercial supplier, and had an ion-nitrided layer beneath the AlCrN. The coating was approximately 5 μm thick. This coating has exhibited excellent solder resistance during aluminum die casting trials.[7]
- The final coating was a silicon-doped diamond-like carbon coating (DLC), produced using plasma-assisted chemical vapor deposition (PACVD) by a different commercial supplier. Again, this coating has exhibited excellent anti-soldering behavior in high pressure die casting trials,[8] and has the additional benefit of providing excellent lubricity. The data in Figure 4 shows the results of pin-on-disk measurements (performed using techniques described in ASTM G-99) of the coefficient of friction of a Si-DLC sample against an aluminum ball, showing a very low coefficient of friction after an initial run-in period.

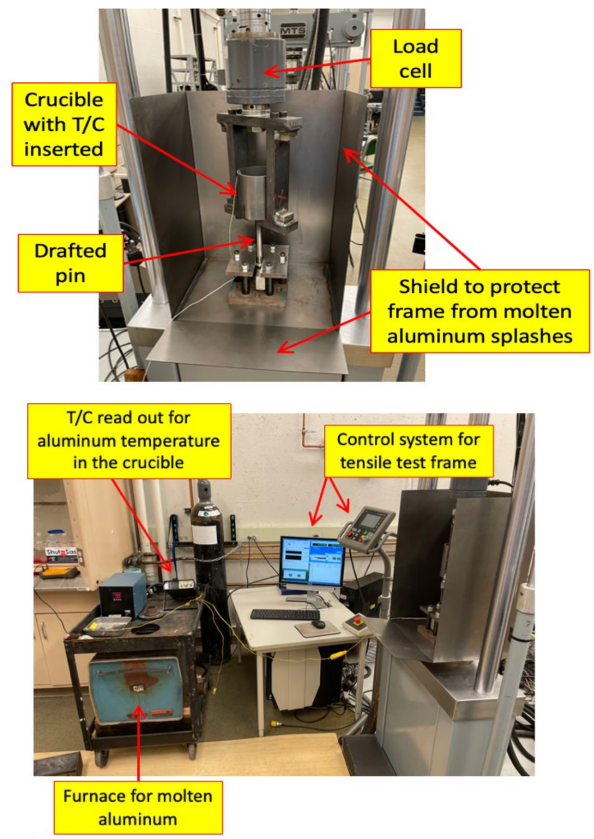

Figure 2. Photographs of the testing apparatus.

Figure 3. Two photographs of the machined core pin.

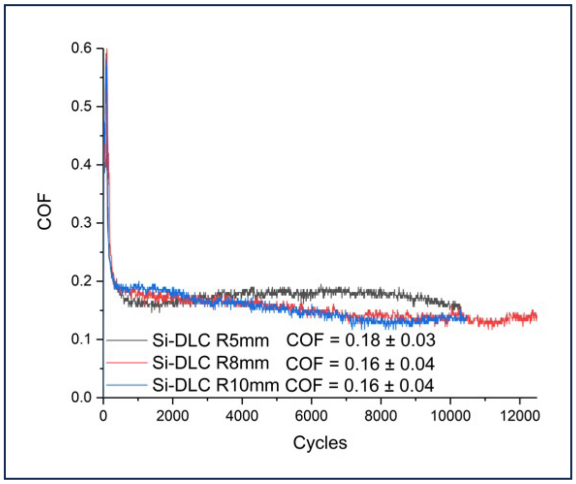

Figure 4. Coefficient of friction measured using pin-on-disk for the DLC coating.

The following four sets of tests were performed as part of this study:

- Consistency measurements, to determine the reproducibility of the testing apparatus. This was performed using two un-coated pins and two pins sprayed with graphite
- Testing of a deliberately tilted crucible, to observe the effect on the load-position curve
- Comparing the efficiency of sprayed graphite and BN coatings
- Measuring the performance of the two thin-film permanent coatings, AlCrN and Si-DLC

RESULTS AND DISCUSSION

CONSISTENCY MEASUREMENTS

To evaluate the consistency of the test apparatus, two surface conditions of core pins were tested, graphite coated and un-coated (bare). Two extraction tests were performed for each condition. The consistency of the results were compared, in terms of the shape of load-position curves and the maximum extraction load.

Figure 5 shows a photograph of one of the graphite-covered core pin prior to the test, indicating that a relatively uniform covering of graphite was obtained.

Figure 5. Photograph of one of the graphite coated core pins

Figure 6 provides an example of a load-position curve measured on the tensile testing cell for one of the graphite coated pins. It shows that the initial movement of the tensile machine takes up slop in the system, and the load then builds up in a relatively linear manner. The maximum load represents the point at which the pin separates from the solidified aluminum, and once the drafted pin loses contact and separates the load rapidly drops. In this case, the maximum load measured in Figure 6 was 207 lbs.

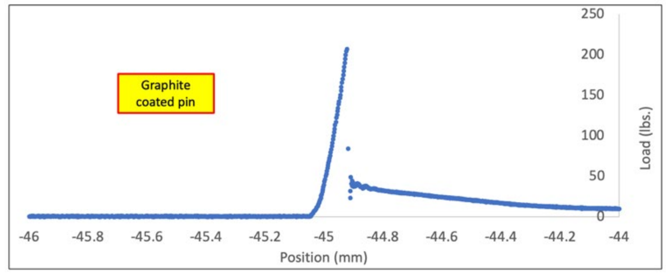

Figure 6. Load-position curve for one of the graphite coated pins.

Figure 7 compares the load-position curves for the two graphite coated and the two un-coated pins. In each case, the shape of the curves are very similar, with only the maximum separation load being different. The data in Table 1 lists the maximum load for each of the four tests, with the graphite sprayed pins exhibiting a maximum load between 207-to-210 lbs., and the uncoated pins being significantly higher, between 898-to-974 lbs.

Table 1. Measured Maximum Loads for Two Graphite Coated and Two Un-Coated Pins (data from Fig. 7)

Test	Maximum Load (lbs.)
Graphite coated – 1	207
Graphite coated – 2	210
Un-coated – 1	898
Un-coated – 2	974

These results show that the degree of consistency attainable with this testing apparatus is good, suggesting that the apparatus is capable of producing reproducible results. The results also show that the separation force for graphite is significantly lower than for the un-coated pin. Figure 8a shows a photograph of one of the graphite coated pins following the test, showing that some of the graphite had been removed as the pin was extracted from the casting, but there does not appear to be any aluminum adhered to the pin surface. Figure 8b shows a photograph of one of the un-coated pins after testing, indicating that there was a small amount of adhesion of the solidified aluminum to the surface of the pin after extraction.

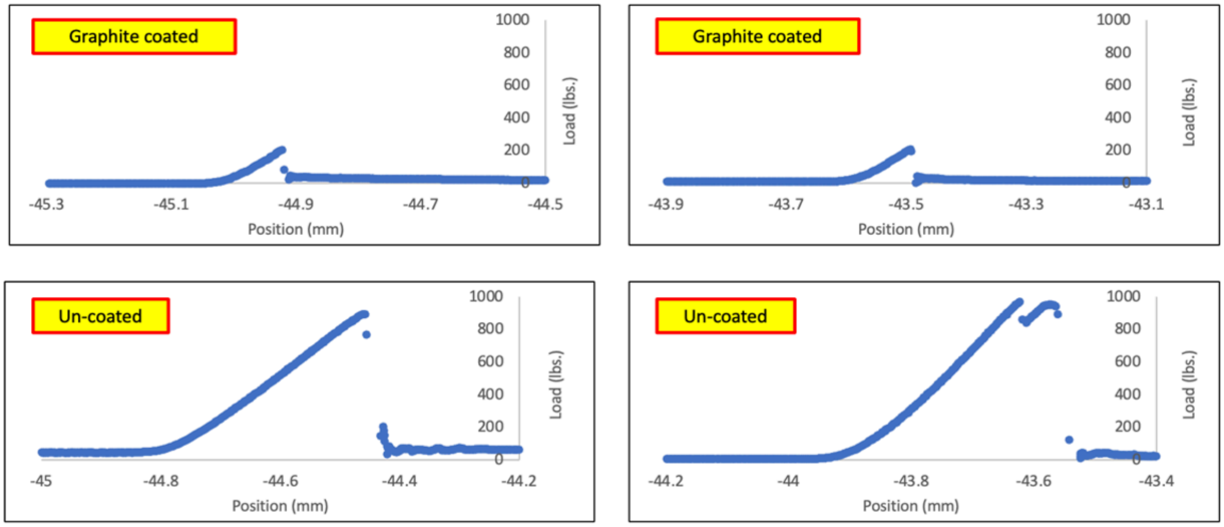

Figure 7. Load-position curves for the two graphite coated pins and two un-coated pins.

a)

b)

Figure 8. Pins after testing: a) Graphite coated pin and b) Un-coated pin.

Figure 9. Photograph of the apparatus utilizing a shim to tilt the crucible by about 1.8 degrees.

TILTED PIN

To further evaluate the reproducibility of the testing apparatus, a test was performed where the crucible was purposely tilted, to determine if the extraction load would increase significantly if the solidified aluminum was deformed during the extraction of the pin. The objective was to tilt the crucible more than the 2^o draft placed on the core pins, ensuring that the aluminum would be deformed during extraction. To achieve this tilt, a machined shim was placed under one side of the crucible (Figure 9). However, as shown in Figure 9, due to constraints of system, the top of the crucible hit against the frame holding the crucible in place, and so the maximum tilt that could be achieved was only 1.8 degrees.

A test was performed using this configuration, with an un-coated pin. The load-position curve for the un-coated pin from the tilted system is shown in Figure 10, where it is compared to one of the non-tilted samples (from Figure 7). The maximum load for the tilted condition is slightly higher (44% higher) than for the non-tilted (straight) condition. It was not clear whether or not deformation of the cast aluminum had actually occurred. However, the results from this test do suggest that, for the non-tilted (straight) condition, the pin is extracted from the solidified aluminum with minimal (or zero) deformation of the solidified aluminum, and therefore the maximum load measured from the load-position curves appears to be related to the separation of the pin from the aluminum, and not due to the deformation of the aluminum casting.

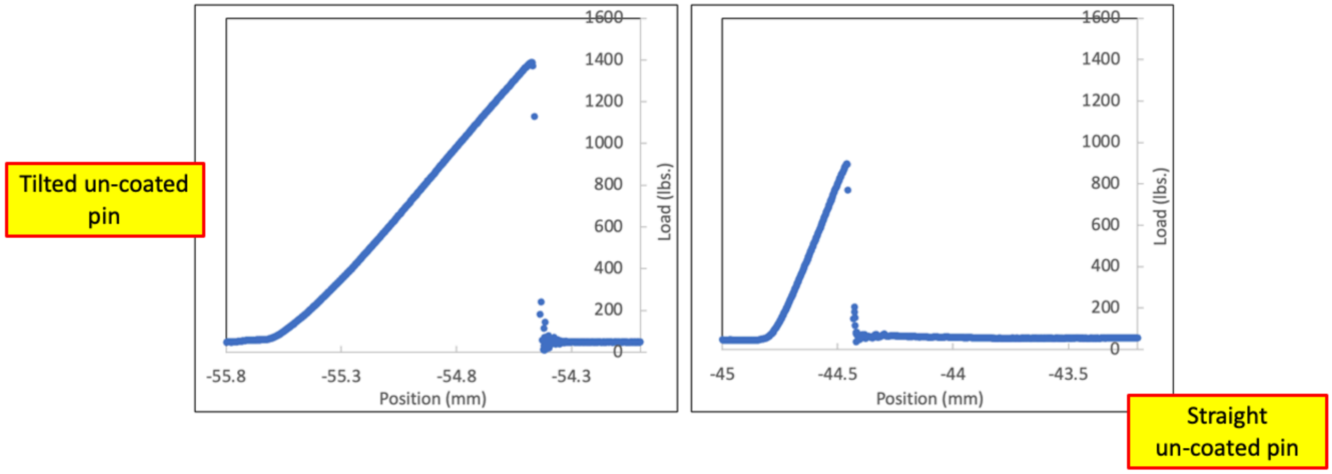

Figure 10. Comparison of the load-position curve for the tilted crucible versus a non-tilted pin.

Table 2. Measured Maximum Loads for Tilted condition (data from Fig. 10), vs. the Two Non-tilted Tests (data from Figure 7)

Test	Configuration	Maximum Load (lbs.)
Un-coated – 1	Straight pin	898
Un-coated – 2	Straight pin	974
Un-coated	Tilted pin	1,344

GRAPHITE VERSUS BN COATED PINS

The next test compared the performance of the graphite and BN sprayed coatings. The load-position curves for the BN coated pin and one of the graphite coated pins are shown in Figure 11, and the shapes of the curves are again extremely similar. The main difference is the slightly higher maximum extraction load for the BN coated pin. However, the extractions loads for both the BN and graphite coated pins are significantly lower than the un-coated pins (~900 lbs.). Figure 12 shows photographs of the pins after the extraction test, demonstrating that the BN coating appeared to survive the test relatively intact, while some of the graphite has been scraped from the graphite coated pin during extraction.

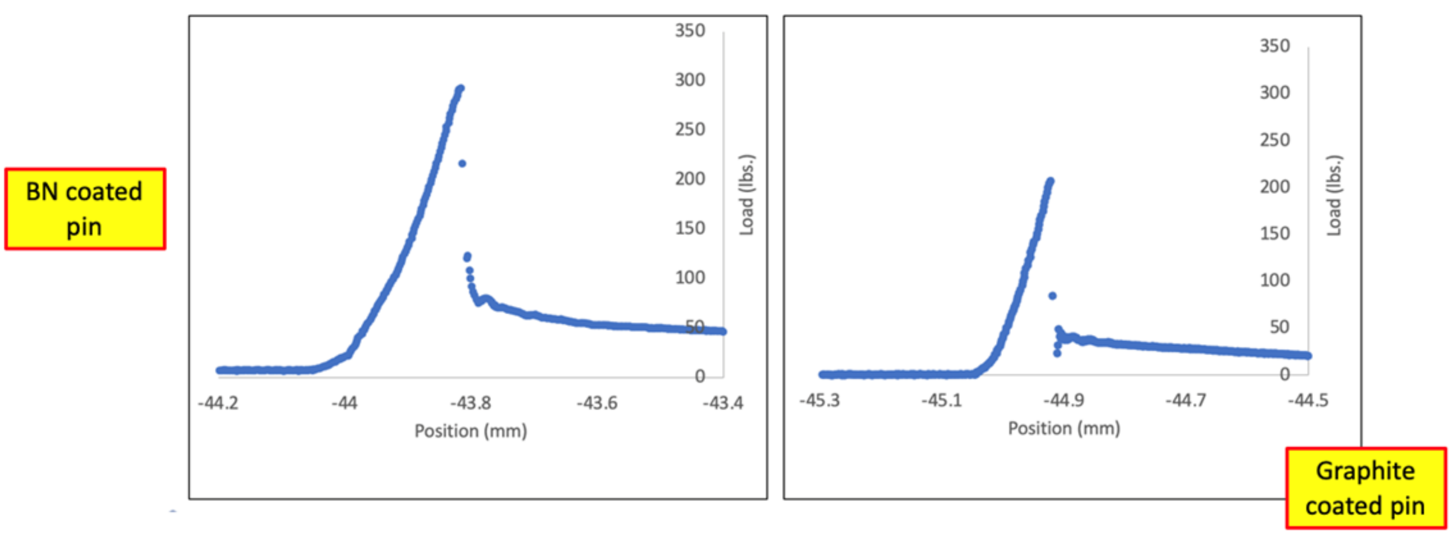

Figure 11. Load-position curves for the BN and graphite sprayed pins.

Table 3. Measured Maximum Extraction Loads for the BN Coated Pin and the Two Graphite Sprayed Pins

Test	Maximum Load (lbs.)
Graphite coated – 1	207
Graphite coated – 2	210
BN	293

a)

b)

Figure 12. Pins after the test: a) Graphite coated pin and b) BN coated pin.

PERMANENT THIN-FILM COATED PINS

The final part of this study was to evaluate the performance of two permanent thin film coatings, Si-doped DLC and AlCrN. Photographs of the two coated pins prior to the test are shown in Figure 13. Two tests were performed using the Si-doped DLC coated pins. The first test used the standard pouring temperature of about 1337F (725C), while the second test with a Si-doped DLC pin utilized a much lower pouring temperature of 1184F (640C). The pouring temperature with the AlCrN pin was 1337F (725C).

The load-position curves measured during the extraction of the pins for these two coatings are shown in Figure 14. Also shown for comparison is the load-position curve for one of the un-coated pins tested earlier. The maximum loads for each test are listed in Table 4, which shows that the extraction loads for the Si-doped DLC pins are significantly higher than all the other measurements, being nearly four times higher than for the un-coated pins. A photograph of one of the Si-doped DLC pins is shown in Figure 15 after the extraction test, and different regions are evident, including where the coating had been removed, where significant aluminum adhesion had occurred, and where the aluminum appears to have reacted with the coating.

a)

b)

Figure 13. Coated pins before tests: a) Si-doped DLC and b) AlCrN.

It was thought that a pouring temperature of 1337F (725C) may be too high for the DLC coating, causing reaction between the molten aluminum and the DLC coating, so a lower pouring temperature of 1184F (640C) was tested.

As shown in Table 4, the maximum extraction load for this lower pouring temperature was even higher. The poor performance of the Si-doped DLC coating was surprising, as it performed well in die casting trials [8]. One difference may be related to the extremely long solidification time measured in this test to cool from the pouring temperature to 400C, between six and ten minutes. This would presumably heat the core pin to a higher temperature, and allow more time for reactions to occur. There are at least two possibilities for this poor performance, that the molten aluminum may have reacted with the carbon in the DLC coating produced Al_4C_3, or that the molten aluminum reacted with silicon in the Si-DLC coating. An SEM analysis was performed on a section cut through one of the regions of the Si-doped DLC coated pin in the region where aluminum adhesion was present, and the results are shown in Figure 16. Figure 16a shows a region of metal adhesion to the coated pin, and SEM analysis shows silicon buildup in the region (Figure 16b), suggesting the second mechanism listed above. It Is worth noting that Vian[9] did not report any reaction between molten aluminum and a Si-doped DLC coating for testing performed at 1150F (621C), but did identify relatively large silicon particles at the interface between the aluminum and the coating.

The maximum extraction load for the AlCrN was much lower (1,206 lbs.), but still slightly higher than measured for the un-coated pins (average of 936 lbs.). As shown in Figure 17, there was only a very small amount of aluminum adhered to the surface of the AlCrN pin after extraction.

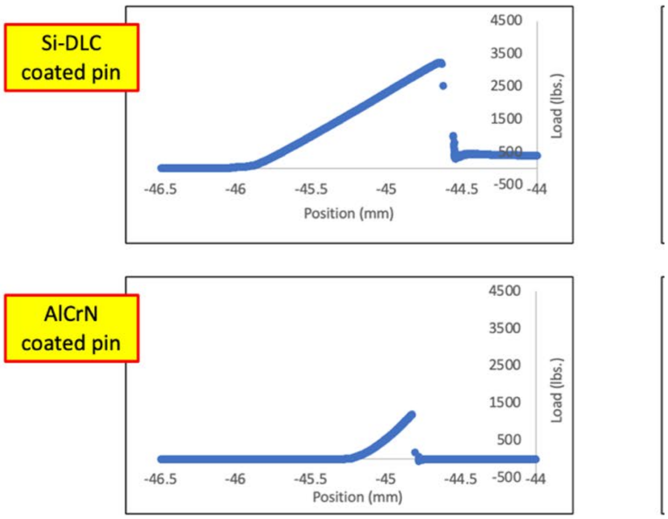

Figure 14. Load-position curves for the Si-doped DLC and AlCrN coated pins. Also shown for comparison is one of the un-coated pins.

Table 4. Maximum Load Value for Thin-film Coated Pins

Test	Pouring Temperature	Maximum Load (lbs.)
Graphite coated – average	~ 1337ºF (725ºC)	209
Un-coated - average	~ 1337ºF (725ºC)	936
Si-Doped DLC – 1	~ 1337ºF (725ºC)	3,240
Si-Doped DLC- 2	~ 1184ºF (640ºC)	4,045
AlCrN	~ 1337ºF (725ºC)	1,206

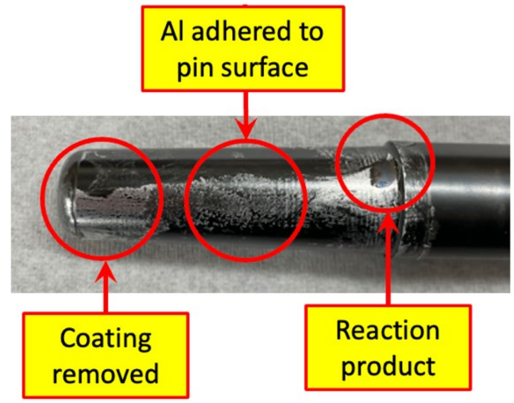

Figure 15. Photograph of the Si-doped DLC coated pin after testing identifying different regions.

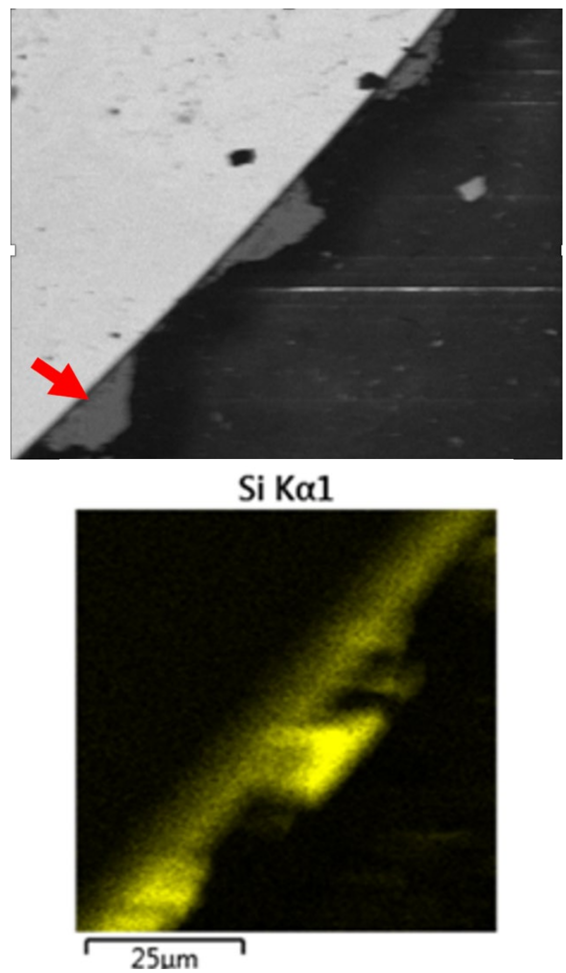

Figure 16. SEM analysis of the surface of the Si-doped DLC pin after testing, showing silicon at the surface.

Figure 17. Photograph of the AlCrN coated pin after testing.

SUMMARY & CONCLUSIONS

- A test has been developed that quantitatively measures the extraction loads for core pins within aluminum castings
- Based on the data presented in this paper, the results of the test appear to be reproducible
- Several conditions were tested, including bare (un-coated) pins, sprayed coatings (graphite and BN), and permanent thin-film coatings (AlCrN and Si-doped DLC).
- Pins coated with graphite and BN exhibited the lowest extraction loads
- PVD coated pins exhibited the highest extraction loads
- Molten aluminum appeared to react with the Si-doped DLC coating, resulting in extremely high extraction loads (nearly four times higher than un-coated pins)
- The reason for poor performance of the AlCrN pin is not clear, as this coating has performed well in high pressure die casting trials

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