Development of Advanced Coating Techniques for Highly-durable Casting Dies

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Abstract. In order to improve the durability of aluminum die-casting molds, we applied microstructure-controlled PVD coating techniques. Single-layer and multilayer films consisting of chromium nitride (CrN) or titanium aluminum nitride (TiAlN) were prepared using an ion plating process. Structures of multilayer films were observed using transmission electron microscopy. Pin-shaped mold steel specimens coated with each of the films were soaked in the molten aluminum alloy at 953 K different periods of time, and the amount of weight loss due to erosion was evaluated. The weight losses for the multilayer CrN and TiAlN specimens were found to be less than those for the single-layer specimens. As a practical test, five specimens of core pins used in aluminum die casting of automobile parts were coated with multilayer films, and the number of maintenance operations required to remove aluminum alloy remaining on the specimen surfaces after several thousand castings was counted and compared with six control specimens (core pins treated using a commercial salt bath diffusion process). The number of maintenance operations for CrN- and TiAlN-based multilayer-coated core pins was found to be lower than for the control specimens.

1. Introduction
Die casting, which is a metal casting process that involves the injection of molten metal into a mold cavity under high pressure, can produce large quantities of complex-shaped castings in a short time. However, during the casting process, casting dies that are exposed to molten metal can degrade quickly [1]. In the case of aluminum die-casting, degradation of the casting die causes the aluminum alloy to stick to the mold surface, and dies must be repaired or replaced according to the level of degradation. In order to reduce the cost of repairing or replacing the mold and the associated impact on productivity, a method of extending the life of the casting dies is strongly required.

According to a previous study [2], a metal nitride film formed by PVD on the die component material can suppress damage caused by erosion [3]. However, damage to the base metal is still thought to occur due to flaws in the PVD film. In the present study, multilayer film techniques to inhibit the formation and development of flaws in the film were developed. The practical performance of the developed coating was evaluated using a coated die component intended for use in an aluminum die-casting machine.
2. Experimental Procedures

2.1. Coating Process

Single-layer and multilayer films consisting of chromium nitride (CrN) or titanium aluminum nitride (TiAlN) were prepared by Multi-Arc PVD system (NISSIN ELECTRIC MC-300) using an ion-plating process. Figure 1 shows cross-sectional images of CrN-based multilayer film with 17 layers and TiAlN-based multilayer film with approximately 300 layers.

![Cross-sectional TEM images of multilayer films: a) CrN-based multilayer film, b) TiAlN-based multilayer film.](image)

2.2. Erosion test

Figure 2 shows the erosion test apparatus used to evaluate the resistance to erosion of the PVD coating materials. The tested specimens were either uncoated, nitrided, or coated with single- or multilayer CrN or TiAlN films. Pin-shaped mold steel (JIS SKD61) specimens (diameter: 10 mm, length: 100 mm) were soaked in molten aluminum alloy (JIS ADC12) at a depth of 50 mm and a temperature of 953 K for different periods of time, and the weight loss due to erosion was measured. Weight measurements were performed after removing the aluminum alloy attached to the surface, and the amount of erosion was then calculated. Erosion pitting of the specimen surface was observed using an optical microscope (KEYENCE: VHX-100).

![Schematic diagram of erosion test apparatus.](image)

2.3. Practical test for aluminum die-casting

For the practical test, five core pins used in aluminum die casting of automobile parts were coated with multilayer films, and the number of maintenance operations required to remove the aluminum alloy remaining on the die surface after several thousand castings was counted. These results were compared with those for six control specimens (core pins treated using a commercial salt bath rotation (30 rpm))
diffusion process). Figure 3 shows the cast products and the positions of the core pins used for the casting test. The dimensions of the cast parts were 400 mm × 300 mm × 60 mm (length, width, diameter), and the test material was ADC12 aluminum alloy.

![Figure 3. Dimensions of cast product and positions of core pins used for the casting test.](image)

3. Results and Discussion

3.1. Erosion test

When observing the surface state of the untreated specimen after soaking two hours in molten aluminum alloy, wear can be seen in entire of soaked area (Fig. 4). Specimen that treated with nitride was also found to wear over almost all of the soaked area (Fig. 5). The amount of weight loss of each specimens were, 5.60g, 2.92g, respectively. Overall weight of the specimen before the test is 84.4g and weight of soaked area is approximately 30.2g. The weight loss of untreated specimen after soaking for two hours is approximately 19% of the initial weight of the soaked area.

![Figure 4. Untreated specimen after soaking for two hours.](image)  ![Figure 5. Nitride specimen after soaking for two hours.](image)

Figure 6 shows the amount of weight loss of specimens coated with single- or multilayer CrN or TiAlN films after soaking in molten aluminum alloy. Testing time for specimens were, 0.5, 1, 2, 3, 4 hours about single-layer film and 4, 8, 12 hours about multilayer film, respectively.

The weight loss of specimens coated with single-layer CrN or TiAlN films at soaking two hours were, 0.003g, 0.226g, respectively. Compared with specimens untreated or nitrided at test time 2 hours, it was found that the amount of wear significantly reduces about the coated specimens.

For multilayer-coated specimens, erosion was not observed by soaking four hours. Slight erosion was observed at soaking 8 hours, and amount of weight loss of multilayer TiAlN and CrN at soaking 12 hours were 0.130g, 0.061g. Amount of the weight loss of the multilayer-coated specimen after soaking 12 hours were much less than that of single-layer coated specimen after soaking 4 hours, so, it is found that multilayer film can improve the resistant to erosion.
Figure 6. Amount of weight loss of specimens coated with single- or multilayer CrN or TiAlN films for several soaking time.

Figure 7 and 8 shows the surface state of the single-layer coated specimen after soaking four hours. About CrN single-layer specimen, erosion pit can be seen sparsely around soaked area. About TiAlN single-layer specimens, erosion was spread all of soaked area and the coating layer was only partially remained.

In order to pursue a mechanism of damage progression, erosion pit of CrN single-layer film was observed. Figure 9 shows one of typical erosion pit on surface of CrN coated specimen. Shape of erosion pit was nearly perfect circle and CrN film had been left around a pit. Figure 10 shows a cross-sectional image of erosion pit. As cross-sectional shape of erosion pit was spreading inside the substrate and remaining the surface film, the damage of the specimen is considered to progress by erosion of the substrate rather than degradation of the film.
Figure 11 and 12 shows the surface state of the multilayer-coated specimen after soaking eight hours. If you watch the surface, in the case of CrN multilayer film is dotted with small defects, in the case of TiAlN multilayer film showed several comparatively large erosion pits (diameter<1mm).

![Figure 11. Multilayer CrN specimen after soaking for eight hours.](image)

![Figure 12. Multilayer TiAlN specimen after soaking for eight hours.](image)

3.2. Practical test for aluminum die-casting

Table 1 shows the results of practical test of multilayer-coated core pins assembled in an aluminum die-casting machine. Core pins coated with multilayer CrN films took four times of maintenance operations during the test casting 2,177 products, whereas control were required to maintain 14 times. Core pins coated with multilayer TiAlN films took none of maintenance operations during the test casting 3,426 products, whereas control were required to maintain 20 times. In both cases that applied CrN or TiAlN multilayer film, the number of maintenance operations was lower than the control specimen of existing product. It is assumed that because the surface damage of core pins was suppressed by multilayer film, adhesion of aluminum was reduced.

|                  | Number of casting tests | Number of core pins | Number of maintenance operations |
|------------------|-------------------------|---------------------|----------------------------------|
| CrN (multilayer) | 2,177                   | 5                   | 2                                |
| Control          | 2,177                   | 6                   | 14                               |
| TiAlN (multilayer)| 3,426                  | 5                   | 0                                |
| Control          | 3,426                  | 6                   | 20                               |

4. Conclusions

CrN and TiAlN film subjected by ion plating can be greatly suppresses damage due to erosion of mold material.

About erosion test the damage of the specimen is considered to progress by erosion of the substrate rather than degradation of the film.

According to the casting test using core pins applied CrN or TiAlN multilayer film, the number of maintenance operations was reduced compared to the control specimen of existing product. It is assumed that because the surface damage of core pins was suppressed by multilayer film, adhesion of aluminum was reduced.

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