INCREASING THE LIFETIME OF ALUMINIUM AND MAGNESIUM PRESSURE DIE CASTING MOULDS BY ARC ION PLATING PVD COATINGS

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Abstract
Nowadays PVD coatings are wide-spread and state of the art in the machining industry. Due to their properties, like high hardness, corrosion resistance and high temperature stability, PVD coatings have achieved large industrial applications.

In this paper, PVD coatings are used for extending the lifetime of a pressure casting mould. A main factor influencing the lifetime of a die is the initiation and propagation of thermal cracks near the contact zone melt/die surface. The initiation and propagation of these cracks are caused by high tensile stresses due to high temperature gradients near the surface. A way to avoid these tensile stresses can be achieved by bringing the surface of a die into a high compressive state and thereby superimposing these harmful tensile with non critical compressive stresses.

Arc ion plating is a PVD process which is known to cause high compressive stresses in coatings due to its high ionisation rate and the applied bias voltage to the substrate. The investigated (Cr,Al)N coatings were deposited on a typical pressure casting mould material (H11/1.2343) and then tested considering their wear and corrosion resistance as well as their resistance against forming thermal cracks.

Keywords: Heat checking, PVD coatings, residual compressive stress, thermal cracking, die casting
INTRODUCTION

Modern thin film surface technologies like Chemical Vapour Deposition (CVD), Plasma Enhanced Chemical Vapour Deposition (PECVD) and Physical Vapour Deposition (PVD) are widely used in tooling industries. Their application on indexable inserts and drills are nowadays state of the art, since they are known to enhance the lifetime in some cases for as much as 5 times the usual life span. A new trend in hard coating application leads to the coating of entire parts. The deposition of hard coatings on dies is just one example in this matter.

The substrate materials used in dies (usually hot working steels) have a typical tempering temperature of about 550°C, see Fig. 1 [1]. Deposition processes like CVD take place at typical deposition temperatures in the range of 800-1200°C. The CVD process therefore proves to be unsuitable for applications on die materials. It would lead to an ultra hard coating on a relatively soft substrate, and could thereby lead to a spalling of the coating, due to the lack of support by the substrate. An additional quenching would be a possibility to solve the tempering effect during deposition, but could cause problems concerning shape tolerances, especially if the width to length ratio of the tools exceeds 1:10 [2].

These properties led to the focus on low temperature deposition processes like PECVD [3] and PVD. This paper will focus on the characterisation of
Arc Ion Plating (AIP) PVD coatings, with respect to their suitability for aluminium die casting application.

**PVD- PROCESSES**

PVD-processes can be divided in three main principals [4]

- Arc Ion Plating Physical Vapour Deposition (AIP)
- Magnetron Sputter Ion Plating Physical Vapour Deposition (MSIP)
- Electron Beam Physical Vapour Deposition (EB)

All these processes have one principle in common, which is the physical character of the process in which a coating system is formed. The differences between these principals are based on the way the target (material containing the basic material needed for building a coating) materials are evaporated. In AIP the target material is evaporated by means of an arc and thereby creating a highly ionised ion flux of target material. The MSIP principal uses the impulse of an inert gas to evaporate material from the target. And finally the EB-PVD-Process uses accelerated electrons to heat up the target material to an extent which will cause the material to evaporate.

The AIP process, Fig. 2, is the focus of this paper, because this process allows to adjust a high compressive residual stress within the substrate sur-
faces by means of a coating. The high residual stress is beneficiary, in case a substrate is exposed to high alternating tensile stresses of mechanical or thermo mechanical nature.

WEAR MECHANISMS ON DIES

Wear on a dies’ surface is, of course, an unwanted effect and has to be reduced as far as possible. To a certain extent wear can be excepted if the products produced with that same die, do not cause problems with required tolerances concerning shape and dimensions or surface roughness. In order to reduce wear, wear mechanisms in die casting first have to be investigated to develop a coating which offers maximum protection to a die [5, 6, 7, 8, 9].

Three main mechanisms of wear on a die’s surface can be differentiated:

- abrasive wear
- physical corrosion by the melt
- thermal fatigue of the surface

These wear mechanisms are not strictly segregated, but usually occur in combinations, which lead to a more complex overall wear mechanism.

The abrasive wear mechanism is caused by the enclosed hard materials like silicates which are often used in aluminium alloys to enhance the mechanical properties of the product. The hard particles encapsulated in the aluminium melt matrix put an intensive strain on a dies’ surface and cause abrasive wear. But due to the low filling velocities (40 m/s on average), which is related to the high latent heat of fusion for aluminium, this abrasive wear mechanism is therefore moderate in aluminium pressure die casting. Where as zinc die casting processes reach filling velocities of up to 200 m/s, thus abrasive wear causes a true problem and requires hard coatings with good adhesive strengths.

Aluminium, as mentioned earlier, owns a high latent heat of fusion, which can be illustrated with the following example. In order to melt 1 kg of pure aluminium a energy of $4.0 \times 10^2$ kJ is needed. In comparison zinc needs an energy of $1.1 \times 10^2$ kJ. Due to these properties of aluminium the moulds are exposed to the aluminium melt for a substantially long period of time, because solidification is slow. This effect can lead to a dissolving of the mould’s material in the melt, initiating the wear mechanism called melt
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Corrosion. Except the damage to the die, it can lead to soldering and thereby to machine down time and waste products.

In order to solidify the aluminium, a lot of heat has to be drawn out of the part and into the die. To cool down the die rapidly mould release agents are often used, which usually own a large amount of water. The evaporation then leads to a massive cooling of the die's surface. Temperature gradients invoke thermal crackings or more popularly known as heat checking. Close to the die's surface the yielding point is then exceeded, leading to cracks in the surface.

**PROTECTION OFFERED BY PVD AIP COATINGS**

The investigated coatings are produced in an AIP PVD Process which allows growing PVD coatings that offer the following properties:

- good thermal stability
- good chemical stability
- high hardness
- protection against abrasive wear
- high residual compressive stress
- good adhesive strength
- no significant influence on the heat transfer

The good thermal and chemical stability offers an excellent protection against the aggressive melts used in aluminium die casting. In order to investigate the corrosion behaviour in an aluminium melt a material screening was carried out in preliminary investigations [10] and more recently a material screening for magnesium die casting is taking place, where TiAlN coatings seem to have a most promising corrosion behaviour. Prior to dip tests in an aluminium melt, coatings were screened by their phase diagrams and solubility of the coating's base materials. Results of these preliminary investigations showed that chromium based coatings can offer a good protection against aluminium melts. Common chromium based coatings like CrN and CrC are commercially available coating systems and can protect a die. However CrAlN coatings show an improved hardness and their soldering
behaviour was enhanced when compared to other chromium based coatings. Therefore a CrAlN coating is the focus of this paper. The hardness of a PVD coating is a parameter which can be adjusted to offer a die maximum protection against abrasive wear. A good adhesive strength is important in all PVD applications. A coating with little or no adhesive strength, but a high hardness, does not offer any protection to a substrate at all. Therefore tests revealing the adhesive strength of coating should be investigated. Although the thermal conductivity of PVD coatings is generally low, coatings do not show any signs of an obstruction in the heat transfer. The reason for this is given by the fact that the applied coatings are very thin.

EXPERIMENTALS

The samples were coated at various deposition times with CrAlN coatings. After deposition, they were characterised with respect to their thickness (calo-test), hardness (HV0.05 and nanoindentation), adhesion (scratch tester), residual stress (bending stripe method and x-ray diffraction), thermal fatigue resistance (thermal cycling test), surface roughness (perthometer and laser profile meter), corrosion tests (against aluminium melt and potential curves with release agent solution) and there structure (SEM scanning electron microscopy). To present all gained data of these tests would exceed the size of this paper, so only the main failure mechanism in die casting of aluminium, which is heat checking was investigated more closely.

THERMAL CYCLING TEST

To simulate the surface conditions of a die, the samples were exposed to a thermal fatigue cycling test, which allows an adjustable thermal gradient. The samples were heated with a carbon dioxide laser with an eight mm focus width up to a temperature of 700°C, then cooled with water, and afterwards dried with compressed air. The required gradient was adjusted by calibration samples. Timing parameters were adjusted in such a way, that a lower temperature limit of 180°C was reached after drying. The cycle sequence is shown in Fig. 3. The amount of cycles were a 100 in total.

SURFACE ROUGHNESS

The roughness of the surface was investigated before and after the thermal cycling tests. Before thermal cycling tests, and after being coated, all
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Figure 3. Temperature/time chart of thermal cycling test.

samples showed a surface roughness of about 0.2 µm RMS. The influence of a PVD coating on a substrate exposed to a thermal fatigue cycling test can be seen in Fig. 4 below. The figure to the left shows an uncoated substrate after 100 thermal cycles. The figure to the right shows a 3.7 µm thick CrAlN coating. The different behaviour of the coatings becomes obvious, when comparing these 3D surface roughness plots. These plots give an impression of the macroscopic behaviour of the substrates surface, with and without residual compressive stresses. Minor cracks can not be detected with this method, but the surface roughness plot clearly shows a wavelike pattern, when not being coated.

SEM (SCANNING ELECTRON MICROSCOPY)

Although the 3D surface roughness plots show a smooth surface in comparison to the untreated sample, SEM (Fig. 5) is able to reveal minor cracks in the surface of a coated substrate (left figure) which is a 2.5 µm thick CrAlN coating. The right figure shows a 12.4 µm thick CrAlN coating. The surface does not show any cracks at all. Both figures were taken in the laser’s focal point. The impurities which seem to be part of the coating, is debris caused by the thermal cycling test.
RESIDUAL COMPRESSIVE STRESS

The exact absolute determination of residual stresses in PVD coatings remains difficult. In order to determine these residual stresses a bending strip method was used and calculated by Senderhoff’s equation. The coating’s Young’s modulus, which is used in Senderhoff’s equation, was obtained in nanoindentation. A more detailed description concerning validity and the use of Senderhoff’s method can be found in the literature [?]. Results of the
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residual stress analysis using Senderhoff’s equation are shown in the Fig. 6 below.

![Figure 6. Residual compressive stress versus CrAlN film thickness.](image)

To compare the influence of coating thickness with the amount of thermal cracking within the samples’ surface, figures of light microscopy are added, see Fig. 7. The five samples were all exposed to the earlier described thermal cycling test and figures were taken in the center of the laser’s focal point. With growing film thickness cracks become fewer and larger in size until a point is reached where finally no cracks are visible (coating thickness > 12.4 µm and a residual compressive stress > 6.25 GPa).

**CONCLUSIONS**

The investigated PVD coatings show a substantial decrease in heat checking with growing film thickness and preliminary investigations have already showed an increase in life span of dies. Mainly high compressive residual stresses are responsible for this effect and therefore an increase in these kind of stresses would be desirable. However the amount of residual compressive stress is limited to a height in which spontaneous spalling will occur, thus leading to local imperfections in the coatings’ surface. The increase in this residual stress can also be achieved by other parameters of the substrate than
Figure 7. Influence of coating thickness on the amount of thermal cracking of CrAlN coated specimens (light microscopy).
increasing the film thickness. The decrease in deposition pressure or the increase in bias voltage are ways to achieve this. However these solutions on their turn create new problems, which are not desirable in a PVD coating. The substrates in this paper were all polished and planar and therefore do not take any geometric aspects into consideration. First, coatings on real moulds showed that a high bias voltage applied on a substrate can lead to spalling near edges, a decrease in bias voltage was able to avoid this effect. Secondly, blind holes should not exceed a certain ratio. Origin for this ratio is the property of the PVD process, which will always show a line of sight character, meaning that deep blind holes will not be fully covered with the coating. Conclusively it can be stated that PVD coatings can substantially reduce several wear mechanisms at a time. The potential of PVD can be fully used provided that the right choice of coating material is made. Industrial praxis shows that too often some regular coatings are applied on dies, with the result of no life time increasement at all. This then leads to a discarding of the entire industry.

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