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THE ROLE OF PECVD HARD COATINGS ON THE PERFORMANCE OF INDUSTRIAL TOOLS

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Abstract

The advantages of the application of hard coatings, which are well knownfor cutting tools, are to a much lesser extent explored for casting, extrusion, molding and forming tools. Increasing the lifetime of these tools is an important task in surface engineering because of complex loading conditionsand often complicated tool geometry. The plasma-enhanced chemical vapor deposition (PECVD) technique is well suited to deposit hard coatings onto large dies and moulds. The aim of this study **was** to discuss deposition processes suitable for coating of the often large three-dimensional molds and dies used in metal forming. Furthermore, results obtained using different hard coatings in industrial applications for several case studies like aluminum pressure die-casting; plastics injection molding and sheet metal forming are presented and discussed. For best coating performance, a careful optimization of both substrate pre-treatment and coating deposition is necessary. The plasma-enhanced chemical vapor deposition (PECVD) technique shows advantages for these applications because of the high flexibility in pre-treatment using chemical etching and plasma-nitriding, because of its ability to coat large complexly shaped tools and because of the possibility of deposition of low-chlorine containing low-friction coatings.
Keywords: PECVD coatings; Aluminum die casting; surface engineering; Sheet metal forming.

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1. Introduction

The advantages of the application of hard coatings, which are well known for cutting tools, are to a much lesser extent explored for forming tools [1-2]. Wear of the mold or die not only results in low lifetime, but also in intolerable surface conditions of the product [3]. In recent years, heavy demands for lower costs, increasing productivity and product quality also stimulated the development of hard coatings for these applications. However, although being an important task in surface engineering, increasing thelifetime of these tools is often difficult because of complex loading conditions and often complicated tool geometry.

These peculiarities impose very specific requirements on the deposition process itself.In the first part of this work, techniques suitable for the deposition of hard coatings on molds and dies and their specific limitations are described.

This work gives a comprehensive survey on hard coatings and their application to various forming processes.

2. Industrial deposition techniques for molds and dies

Industrial implementation of hard wear-resistant coatings started with chemical vapor deposition (CVD) about 30 years ago [4]. The process temperature which is in the range between 800 and 1000^{O}C limits this technique to thermally stable materials**,** like cemented carbides**. S**ometimes steel tools of relatively low tolerances, where the risk of dimensional changes after coating and subsequent heat treatment is low, might also be coated by CVD.The development of physical vapor deposition (PVD) processes in the 80-ies boosted coating of high speed and hot work tool steels because deposition temperatures usually do not exceed 500^{O}C**,** which is below the tempering temperature of these steels. However, since their low operating pressures (usually between 0.1 and 1 Pa) make PVD methods line-of-sight processes [5], substrate rotation is necessary to obtain homogeneous and uniform coatings.

The deposition of hard coatings onto molds and dies used e.g. in pressure die casting, plastics injection molding or sheet metal forming differs to a large extent from coating of many cutting tools, e.g. cemented carbide inserts or drills, because of the following reasons:

1-The costs for these dies and molds are often extremely high. Depending on the complexity of the part being produced, a die may cost more than $100 000 [2]. In many cases, these high costs are significant handicaps for the optimization of hard coatings, because of the possible high risks for the customer.

2-These molds often show complicated three-dimensional shapes with large numbers of cooling channels or cavities. Their weight often reaches several hundreds of kilograms and size exceeds several tens of centimeters in two dimensions [6], which make substrate rotation in PVD processes difficult.

3-Complicated tool geometries are often manufactured using spark erosion, resulting in a quenched defect zone on the surface (the so called white layer), which often negatively affects adhesion of PVD coatings [7, 8, 9].

4-For several molding and casting processes, hot work tool steels with relatively low hardness, i.e. in the range of 29 to 48 HRC are used [10, 11], giving rise to insufficient load support of the hard coating.

5-In many cases, e.g. plastics injection molding, tools have to be coated after they have been in contact with molten plastics due to necessary run-in procedures performed by the customer [7]. Often, the coating process is also part of the refurbishing procedure of expensive tools which means that in addition to adhered material cooling channels might be rusty or filled with water. These residuals might de-**gassed** during heating in the vacuum chamber of a PVD plant, which can be assumed to have a negative influence on coating adhesion. Removal of the adherent residuals without damage of the die is often difficult and requires sophisticated know-how of the job-coater.

To overcome some of these problems, the plasma assisted chemical vapor deposition (PECVD) technique tries to combine some of the advantages of both CVD and PVD techniques. Typically, the operating pressure is in the range of several tens to hundreds of Pa which allows coating of big and heavy tools without rotation. The higher pressure can also be assumed to reduce de-gassing times during heating, as compared with PVD processes. At present, the maximum size of PACVD chambers is Ø1000×1800 mm, and casting dies with a volume of 520×520×300 mm^3 and a weight of several hundreds of kilograms have been routinely coated [6]. The deposition temperature in PECVD is typically in the range between 480 and 510^{o}C [2, 6] which makes this technique suitable for coating of steel substrates. For pre-treatment of the tools, the surface can be cleaned using combined sputtering and chemical etching. Another advantage of PECVD is that the load support of relatively soft hot work tool steels could be relatively easily enhanced using plasma nitriding prior to coating deposition. This has been shown in an earlier paper [14] to significantly enhance coating adhesion and fatigue limit. From the above, one can conclude that these characteristics of the PECVD process should make this technique ideally suited for coating of the large and complexly shaped tools used in casting, molding or sheet metal forming.

3. Practical examples from coating development

3.1. Aluminum pressure dies casting

During the last years, several hundreds of cores and dies for aluminum pressure die casting have been coated and tested in foundries. In aluminum die casting, the hard coating primarily has to reduce erosion, corrosion and soldering due to the liquid aluminum. Another benefit of applying hard coatings could be the usual compressive stresses which might increase the thermal fatigue limit of near-surface zones of the die [2, 3]. Thus, to achieve an optimum performance, adhesion, hardness, soldering behavior, oxidation resistance and stress state have to be carefully optimized, before big and heavy dies can be coated. The performance of cores coated with different PECVD PLASTIT coatings in pressure die casting is summarized in Fig. 1, where the end of lifetime is determined by heavy soldering of aluminum or insufficient surface quality of the casting.

Compared to the Tenifer treatment (which is the standard treatment for cores and dies for aluminum die casting), the increase in lifetime was up to 300 % for Ti(C,N) coatings. The higher service life of Ti(C,N) coated cores compared to TiN coated ones could be related to the onset of oxidation of these coatings, which occurs in the temperature range of aluminum die casting. Ti(C,N) shows lower oxidation resistance than TiN, i.e. Ti(C,N) coatings are oxidized after a significantly lower exposure time [2, 3], resulting in the formation of a less-reactive oxide surface on top of the coating.

Figure 2 shows a Ti(C,N) coated die used for pressure die casting of an oil pump housing made of $AlSi_9Cu_3$. The size of the die made of AISI H13 hot work**ed** steel is 450×450×200 $mm^3$and the weight approximately 200 kg.

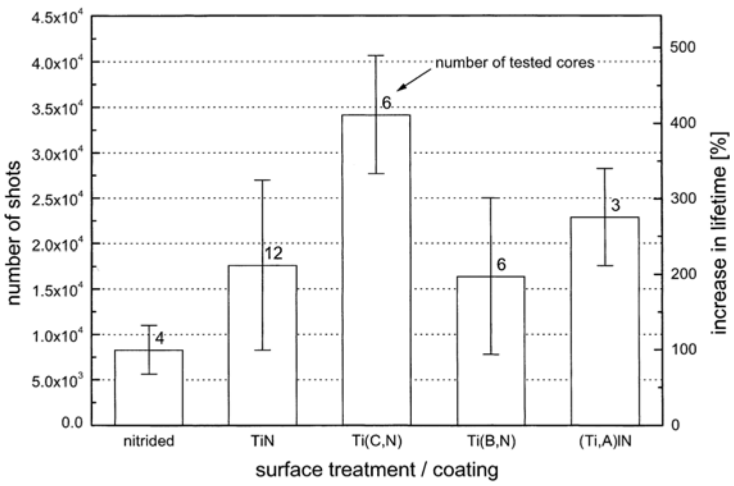


Figure 1.Number of shots achieved in aluminum pressure dies casting for cores of oil pump housing for nitriding and different PECVD coatings. The end of the lifetime is determined by insufficient surface quality of the casting.

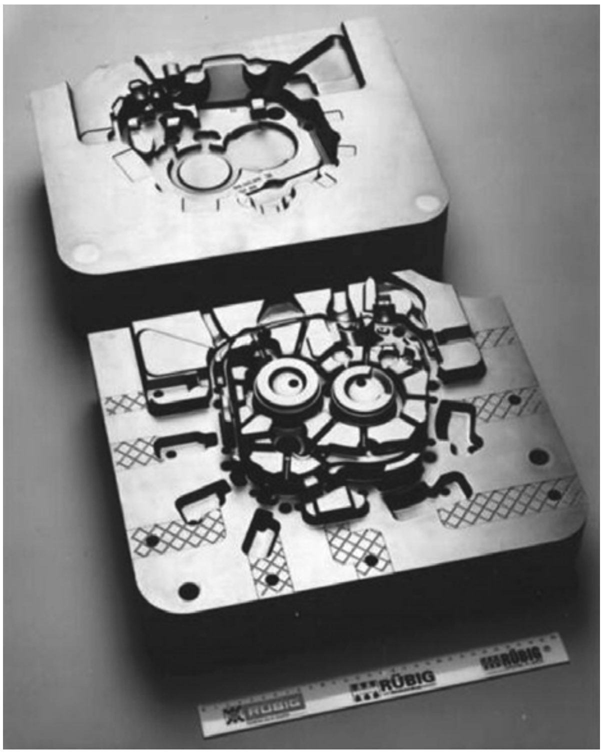


*Figure 2. PECVD Ti(C,N) coated die (AISI H13 hot work**ed** steel) for aluminum pressure die casting of an oil pump housing.*

Uncoated, Tenifer treated molds showed first heat checks already after 8500 shots. In addition, the surface roughness increased steadily till after about 50000 shots; more than 60% of the casting showed a roughness Ra of more than 10 μm. After the same number of shots, erosion had caused increasing rounding of the die contour at the feeder side; at the ejector die half the material loss was locally higher than 1 mm. The practical experience for coated molds and dies showed a slightly higher tendency to soldering during the first shots (using the same conditions for applying lubricating and parting compounds as for uncoated dies), although cleaning and removal of soldered aluminum was required from time to time. However, after a few hundreds of shots the soldering tendency was significantly lower compared to the uncoated die which could be related to the onset of oxidation. More than 45000 shots could be made without interruption of the casting process for maintenance of the mold, thus enabling a more continuous production.

The number of shots achieved before the first refurbishing and re-coating was necessary after about 65000, and the total number of shots was higher than 160 000.

3.2. Plastics injection molding

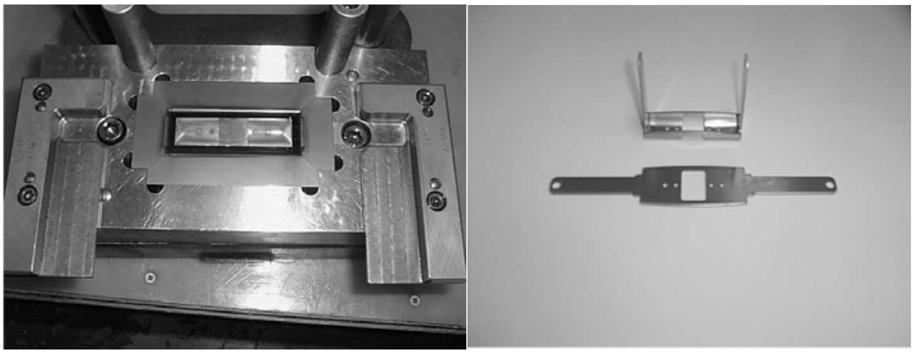
In plastics injection molding, wear of the molds occurs due to corrosion caused by exhaust gases or decomposition products, abrasion from the flow of material in contact with tool surfaces, adhesion between tool surface and molten material and due to the thermo-mechanical loads applied [12]. Increasing wear results in intolerable surface quality of the part, filling and release problems. An industrial application**,** where the surface quality is extremely important, is the production of reflectors for automotive headlamps, made of polyetherimide (PEI, ULTEM 1010). Figure 3 shows such a mold coated with Ti(C,N). Without coating, the mold had to be polished manually after a few hours of operation. With a Ti(C,N) coating, the adhesion tendency of PEI could be significantly reduced [15, 16, 17] and the service life without polishing was increased to more than one week.

Figure 3.PECVD Ti(C,N) coated injection mold (AISI H11 hot work steel) for an automotive headlamp.

3.3. Sheet metal forming

In sheet metal forming, the main wear mechanisms have been identified as adhesive wear due to the high loads applied, abrasive wear by highly strain-hardened wear debris, and mechanical fatigue due to cyclic loading [18]. To meet these requirements, it is essential that the interface between coating and cold work**ed** steel is appropriately designed to yield an optimum mechanical support of the coating. This may be done using plasma nitriding prior to deposition [14].

Another important task in surface engineering for sheet metal forming processes is the reduction of frictional forces between metal sheet and die [19] which is normally done using lubricants like chlorinated paraffin’s. It has been pointed out by several authors that hard coatings like TiN or CrN [20, 21] are well suited to reduce these hazardous lubricants. A Ti(C,N) coated tool for sheet metal forming of a cold-strip steel, and a part produced **using this tool** are shown in Fig. 4.



(a) (b)

*Figure 4. PECVD Ti(C,N) coated forming tool (AISI A11 cold- work**ed** steel) and parts produced using this tool.*

The uncoated tool made of AISI A11 cold-worked steel was lubricated every 20 strokes by a brush, and the forming radius had to be cleaned continuously. After a maximum of 2000 parts, the tool had to be disassembled for thorough cleaning and re-polishing. By applying a PECVD Ti(C,N) coating, brush lubrication could be reduced to every 50 strokes, and 26000 parts could be produced without cleaning until the test was stopped due to the limited production quantity. This remarkable result may be explained by the low friction coefficients of these coatings. Figure 5 shows a typical friction curve for room temperature ball-on-disc testing of an unalloyed steel ball against a TiN coated disc (load, 2 N; sliding speed, 10 cm/s; relative humidity, 35 %).

It can be seen that the friction coefficient drops to very low values of about 0.16 after a running-in period of about 300 m. This low coefficient of friction appears to be related to a small amount of chlorine in this coating which facilitates the formation of an interfacial lubricating film [22, 23, 24]. This makes PECVD TiN based coatings an alternative to DLC coatings and promising candidates for sheet metal forming with reduced lubricants.

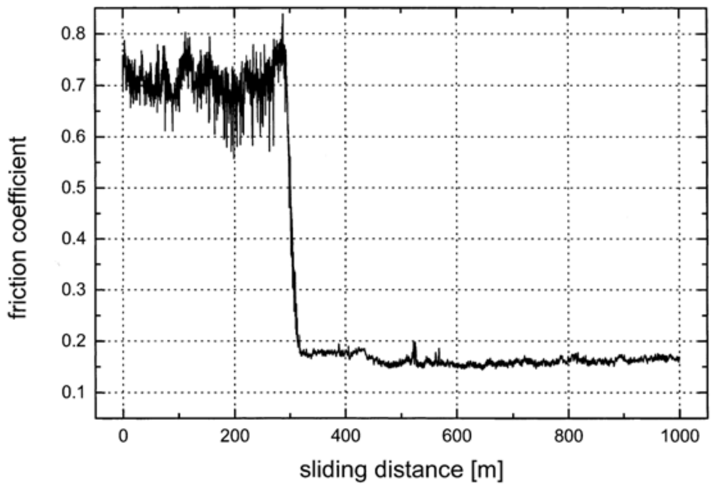


Figure. 5. Dependence of the friction coefficient of an unalloyed steel ball sliding against a PACVD TiN coated disc on the sliding distance (normal load, 2 N; sliding speed 10 cm/s; relative humidity, 35%).

Conclusions

Within this work it has been shown that the PECVD technique is well suited to increase the lifetime of different tools used for forming processes.These benefits are essentially based on the effects of possible combining of pre-treatments methods like sputtering and chemical etching with plasma-nitriding, on the ability to homogeneously coat large three-dimensional tools. This process may be performed without substrate rotation due to the development of new low friction TiN-based hard coatings with low chlorine contents. Several case studies on industrial application of these coatings in aluminum pressure die casting, plastics injection molding and sheet metal forming have proved that the lifetime of dies and molds could be increased by factors between 2 and 13. In addition, the surface quality of the parts being produced could be improved due to reduced adhesion. In metal forming, the usage of hazardous lubricants could also be reduced.The aim of future developments in the field of PACVD coatings will be to up-scale the process to even bigger tools, to expand the spectrum of coatings available and to explore new applications in the field of forming processes.

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