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RESEARCH

Ejection Performance of Coated Core Pins Intended for Application on High Pressure Die Casting Tools for Aluminium Alloys Processing

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A B S T R A C T

In high pressure die casting (HPDC) process of aluminium alloys cast alloy soldering severely damages tool surfaces. It hampers casting ejection, reduces the casting quality and decreases the overall production efficiency. Thin ceramic PVD (physical vapor deposition) coatings applied on tool surfaces successfully reduce these effects. However, their performance is still not recognised for surfaces with various topographies. In this investigation, soldering tendency of Al-Si-Cu alloy toward EN X27CrMoV51 steel, plasma nitrided steel, CrN and TiAlN duplex PVD coatings is evaluated using ejection test. The coatings were prepared to a range of surface roughness and topographies. After the tests sample surfaces were analysed by different microscopy techniques and profilometry. It was found that the ejection performance is independent of the chemical composition of investigated materials. After the ejection, the cast alloy soldering layer was found on surfaces of all tested materials. This built-up layer formed by effects of mechanical soldering, without corrosion reactions. Coated samples displayed a pronounced dependence of ejection force on surface roughness and topography. By decreasing roughness, ejection force increased, which is a consequence of intensified adhesion effects. Presented findings are a novel information important for efficient application of PVD coatings intendent for protection of HPDC tools.

1. INTRODUCTION

In production of aluminium alloy castings by HPDC process the tool surfaces are exposed to harsh operating environment [1]. Although, these effects are reduced by application of die lubricant the tool surfaces wear due to erosion, soldering and thermal fatigue, which commonly act simultaneously [1,2]. Due to wear, tool operation becomes difficult, production efficiency is reduced, castings lose tolerances and quality of their surface finish is reduced [3]. By continuing the production with worn tools both castings and tools integrities are endangered [4].

Nowadays the cast alloy soldering becomes a major concern in the industry [3]. Therefore, diffusion layers, thin ceramic coatings and their combinations are applied for increasing the wear resistance of HPDC tools [1,2]. Coatings produced by physical vapor deposition (PVD) have a range of required mechanical properties and high chemical inertness in molten metals [1,2,5]. Ceramic coatings efficiently suppress different types of wear and especially the corrosion caused by molten aluminium [1,5]. However, PVD coatings are also prone to formation of cast alloy built-up layer (sticking) on their surfaces [3]. Such cast alloy built-up layer hampers the castings ejection and increase the tool maintenance. Therefore, it is essential to further investigate and develop PVD coatings tailored for application on HPDC tools.

In this study ejection test is employed for the evaluation of soldering (sticking) tendency of Al-Si-Cu alloy toward EN X27CrMoV51 (AISI H11) steel, plasma nitrided EN X27CrMoV51 steel, CrN and TiAlN duplex PVD coatings. The effects of surface roughness on the performance of duplex coated samples are detailly evaluated.

2. EXPERIMENTAL

Investigation concerned quenched and tempered EN X27CrMoV51 hot-working tool steel, plasma nitrided EN X27CrMoV51 steel, CrN and TiAlN PVD coatings produced as duplex layers on plasma nitrided samples. Cylindrical pin-shaped samples (ϕ15×100 mm) were produced by procedures regularly employed in production of HPDC tool parts (Fig. 1a).

Plasma nitriding was performed using ION-25I (IonTech) unit, CrN coating was deposited by BAI730 (Balzers) unit and TiAlN coating by CC800/7 (CemeCon) unbalanced magnetron sputtering system. In order to accurately compare the performance of different materials, samples were produced applying the same surface finishing treatments. However, the coated samples were prepared with two additional degrees of surface roughness. Samples used in this investigation are denoted as follows: EN X27CrMoV51 steel samples as H11, plasma nitrided samples as PN, PVD coated samples were denoted with their types as CrN and TiAlN respectively. Additionally, suffixes are added after sample names to distinguish the samples with different surface roughness: rough-R; smooth-S; post deposition polished-PP.

Cast alloy soldering (sticking) tendency was practically evaluated by ejection test. In this test, pin sample is used as a core for production of simple casting with a hole (Figs. 1b and 1c). As a result of a casting process a pin-casting assembly is obtained (Fig. 1c). Using a tensile testing machine ZDM 5/91 (VEB) the pin sample is ejected from the casting and a force displacement curve is recorded (ejection curve). This test imitates the process of core removal from a casting produced by HPDC technology. Therefore, the force recorded during the test carry information about the soldering tendency of cast alloy toward the investigated material. Ejection tests were performed with three-time repetitions of every sample type.

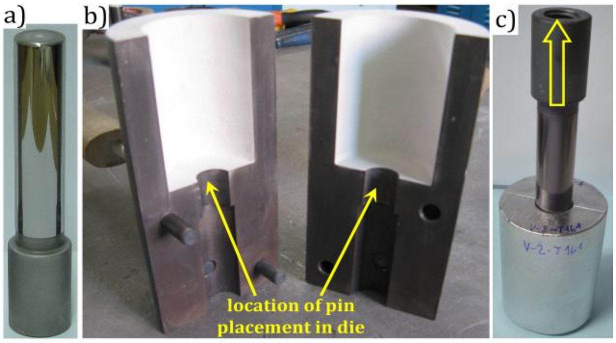

Fig. 1. Experimental setup: a) Pin sample, b) experimental casting die, c) pin-casting assembly.

Casting process was performed by gravity melt pouring of EN AC-46200 alloy, at temperature of 730 °C, into a specially designed steel die (Figure 1b), preheated to temperature of 320 °C. After each casting (solidification) cycle, the process is repeated for next sample.

Surface topography of samples was acquired by 3-D-profilometer (Taylor Hobson Talysurf). Instrumented hardness tester H100C (Fischerscope) was employed for the evaluation of mechanical properties of layers and thin coatings, employing 100 mN indentation loads. After the ejection tests, samples surfaces were evaluated by confocal optical microscope Axio CSM700 (Zeiss).

3. RESULTS AND DISCUSSION

All samples were produced of quenched and tempered EN X27CrMoV51 hot working tool steel with hardness of 455 HV_{30}. For plasma nitrided samples a maximal surface hardness of 1300 $HV_{0.01}$

was achieved, while the CrN and TiAlN coatings had 2575 $HV_{0.0025}$ and 3600 $HV_{0.0025}$ respectively. The hardness of investigated layers and coatings are appropriate for application on HPDC tools with increased wear resistance. Surface roughness parameters of all investigated samples are presented in Table 1. Roughness of all investigated samples belongs to the range of low surface roughness. In Table 1 samples having nearly the same roughness are circled with dashed lines.

Table 1. Average values of surface roughness parameters of investigated samples.

Sample group	R_a [μm]	R_{sk}	S_{dr} [%]
Rough samples (R)			
CrN-R	0.145	-0.179	0.055
TiAlN-R	0.153	0.990	0.157
Smooth samples (S)			
H11-S	0.198	-0.889	0.039
PN-S	0.183	-0.026	0.075
CrN-S	0.032	0.491	0.021
TiAlN-S	0.059	4.562	0.363
Post deposition polished samples (PP)			
CrN-PP	0.027	-1.162	0.020
TiAlN-PP	0.059	-0.947	0.016

Average values of maximal ejection force obtained for samples with comparable roughness are for different materials presented in Fig. 2. Generally, values of measurement standard deviations (SD) are averagely less than 10 % of a measured value, which indicate a satisfactory experimental repeatability for this kind of examinations.

A small difference in ejection force, which is observed for investigated materials, falls in the range of test deviations. This means that investigated materials have nearly the same value of ejection force and the same soldering tendency Al-Si-Cu alloy. Therefore, the casting ejection performance from the HPDC tool with a PVD coating would be the same as from those made of X27CrMoV51 steel.

Such finding is not in agreement with results published so far in literature, as in papers [1], [2]. In their case, a considerably higher force was recorded for X27CrMoV51 steel and plasma nitrided X27CrMoV51 steel than for PVD coated samples. However, in these investigations the comparison between materials is not made on samples with the same roughness. Considering that surface topography affects the initial pin-casting interlocking conditions and the tribological performance during sliding [3], disregarding its influence could lead to inaccurate results interpretations. The effect of surface roughness on the ejection performance is in more detail elaborated by results obtained for coated samples with different roughness.

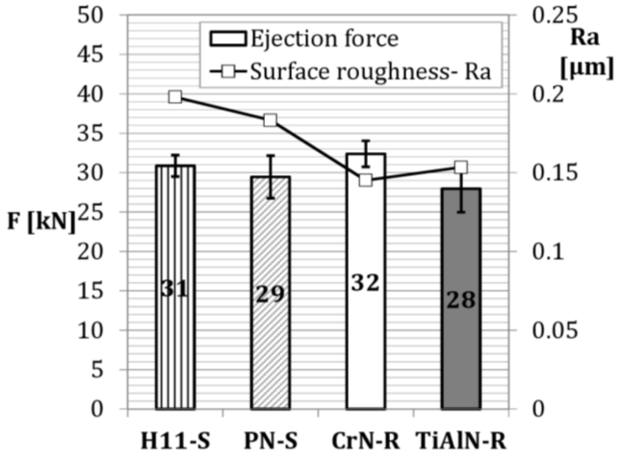

Fig. 2. Average values of maximal ejection force recorded for different pin materials, error bars represent ±1 SD.

Surface morphology of pin samples after the ejection tests holds qualitative information about the soldering tendency of cast alloy toward pin material and galling processes that develop during the pin ejection. Macroscopic appearance of samples and confocal optical microscopy (CFM) images of surfaces with built-up layer are presented in Fig. 3.

The cast alloy built-up layer is present on the surfaces of all investigated materials. It is distributed mostly inside the pronounced grinding marks, cavities, around asperities or coatings nodular defects (circled areas in Fig. 3b). For H11, CrN and TiAlN rough samples the built-up typically agglomerates inside grinding grooves. This is not typical for PN samples where the built-up distributes in form of lumps around asperities on the surface. For coated samples, the built-up piles up around the nodular defects and on the sides of cavity defects. This suggests that both kind of coating defects (surface irregularities) have their own effect on distribution of cast alloy on pin surfaces. During ejection, nodular defects plough through the casting material and aggregate the cast alloy in front of them (detail for CrN in Fig. 3b).

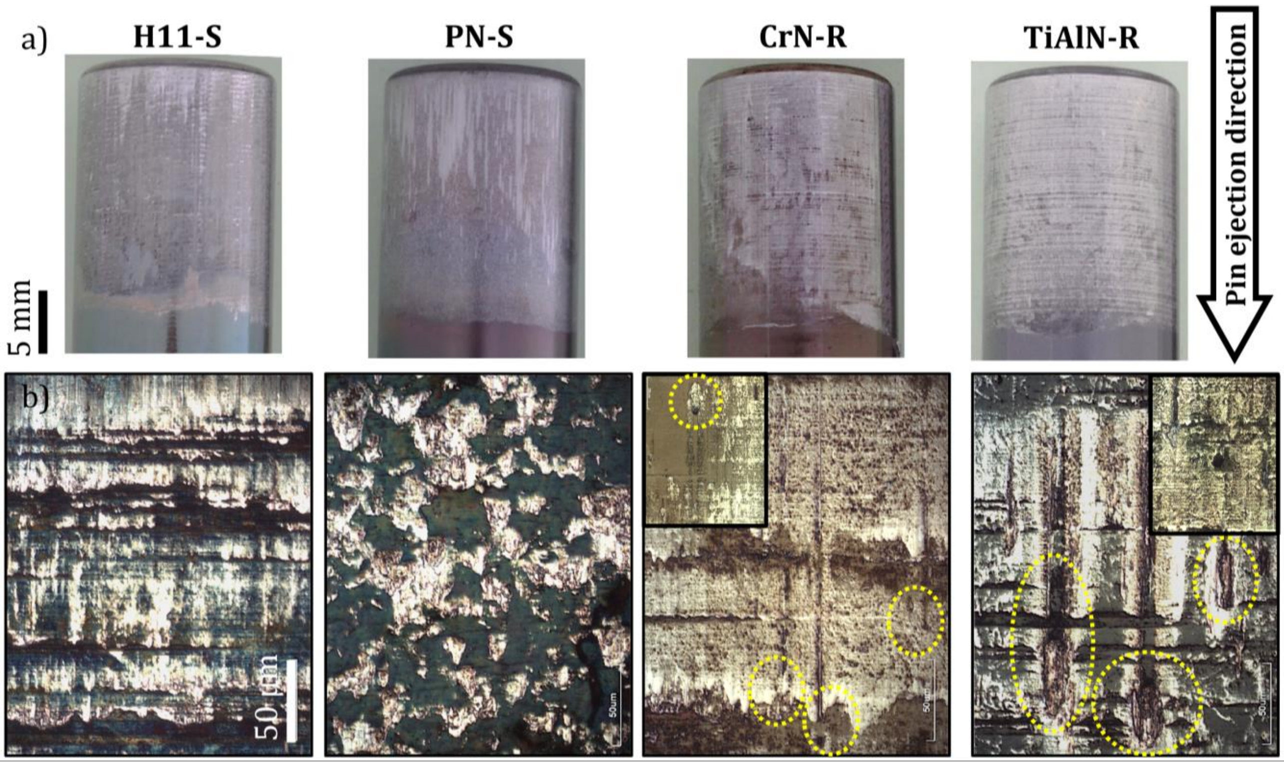

Fig. 3. Appearance of the samples with built-up layer, a) macroscopic images, b) confocal optical microscopy images of pin areas submerged 5 mm in the casting, image inserts are with higher magnification; areas circled with dashed lines are typical locations around coating growth defects.

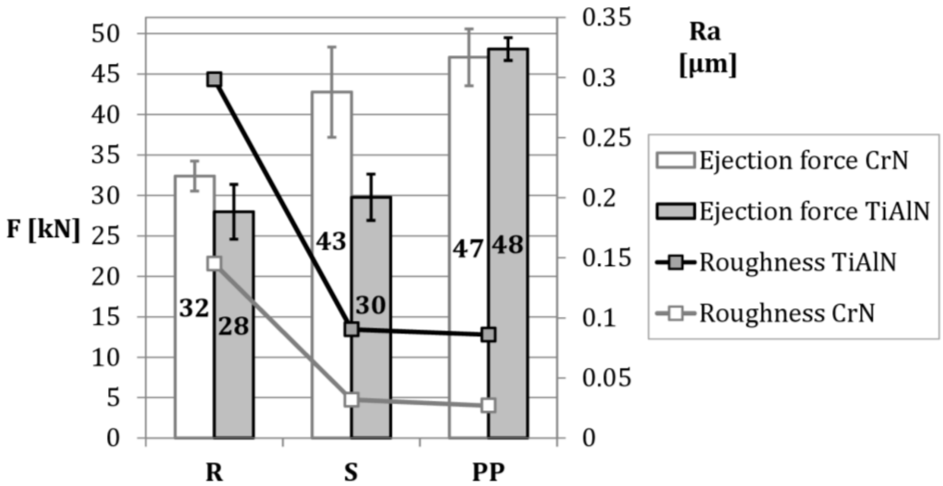

Fig. 4. Average values of ejection force recorded for coated samples (CrN, TiAlN) prepared to a different degree of surface roughness, error bars represent ± 1 measurement standard deviations.

On the other side, the cast alloy present in cavities, or in coating pinholes, is cut off the casting due to the shear stresses generated on pin-casting interface during the ejection process. During ejection process both surface features have distinct effect on the stress concentration in casting material, friction force and accordingly on the values of the ejection force [3].

After examinations, the cast alloy was dissolved by NaOH solution and no remnants of built-up layer remained on the surfaces. This indicates that a condition in the employed test promotes only the effects of mechanical soldering (sticking).

Further, the investigation is directed toward performance evaluation of hard nitride coatings, as these are materials with highest corrosion resistance and great importance for practical application on HPDC tools. A special attention is given to the influence of surface roughness on their ejection performance. The maximal ejection force measured for coated samples with different surface roughness are presented in Fig. 4. It can be seen, that decrease in average surface roughness (R_a) induces a considerable increase of ejection force. The highest values of ejection force were recorded for post deposition polished samples of both kinds of coatings (CrN, TiAlN). However, a small difference in R_a parameter between the smooth (S) and the post polished (PP) samples resulted with a considerable difference in ejection force. This is a consequence of a large difference in surface morphology of these samples, which can be distinguished by other roughness parameters such as skewness (R_{sk}) and developed area ratio (S_{dr}) (Table 1, Fig. 4).

By examining the representative topographies of coated samples, shown in Figure 5, it is clear that a great difference exists between the smooth and post polished samples. Surfaces of smooth coatings are characterized by a large quantity of peaks (nodular coating defects) and accordingly high values of R_{sk} parameter, while the surfaces of post polished coatings are smooth, characterized by numerous cavities (wrenched defects) and accordingly negative values of R_{sk}. Surfaces of CrN coatings are generally smoother than of TiAlN coating. For CrN samples a decrease of roughness (R_a) is followed by almost gradual decrease of (R_{sk}) parameter and continuous increase of ejection force (Table 1, Fig. 5). On the other side for TiAlN coatings a somewhat different behaviour is observed. The TiAlN-S samples have lower R_a parameter than TiAlN-R samples, but a considerably higher R_{sk} parameter. Accordingly, the values of ejection force for TiAlN-S are almost similar as for the TiAlN-R samples.

Explanation concerning the revealed behaviour in ejection test could lie in the pin-casting interlocking conditions or in the nature of stress concentration that develops on the pin casting interface during ejection process. By cross sectional evaluations, not presented herein, it has been shown that casting exhibit a fully interlocked contact with CrN and TiAlN samples [6]. Therefore, it is concluded that the ejection force required for pin release depends predominantly on the stress conditions in the pin-casting contact during ejection. During the ejection process, asperities of rough surfaces (CrN-R, TiAlN-R, TiAlN-S) induce shear stress concentrations on the pin-casting interface, which consequently reduce the force required for the initial pin release. The morphology of the built-up layer around surface features as grinding marks and defects undoubtedly support this theory (Fig. 3). However, on very smooth surfaces (CrN-PP, TiAlN-PP), due to high tangential forces [7], adhesion is enhanced, a stress concentration does not excist and consequently higher forces are needed for pin release.

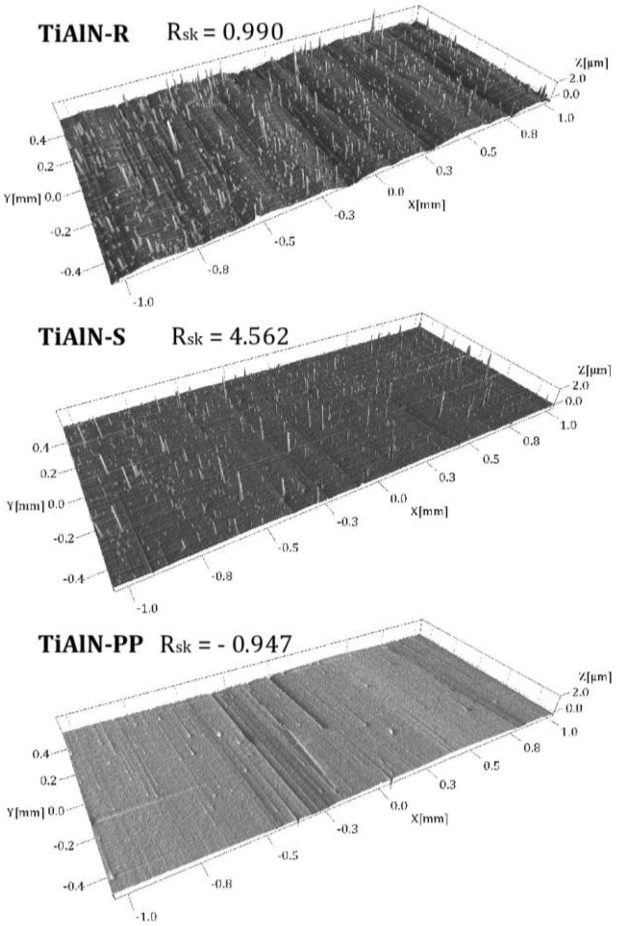

Fig. 5. Surface topography images of TiAlN coated samples.

Application of very smooth tool surfaces is beneficial for obtaining narrow casting tolerances and highest surface finishes [3]. However, considering the results of presented investigation, together with the fact that coatings provide adequate protection against effects of cast alloy, coatings with post polished (very smooth) surfaces are not beneficial for efficient application on a HPDC tools.

4. CONSLUCIONS

Presented investigation employed ejection test for evaluation of Al-Si-Cu alloy soldering tendency toward different tool materials, layers and PVD coatings intended for application on HPDC tools. The performance of PVD coating is evaluated on samples prepared to a range of surface roughness.

Mechanical characteristics of investigated plasma nitrided layer and duplex CrN and TiAlN coatings are adequate for the application on high performance HPDC tools.

For investigated materials, prepared to the same degree of surface roughness, it was found that the ejection force is independent of their surface chemical composition. This is a novel information which is revealed by considering the effect of surface roughness.

It was found that all investigated materials are prone to mechanical soldering by Al-Si-Cu alloy. The identified built-up layer of cast alloy formed by the effects of mechanical soldering.

The ejection performance of samples with CrN and TiAlN coating greatly depends on their surface roughness. The ejection force increases with decrease of their roughness. The highest values were recorded for post deposition polished surfaces for both kinds of coatings.

Performance of PVD coatings on HPDC tools, beside surface chemistry greatly rely on surface roughness and surface morphology of tool parts.

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