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STICKING AND GALLING PHENOMENA IN EJECTION PROCESS OF COATED CORE PINS FROM Al-Si-Cu ALLOY CASTING

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Abstract: *Wear of high pressure die casting (HPDC) tools used for processing of aluminum alloys is nowadays successfully reduced by application of physical vapor deposited (PVD) coatings. Although the coated tool parts are inert to cast alloy and resist erosion, their performance and endurance are dependent on cast alloy sticking and galling phenomena which occur during casting ejection. Considering that knowledge about these specific wear mechanisms is the driving force for development of coatings for HPDC tools, further research is required on this topic. To study wear phenomena of duplex CrN and TiAlN coatings in contact with Al-Si-Cu alloy ejection test is employed. The coatings were produced with different roughness. Before and after the tests, samples were evaluated by profilometry and different microscopy techniques. Cross sectional analyses of pin-casting assemblies revealed that pin and casting form a completely interlocked contact. Intermetallic phases of Al-Si-Cu alloy more intensively precipitate on the pin surfaces than the aluminum matrix. For both coatings it was found that the shape of the ejection curve and values of ejection force depend on the roughness of pin samples. After the ejection, as a result of sticking and galling, a thin layer of cast alloy remained on all investigated samples. Its morphology reveals the pin release mechanisms, sticking effects and type of sliding wear. For rough samples, as a result of ploughing and adhesion the cast alloy remained inside the grooves on the surface. Such release process requires less load but induce a stick slip effect that promotes adhesion. On smooth samples random islands of sticking layer are observed which mostly consist of Al-Si-Cu alloy intermetallic phases. On these samples, cast alloy agglomerates on nodular coating defects which promotes thickening of a built-up layer and wrenching of defects. The post polished samples exhibited the thinnest built-up but required the highest forces for ejection.*

Keywords: *HPDC, aluminum alloy, tool wear, PVD coating, surface roughness, sticking, galling*

1. INTRODUCTION

The erosion, corrosion, soldering and thermal fatigue wear of HPDC tools, for casting of aluminum alloys, is nowadays successfully reduced by application of duplex PVD coatings [1,2]. Although PVD hard coatings display high inertness to molten aluminum alloys, the cast alloy still sticks (mechanically or metallurgically) to coating surfaces. That process together with cast alloy galling cause difficulties in casting ejection and affect casting quality and productivity [3]. Therefore, proper exploitation and further development of these protective layers requires further research for deeper understanding of these wear phenomena. Surface topography controlled by pre and post treatment of coated surfaces greatly affect the performance, durability and cost of HPDC tools [1,3]. However, this topic is rarely addressed in the investigations from the field and it is even less concerned in industry.

Soldering can be evaluated by practical (industrial) and laboratory experiments [2,4]. Evaluation of coatings performance in industrial environment provides information about the specific production case (tool) [2]. However, it is usually not appropriate for analysis of a single wear mechanism [4]. On the other side, laboratory experiments allow isolation of specific wear mechanism, isolation of target parameters and better control of experimental conditions. Therefore, laboratory experiments are better suited for fundamental investigations of coatings wear mechanisms.

In this work the improved ejection test is employed for the evaluation of sticking and galling mechanisms of two the most used PVD coatings for HPDC tools (CrN, TiAlN), which were prepared to different roughnesses.

2. MATERIALS AND EXPERIMENTAL

Investigation concerned the performance of CrN and TiAlN PVD duplex coatings produced to a different degree of surface roughness. Cylindrical pin-shaped samples (ϕ15×100 mm) and disc samples (ϕ20×5 mm) were produced of quenched and tempered EN X27CrMoV51 hot-working tool steel (hardness of 42 HRC ± 1). Samples were prepared to three degrees of surface roughness by procedures regularly employed in production of HPDC tool parts. The steel samples were subjected to plasma nitriding which was followed by polishing (compound layer removal) and coating deposition. Plasma nitriding was performed using ION-25I (IonTech) unit, CrN coating was deposited by BAI730 (Balzers) termionic arc ion plating system and TiAlN coating by CC800/7 (CemeCon) unbalanced magnetron sputtering system. After coatings deposition a group of samples was subjected to post-deposition polishing. All polishing treatments were performed by 6 and 3 µm granulation diamond paste.

Sample denotation contains the type of the coatings (CrN or TiAlN) and suffixes which indicate the surface treatment of the samples: Rough-R; smooth-S; post deposition polished-PP.

Cast alloy soldering (sticking) tendency was evaluated by laboratory test, the improved ejection test. In this test, pin sample is used as a core for production of simple casting with a hole. Figure 1 schematically presents the employed test. As a result of a casting process a pin-casting assembly is obtained. Using a tensile testing machine ZDM 5/91 (VEB) the pin sample is ejected from the casting and a force displacement diagram is recorded (ejection curve). This test imitates the process of core removal from a casting produced by high pressure die casting technology. Therefore, the force recorded during the test carry information about the soldering tendency of cast alloy. Details about this test are given in our previous works [3,4].

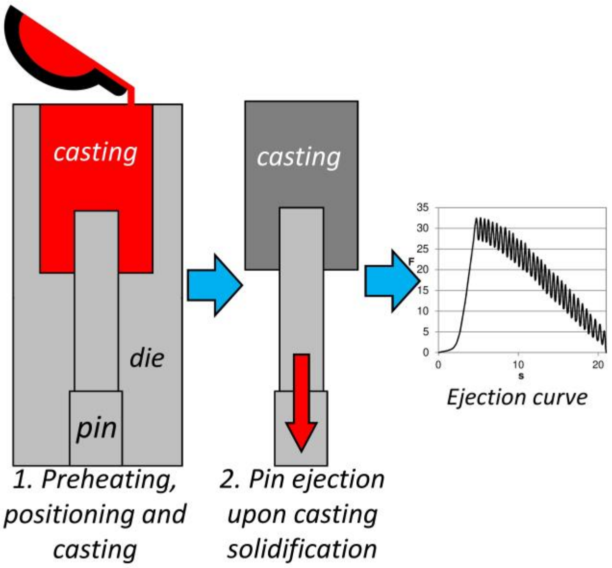

Figure 1. Schematic illustration of the employed ejection test

Casting process was performed by gravity melt pouring of EN AC-46200 alloy, at temperature of 730 °C, into a specially designed steel die, 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 stylus profilometer (Taylor

Hobson Talysurf). Instrumented hardness tester H100C (Fischerscope) was employed for the evaluation of mechanical properties of layers and thin coatings, applying 50 and 100 mN indentation loads. Average values of hardness were determined from twelve repetitive measurements.

After the ejection tests samples surfaces and cross section were evaluated by confocal optical microscope Axio CSM700 (Zeiss), Focused ion beam (FIB) Helios Nanolab 650i (Fei) and scanning electron microscope (SEM) Ultra Plus (Zeiss). Both FIB and SEM devices are equipped with energy dispersive spectroscopy (EDS).

Table 1. Pin samples surface roughness

Sample group	**S_a** [μm]	**S_{sk}**	**S_{dr}** [%]
Rough samples (R)			
CrN-R	0.231	-0.863	0.055
TiAlN-R	0.214	0.878	0.157
Smooth samples (S)			
CrN-S	0.066	0.296	0.21
TiAlN-S	0.095	4.820	0.363
Post deposition polished samples (PP)			
CrN-PP	0.029	-1.087	0.020
TiAlN-PP	0.078	-1.750	0.016

3. RESULTS AND DISCUSSION

Plasma nitriding process of EN X27CrMoV51 steel pins resulted with 90 µm thick nitrided layer with maximum hardness of 1300 $HV_{0.01}$. The thickness of investigated duplex CrN coating was 2.7 µm and its hardness was 2735 $HV_{0.05}$. TiAlN coating was 3.4 µm thick and exhibited hardness od 3340 $HV_{0.05}$. Samples surface roughness parameters are presented in Table 1. It can be seen that all groups of the investigated samples belong to the group of very low surface roughness which are applied for HPDC tools of highest quality. Difference in S_a between the smooth and post deposition polished samples is small, however a significant change in morphology is evident by a considerable change in S_{sk} parameter. This is the most pronounced for post deposition polished samples. For these samples S_{sk} parameter indicate that the polishing treatment induced formation cavities on the surface as a consequence of nodular defects wrenching [3].

Figure 2 presents the most representative cross sections of pin-casting assemblies, before the ejection process. It can be seen that eutectic phase and other intermetallic phases of Al-Si-Cu alloy more intensively precipitate in proximity of the pin surface than the aluminum alloy matrix (Figure 2. a). For both coatings it was found that the pin casting contact is mostly established through different intermetalic phases which grow from the coating surfaces (Figure 2. b). Most of the intermetallics form a sharp interface with coated surfaces, which suggests a firm bond established between them (Figure 2. c). Such findings are not reported in the literature, yet. Cross sectional analysis also revealed that the pin and the casting exhibited a completely interlocked contact. Cast alloy closely follows the micro surface irregularities like grinding grooves and growth defects [3]. All these findings are typical for both types of investigated coatings.

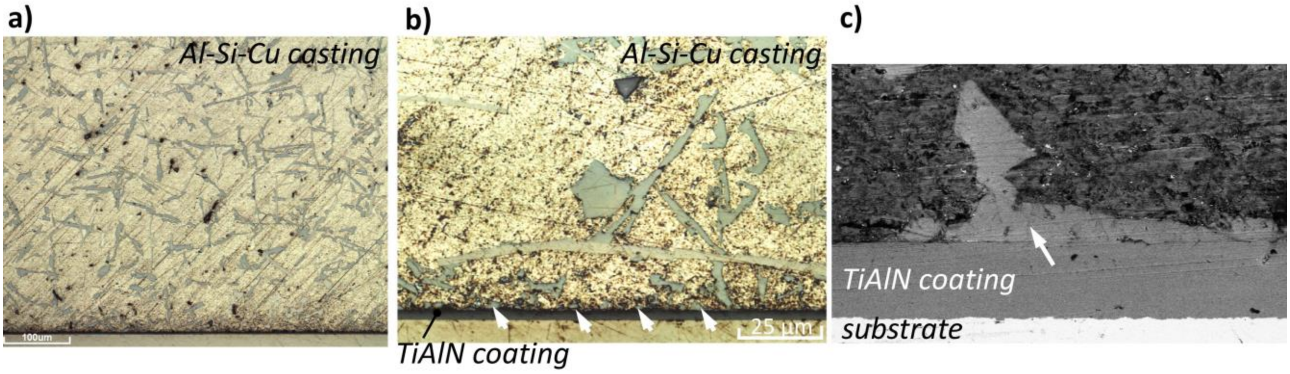

Figure 2. Cross section of pin-casting assembly before the ejection test of TiAlN-R sample, arrows indicate intermetallic of Al-Si-Cu alloy that precipitated on the coated surface, a) and b) CFM images of cross sections; c) SEM image of typical intermetallic phase that precipitate on coated surface

Figure 3 presents the most representative ejection curves of samples with different roughness. For the rough group (R) of samples, a sawtooth shape of the ejection curve typically appears. The sawtooth shape is a consequence of the stick-slip effect caused by two phenomena. One is the casting sliding over the pin surface covered with a built-up layer. The other is the repetitive ploughing of highest pin asperities through cast alloy [3]. The smooth (S) and post polished (PP) samples displayed higher maximal ejection force than the rough samples and their ejection curves are almost smooth and linearly decreasing. The stick-slip effect is absent for smooth and post polished samples. However, their higher ejection force is a consequence of increased adhesion of cast alloy promoted by high tangential force [5].

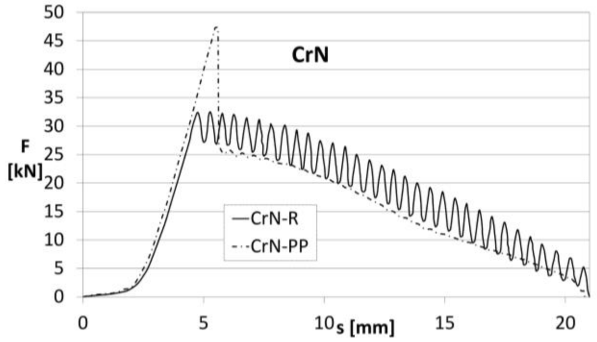

Figure 3. Ejection curves of CrN-R and CrN-PP samples

After the ejection process, cast alloy built-up layer was found on the sample surfaces of both kind of coatings. The built-up layer forms due to sticking of cast alloy, due to galling process, and due to the combination of these two. Morphology of the cast alloy built-up layer can reveal the release mechanisms, sticking effects and type of sliding wear. Figure 4 presents the surface of CrN-R sample. It can be seen, that the built-up on rough samples is mostly located in the grinding grooves and it is redistributed on the side of the groove, opposite to the ejection direction (Figure 4. c). Considering that initially the pin-casting contact was completely interlocked and that the space in grinding groove is limited, remained material in the groove could only be cut off the casting. Another typical form of a built-up is agglomeration of cast alloy around the coating nodular defects (circled in Figure 4. b and d). This is typical for all kind of samples which have nodular defects rough and smooth. Such features form due to the ploughing of higher nodular defects through casting material. The built-up in the grinding grooves together with those around nodular defects, or high asperities, contribute to effects which hamper the pin sliding, inducing the stick-slip effect [3]. During sliding, due to the effects of galling the built-up easily thickens on the layer formed during the initial release of the pin.

The appearance of TiAlN-PP sample after the ejection test is presented in Figure 5. As can be seen the built-up is distributed almost evenly over the whole pin surface. Generally, on surfaces of smooth and post polished pins the built-up layer is thinner. On pin regions which were shallow in the casting, thin

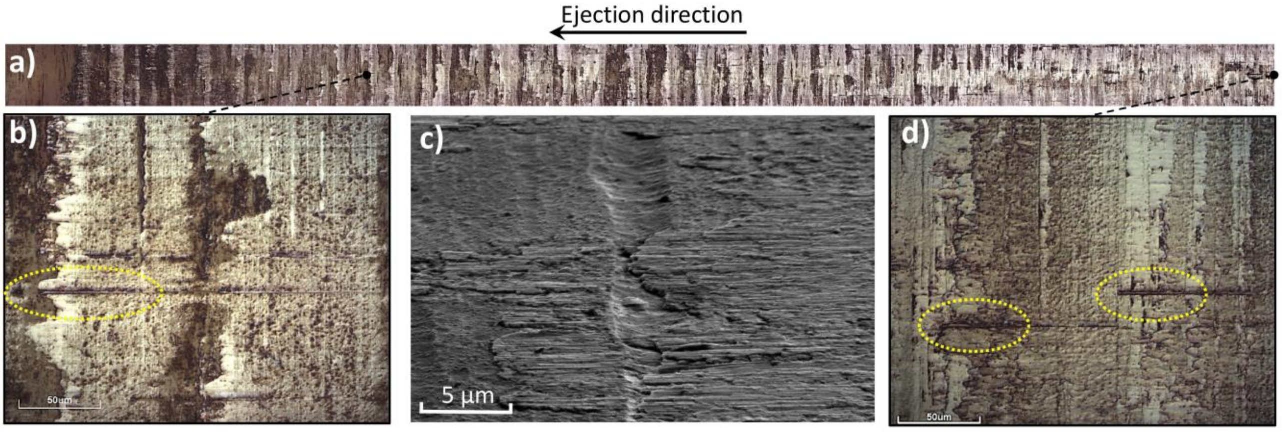

Figure 4. Surface of CrN-H sample after the ejection test: a) CFM panorama view along the sample; b) detail of built-up on the pin 5 mm deep in the casting; c) SEM image of typical built-up in a grinding groove; d) CFM image of built-up in the location 20 mm deep in the casting; circled areas are nodular defects with agglomerated built-up

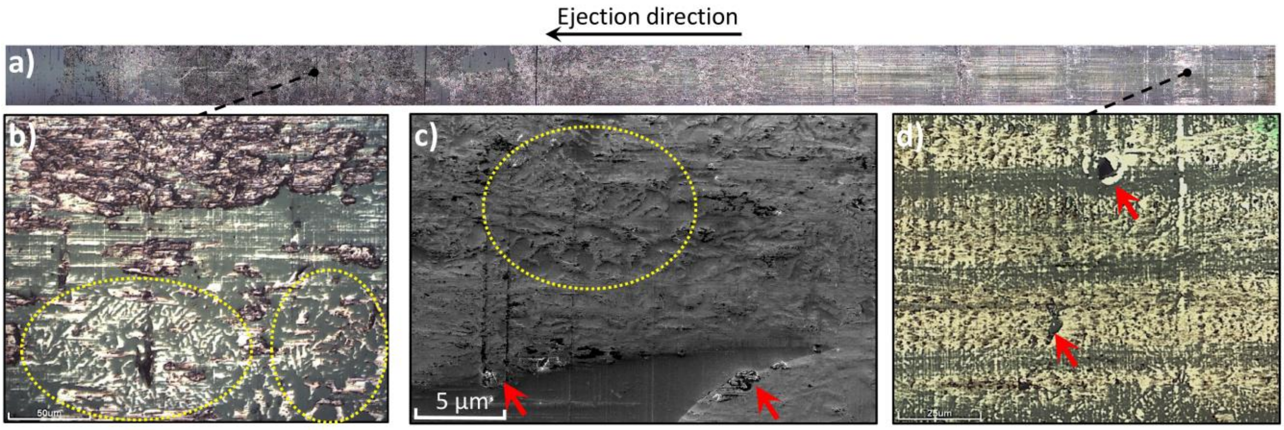

Figure 5. Surface of TiAlN-PP sample after the ejection test: a) CFM panorama view along the sample; b) detail of built-up on the pin 3 mm deep in the casting; c) SEM image of typical built-up on a smooth surface; d) CFM image of a built-up in the location ~18 mm deep in the casting; circled areas in the images indicate sticking layer in form of “chinese-script”, arrows indicate the crater defects filled with

built-up layers have typical shape of “chinese-scripts” (Figure 5. b). These shapes are also typical for intermetallic phases from the cast Al-Si-Cu alloy, which mostly contain Al and Fe (Figure 2. b and c). The number of built-up layers with these shapes agree with the amount of cast alloy intermetalics that precipitate on pin surfaces (Figure 2.). The EDS analysis (not presented here) confirmed that small islands of built-up layers mainly consists of Al-Si-Fe intermetallics. Therefore, it is believed that this kind of built-up forms due to better sticking of cast alloy intermetallics to PVD coatings than its aluminum matrix. The built-up on pin regions positioned deeper in the casting, has the morphology characteristic for wear caused by galling (Figure 5d). In these regions the morphology of a sticking layer, formed in the initial release of the pin, is changed by material transfer from casting to pin, which increases the built-up thickness. Therefore, for the pin regions positioned deeper in the casting the built-up morphology is not representing the sticking (soldering) processes. For post deposition polished samples (PP), a characteristic feature is that cast alloy also agglomerates in coating crater defects (Figure 5. c and d). This occurs on coating defects formed during deposition and on those created (wrenched) by polishing (Figure 5. c and d). Beside their tribological effects, the coating growth defects have large influence on coatings deterioration by corrosion in aluminum alloys [6].

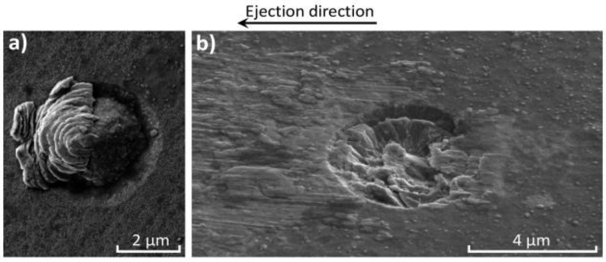

Figure 6. FIB-SEM images of details on CrN-S sample: a) nodular defect with agglomerated cast alloy, b) nodular defect wrenched during sliding

Figure 6 presents two typical phenomena that occur during sliding of coated pins over the casting surface. These micrographs give better prospective on the ploughing phenomena presented in the images of Figure 4 d. Intensive ploughing of highest coating nodular defects induces agglomeration of cast alloy in front of the defect (Figure 6. a). This process enhances the adhesion, increases the friction, which means that higher stress is put on nodular defect. This process can lead to two scenarios. If this stress reaches the shearing strength of a defect, the defect will crack (Figure 6. b). If the stress reaches the strength of bond between the defect and the substrate, the defect will be wrenched out and a cavity defect is formed. In subsequent casting cycles the locations of both cases would lead to the substrate corrosion through growth defects. Such process greatly endangers the coatings integrity because it induces coating cracking and spallation from the substrate which on longer runs puts the coated HPDC tool out of the service [1,6].

4. CONCLUSIONS

From the investigation presented in this paper the following conclusion are drawn.

- The pin and the casting form a completely interlocked contact which is mostly established through eutectic and other intermetallic phases of Al-Si-Cu alloy.
- Shape of the ejection curve depends on the roughness of pin samples. Ejection of rough samples is characterized by prominent stick-slip effect which results with a sawtooth shape of the ejection curves. Smooth and post polished coated samples ejects under higher loads because of the enhanced adhesion of cast alloy to smooth surfaces.
- CrN and TiAlN coatings displayed similar behavior in term of the effects of surface roughness and morphology on sticking and galling processes.
- Although, the rough surfaces exhibit lower ejection force the built-up agglomerates in grinding grooves and it further easily builds up by mechanisms of adhesive wear. During the sliding in process of casting ejection, nodular coating defects agglomerate cast alloy around them. This hampers the ejection process and cause nodular defects cracking or wrenching.
- Intermetallic phases from Al-Si-Cu cast alloy have higher tendency of sticking to coated surfaces than the aluminium matrix. The morphology of such sticking layers, have typical shape of “chinese-scripts”.
- The evaluation of pure sticking phenomena by ejection test is difficult on cylindrical samples because the galling process during the pin ejection covers the built-up layer formed by sticking of cast alloy.
- The morphology of coating growth defects can be significantly changed in casting ejection processes. This in the following casting cycle can change the coating performance and even induce coating deterioration.

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