Possibilities of reducing the degradation of molds for high-pressure of Al alloys

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Abstract: *The paper focuses on the degradation of molds that are used for the technology of high-pressure casting of Al and its alloys. The method of high-pressure casting of aluminum products is one of the widely used production methods, which at the same time meets the requirements for precision and productivity in the production of cars and various mechanical parts. In the high-pressure casting process, the molds are exposed to various thermal and mechanical loads, where the molds and their shaped parts are degraded. The paper presents the results of research focused on the use of duplex PVD coatings to increase the life of shaped parts of molds for high-pressure casting of Al and its alloys.*
***Keywords**:* ALUMINUM, DIE CASTING, DEGRADATION, COATINGS, ADHESION, CRACKS

1. Introduction

The high-pressure die casting process is used to produce parts mostly from aluminum, magnesium, zinc, and cooper alloys by injection of the molten metal in the mold cavity. The mold cavity that are used to produce those parts are constantly exposed to highly severe conditions, such as high pressure, rapid temperature fluctuations and erosion from fast moving molten metal. The usual molten metal input speed is comprised between 20 and 60 m/s and the temperature, depending on aluminum alloy type is around 700 °C. The maintenance of replace of these molds require a huge cost which implies that producers need to find the best solution to increase their lifespan. The industrial environmental and working conditions increase the capacity to induce some failure mechanisms on hot work tool steel, such as erosion, corrosion, wear, and thermal fatigue. Parts produced by this method conform accurately to the die size, have favorable mechanical features and are low in cost [1,2].

The die casting method of aluminum products is one of the widely used manufacturing methods as it is a technology that can simultaneously satisfy precision and productivity requirements during the production of automobile and various mechanical parts. However, during the rapid solidification process, defects like porosity and shrinkage might remain and significantly reduced the ultimate mechanical properties, e.g., tensile strength, wear resistance and fatigue strength [3]. During die casting process operations, the tools steel used to this process are exposed to a several thermal and mechanical loads, which can lead to damage the molds for high-pressure die casting. The improvement of these structures' lifetime was strongly required due to several economic and environmental reasons. Corrosion, soldering, erosive wear, and thermal fatigue are the primary failure mechanisms that limit die life in aluminum high-pressure die casting. Corrosion and soldering are caused by the physical impingement of the incoming liquid aluminum. Thermal fatigue results from the change in stress caused by alternate heating and cooling of the die surface during the casting process. Under the combined effects of these failure mechanisms, the die will crack; fragments are broken off the die, necessitating die removal and a consequent increase in process costs. One of the major damage mechanisms occurring in die casting process, under cyclic thermal loads is the formation of a network of interconnected cracks [4-6].

The stress cracking, which presents another variant of thermal fatigue cracks, was clearly marked in areas exposed to local stress concentrations and can lead to crack initiation in a die casting mold. Then, these cracks can grow and became, more pronounced driven by several factor including thermal fatigue, erosion, oxidation, soldering of the molten metal to the die surface, deformation of die contact surface and dangerous fracture. The formation of thermal fatigue cracks may lead to a loss of surface material as small fragments splinter off from the surface. To endure these severe conditions the tools are made of hot-work tool steel, designed to have and adequate combination of hot strength, toughness, and ductility, as well as thermal conductivity and thermal expansion. Die and its shaped parts maintenance may be done by grinding or welding if the surface quality or dimensions of the castings are no longer sufficient [4-6]. However, the tool and service costs constitute a remarkable part of the production costs in die casting and there are numerous approaches to optimize the lifetime of the dies. In general die life may be enhanced by geometric factors in die design (governing stresses and thermal gradients), die material considerations e.g., machinability, heat treatment, toughness, resistance to wear and heat checking, processing conditions (preheating, heating and cooling cycles, machine closing force, lubricants, service intervals) and die surface considerations [5,6]. The Fig. 1 shows the degradation mechanism of the mold part - the mold insert used for high-pressure aluminum die casting due to the repetitive cycles of the casting process.

Fig.1 *Degradation of the mold part*

Surface treatments, such as nitriding, hard PVD coatings and others are often applied for casting dies to reduce failure mechanisms (abrasive wear) and improved thermal fatigue resistance. In recent years, hard PVD coatings on nitride-based to the surface of the mold and its shaped parts have been applied to increase the overall life of the molds and their parts used in high-pressure die casting of aluminum and its alloys. In Fig. 1 is a comparison of the life of a mold for high-pressure aluminum die casting without the use of PVD coatings and using PVD coating based on nitrides CrN, Ti (C, N). Hard coatings based on nitrides and carbides of transitions metals (TiN, CrN, CrAlN, CrC) and duplex treatments that combine surface modification of the die with a hard coating have also been developed. The use of PVD coatings has been shown to increase the service life several times (4 to 17 times). The die coating system to be far superior to that of the uncoated die with respect to cost performance criteria. The die coating system must be [7-9]:

- Non-wetting with liquid aluminum
- Wear and oxidation resistance
- Able to accommodate the thermal residual stresses induced by shot cycling (temperature and pressure) during pressure die casting process

- Adherent to the die material – and engineered interface
- Able to delay the onset of thermal fatigue cracking (heat checking)

The Fig. 2 represents a diagram of an optimized coating architecture for die coatings used in aluminum high pressure die casting [7]:

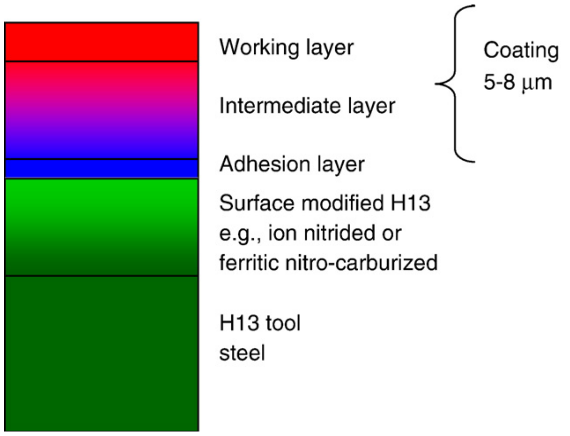


Fig.2 *A diagram of an optimized coating architecture for die coatings used in aluminum high pressure die-casting.*

2. Materials and Methods

Uddeholm Dievar was used as the base material for experiment, which is used in the production of die casting molds for aluminum and their shaped parts. The chemical composition of the base material is in Tab.1.:

Table 1: Chemical composition of Uddeholm Dievar

Element	C	Si	Mn	Cr	Mo	V
Wt. %	0.38	0.2	0.5	5	2.3	0.6

The mold parts were manufactured according to the drawing documentation and were tempered to a hardness of 48 HRC and subsequently fitted into the mold body for high-pressure casting of aluminum alloy base on Al-Si-Cu realized on machines with a cold filling chamber. The mechanical properties of the base material are shown in Tab.2:

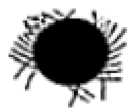
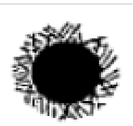
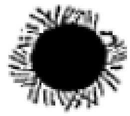
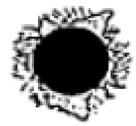
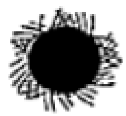
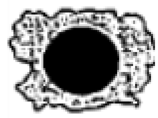
Table 2: Mechanical properties of Uddeholm Dievar

Mechanical properties of Uddeholm Dievar				
Hardness [HRC]	Tensile strength Rm [MPa]	Yield strength $Rp_{0,2}$ [MPa]	Ductility [%]	Relative narrowing [%]
52	1900	1560	12.5	52

$AlXN^3$ and $nACRo^3$ coatings were used to perform PVD coating. For the nano-multilayer coating, ALXN3 (X=Cr) is the basic adhesive coating of CrN, followed by Al/CrN nano-coating and the top coating is AlCrN. It is a tough coating with high resistance to abrasion at high temperatures up to 900 °C.

The $nACRo^3$ is a nanocomposite coating consists of AlCrN nanocrystalline grains that are embedded in an amorphous Si_3N_4 matrix. The coating are three layers: the first adhesive coating consists of CrN, the second coating is AlCrN, and the three final top coating is formed by a nc-AlCrN/a-Si_3N_4 nanocomposite coating. This nanocomposite coating is very tough, resistant to abrasion to high temperature up to 900 °C – 1100 °C. The light microscopy technique was used for crack site analysis. The quality control of the mold surface before coatings process consisted of a visual control, which was carried out in accordance with ISO 13018. The visual control was followed by a capillary control according to ISO 23277. Scanning electron microscopy was used for chemical elemental analysis at the crack site. The Mercedes test (Tab.3) was used to measure the adhesion of the coatings, which was performed on a universal hardness tester UH 250 with a Rockwell indenter at a load of 1500 N according to ISO 18265. The evaluation is performed by assigning it to the appropriate category with the adhesion number HF1 – HF6, which characterizes the degree of cracking and peeling layer.

Table 3: Coating adhesion by the Rockwell indentation test

Evaluation of coating adhesion by the Rockwell C indentation test			
	HF 1- good adhesion a small amount of cracks		HF 4 - reduced adhesion peeling around the edge of the indent
	HF 2 - satisfactory adhesion small peeling between cracks		HF 5- insufficient adhesion peeling even at greater distances from imprint
	HF 3- reduces adhesion peeling over more than two cracks		HF 6- unsatisfactory adhesion complete peeling around the indentation

A Jeol JSM 7000F scanning electron microscope with an EDX analytical unit was used to determine the chemical elemental analysis of the defect environment according to ISO 15362. Microhardness measurements were performed on a Leco LM 700 microhardness tester with a Vickers indenter HV 0.025 according to ISO 6507-1. Scratch test was used to evaluate adhesion of coatings and was performed on an AMI CSEM -Revertest device (feed 10 N/mm, load up to 80 N, track length approx. 8 mm). All samples for analysis were prepared by metallographic procedure. The samples were prepared in conductive dentacryl Polyfaste, then were ground on sandpaper of various grits (240, 400, 600 and 800), moistened with water, polished with 1/0 diamond paste, washed, and rinsed with benzine alcohol. Prior to observation, all samples were purified in methanol in an ultrasonic device. Samples were taken from the molded parts of the mold half according to Fig. 3:

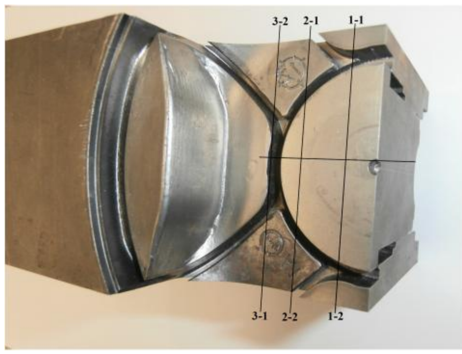


Fig.3 *Sampling procedure from the mold part*

3. Results and discussion

In Fig.4 is worn solid half of the mold part - mold insert and appearance of cracks of the mould after capillary test.

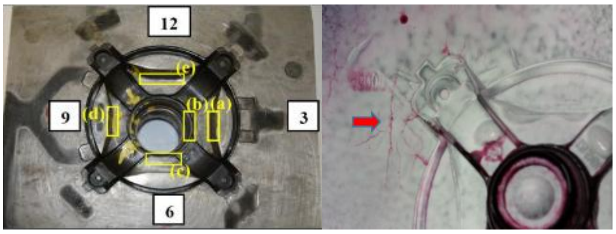


Fig.4 *Worn solid half of the mold insert (left); appearance of cracks by capillary method (right)*

Wedge-shaped branched crack were observed in the analyzed places of the mold part due to cyclic stressinf of the mold parts in the area of elastic deformations. The cracks that formed in the areas of sharp transitions in the corners of the mold parts were filled with oxides and a release agent during the repetitive casting process. It is precisely due to the repetitive elastic deformations during the repetitive cycle of the casting process that the oxide filler and the release agent acted as a wedge, which was pressed into the mold material and caused wedge branched cracks. The analyzed cracks observed by light and electron microscopy are shown in Fig.5:

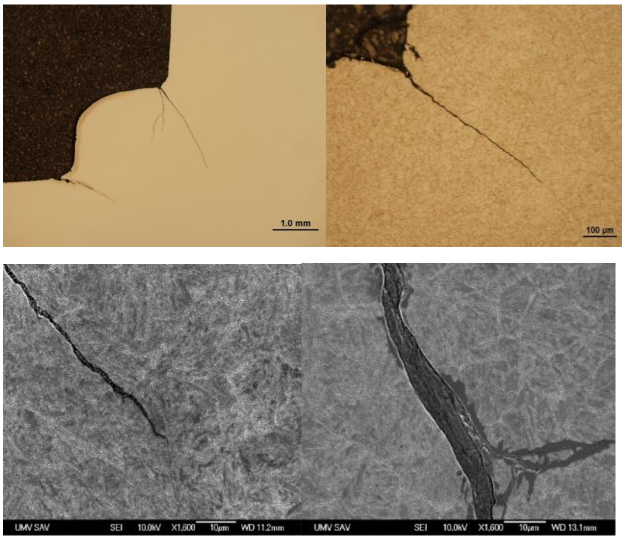


Fig.5 *Cracks in the zones of sharp transitions of the surfaces of shaped parts of the mold (light and electron microscopy)*

The presence of other chemical elements, namely the presence of oxygen, calcium and silicon, was observed in the filling of wedge shaped cracks formed by oxide and a separating agent. Outside the crac-containing zones, the microstructure was formed by heterogeneous sorbitol together with fine globulite carbides on Fe-Cr-Mo-V.

The presence of other chemical elements, namely the presence of oxygen, molybdenum, chromium and silicon, was observed in the filling of wedge shaped cracks (Fig.6) formed by oxide and a separating agent. Outside the crac-containing zones, the microstructure was formed by heterogeneous sorbitol together with fine globulite carbides on Fe-Cr-Mo-V. EDX analysis was also performed at the crack location according to the Fig.6 on the mold part shown in the Tab. 4:

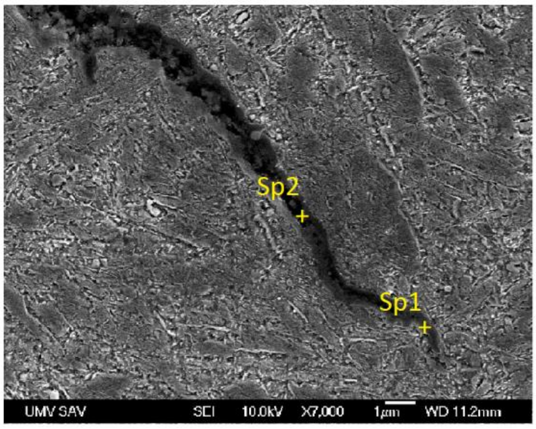


Fig.6 *Zone of sharp transitions of the surfaces of the shaped parts of the mold*

Table 4: EDX analysis (Sp1, Sp2) at a crack site

	Element	*Wt. %*	*At. %*
Sp1	O	24.85	52.57
	Si	3.13	3.78
	Fe	7.2	43.65
	Totals	**100**	
Sp2	O	23.58	51.02
	Si	3.91	4.82
	Fe	65.83	40.8
	Cr	3.13	2.8
	Mo	3.54	1.28
	Totals	**100**	

3.1 Adhesion of PVD coatings

Good adhesion of PVD layers to the substrate was confirmed, determined by the ratio cohesive and the degree of HF = 1, which was characteristic for the occurrence of only isolated cracks and minimal disruption of the integrity of PVD coatings around the indentations. Fig.7 shows the morphology the indentations into the coating surfaces, with only isolated radial cracks in both cases reaching of max. 200 µm. It was measured a degree of adhesion HF = 1-2 according to the Tab.3, which means good adhesion of a coating.

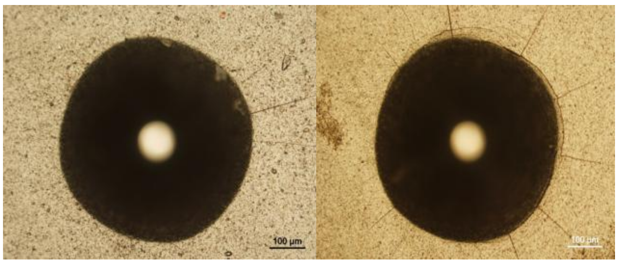


Fig.7 *Indentation impression after Mercedes test; $AlXN^3$(left), $nACRo^3$ (right)*

3.2 Tribological properties of PVD coatings

The device records the course of the increasing normal Fn and the tangential force Ft acting on the indenter, the values of the coefficient of friction and the acoustic emission signal AE. The output is a graphical record of the AE emission signal and the COF depending on the size of the load. The value of the critical load Fz at which the substrate. In practice, the value of the critical load Fz = 40 N is referred to as satisfactory adhesion. Satisfactory adhesion was recorded on the subject tested samples with applied coatings, because the failure or detection of the substrate occurred at values of about 50 N (Fig.8).

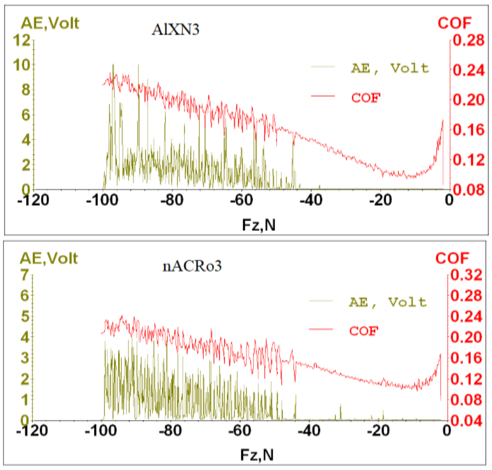


Fig.8 *Dependence of acoustic emissions (AE) on the coefficient of friction (COF) of coatings*

3.3 Microhardness of PVD coatings

By evaluating the microhardness of the Vickers indenter HV 0.025 of PVD coatings, an increase of about 18% - 25 % compared to the base material of mold was recorded. The microhardness measurement was performed in 16 places, and a graph of microhardness values was subsequently constructed from the measured values. Both minimum and maximum values were measured:

- In the case of the $ALXN^3$ coating, the minimum microhardness value was 600 HV and the maximum microhardness value was 720 HV
- In the case of the $nACRo^3$ coating, the minimum microhardness value was 610 HV and the maximum microhardness value was 810 HV

Fig.9 presents hardness profile of coatings and shows an arrow from the area of the coatings to the base material:

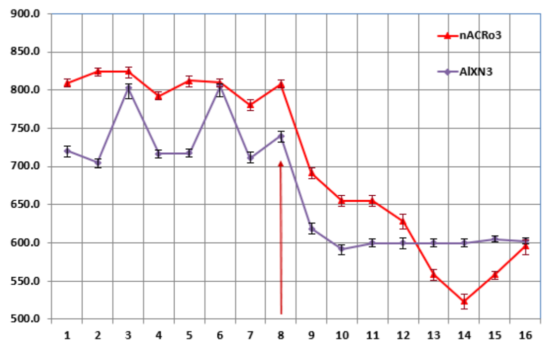


Fig.9 *Graph of measured microhardness values*

4. Conclusions

The paper is the results of research aimed at finding out the degradation mechanisms of molds for high-pressure aluminum die casting and the possibility of modifying the quality of functional surfaces of molds using PVD nanostructured coatings of a new generation. In the first phase, the degradation mechanisms in the corners of shaped parts (inserts) of the mold in the form of branched cracks due to elastic deformation due to repeated of the casting process were analyzed. In the second phase, a conventional ALXN3 coating and a new generation nanostructured nACRo3 coating were applied to the mold parts. The PVD coatings were of high quality, which was confirmed by tests performed to assess the adhesion, hardness, and COF of coatings. The coatings were compact, intact, and formed a barrier between the base material and the molten metal Al after the high-temperature corrosion test (680 ±20 °C).

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6. References

1. D. Abid, A. Ktari, D. Mellouli, N. Gafsi, N. Haddar: Failure analysis of shot-sleeves used in brass high pressure die-casting process, In: Engineering Failure Analysis, 2019, Volume 104, pp. 177-188

2. V. Nunes, F.J. Silva, M.F. Andrade, R. Alexandre, A.P.M. Baptista: Increasing the lifespan of high-pressure die cast molds subjected to severe wear, In: Surface & Coatings Technology, 2017, Volume 332, pp. 319-331

3. S. H. Kang, J.J. Han, W.T. Hwang, S.M. Lee, H.K. Kim: Failure analysis of die casting pins for an aluminum engine block, In: Engineering Failure Analysis, 2019, Volume 104, pp. 690-703

4. D. Mellouli, N. Haddar, A. Koster, H.F. Ayedi: Thermal fatigue failure of brass die – casting dies, In: Engineering Failure Analysis, 2012, Volume 20, pp. 137-146

5. J. Wang et.al.: On the failure mechanism for high pressure die casting A390 hypereutectic alloy in low cycle and high cycle fatigue, In: Materials Science & Engineering A, 2018, Volume 723, pp. 48-55

6. R. Ding et.al.: Failure analysis of H13 steel die for high pressure die casting Al alloy, In. Engineering Failure Analysis, 2021, Volume 124, pp. 105330

7. J. Lin et.al.: Design methodology for optimized die coatings: The case for aluminum pressure die-casting, In: Surface & Coating Technology, 2006, Volume 201, pp. 2930-2941, Elsevier

8. K. Bobzin, et. al: Analysis of $CrN/AlN/Al_2O_3$ and two industrially used coatings deposited on die castings cores after application in an aluminum die casting machine, In: Surface & Coating Technology, 2016, Volume 308, pp. 374-382, Elsevier

9. B. Wang, et.al.: Method to evaluate the adhesion behaviour of aluminum-based alloys on various materials and coatings for lube-free die casting, In: Journal of Materials Processing Technology 2016, Volume 237, pp. 386-393, Elsevier