PVD Coatings in Aluminium die Casting dies and Steel Forming Tools

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Abstract

The behaviour of PVD coatings in aluminium die-casting and steel forging was investigated. As far as the die-casting process is concerned, three series of core pins surface treated by means of the Balinit PVD technology with CrC, CrN or TiAlN were examined. For steel forging dies a PUSK PVD process was used to coat a cold extrusion punch with TiN while warm and hot forming tools were CrC coated with the same technology. The analyses carried out on the CrC coated core pins showed a great tendency to the formation of multiple layers of Al alloy which protected the steel from erosion effects. However, this behaviour was detrimental for the surface roughness of workpieces. The TiAlN coated pins were subjected to a service life almost double with respect of that of the other series of core pins. They demonstrated to be particularly resistant to wear and to aluminium soldering. Limited soldering was also observed on CrN pins. However, discontinuities at the steel/coating interface made easy the removal of the coating layer and thus the direct erosion of steel. PVD coated forging tools showed an early depletion of surface characteristics consisting in the formation of surface scuffing which locally reduced the thickness of coatings. As the workpiece material flow and pressure increased, scratches depth reached the steel underlying the external layer. The above features were mainly observed in the cold forming tool. In punches for warm and hot forging, a number of cracks nucleated from radial/longitudinal scratches due to heavy thermomechanical cycles. A further surface degradation took place in areas of heavy rubbing. Laps caused by the extensive deformation of the steel originated cracks initially oriented parallel to the surface which then grew into the material depth.

Riassunto

È stato valutato il comportamento di rivestimenti PVD nei campi della pressofusione di leghe di alluminio e della fornatura di acciaio. Per quanto riguarda il processo di pressofusione, sono state esaminate tre serie di spine per la realizzazione di fori rivestite con CrC, CrN e TiAlN mediante la tecnologia Balinit. Relativamente al campo della formatura sono stati osservati tre punzoni rivestiti mediante il processo PVD PusK. Un primo punzone, per estrusione a freddo, è stato rivestito con TiN, mentre per gli altri utensili, per formatura a semicaldo e caldo, per il rivestimento è stato scelto CrC. Le analisi condotte sulle spine rivestite con CrC hanno mostrato una notevole tendenza alla formazione su di esse di strati multipli di lega di alluminio in superficie. Questi hanno dimostrato di avere un effetto protettivo per la superficie nei confronti dei fenomeni erosivi; tuttavia la presenza di tali strati danneggia la finitura superficiale dei pezzi pressofusi. Le spine rivestite con TiAlN, esaminate dopo un numero di colpi all'incirca doppio rispetto alle altre serie, hanno dimostrato una particolare resistenza sia all'usura che ai fenomeni di incollaggio di alluminio. Nelle spine rivestite con CrN è invece stato riscontrato un limitato incollaggio di lega di alluminio. In questo caso inoltre la presenza di discontinuità all'interfaccia acciaio/rivestimento ha favorito la rimozione di quest'ultimo con l'esposizione diretta dell'acciaio e la conseguente erosione. Le osservazioni condotte sui rivestimenti PVD su punzoni per formatura hanno dato modo di osservare l'evoluzione delle caratteristiche superficiali che si riflette nel peggioramento della finitura superficiale e delle tolleranze dimensionali dei manufatti. Il primo passo di questo processo è costituito dalla formazione di rigature superficiali nella direzione di scorrimento del materiale da formare. All'aumentare delle pressioni e dello scorrimento del materiale tali rigature si approfondiscono fino ad esporre direttamente l'acciaio. Gli aspetti sinora illustrati sono stati osservati principalmente nel punzone per lavorazioni a freddo mentre in quelli per formatura a semicaldo e caldo si sono osservate anche cricche nucleatesi a partire da solcature ad andamento radiale/longitudinale a causa dei cicli termomeccanici corrispondenti ad ogni battuta. Un'ulteriore degradazione superficiale ha avuto luogo nelle regioni a forte strisciamento, con la formazione di ripiegature superficiali nell'acciaio fortemente deformato, difetti dai quali si sono sviluppate cricche di fatica con direzione di crescita inizialmente parallela alla superficie ed in seguito orientata verso l'asse del punzone.

INTRODUCTION

A primary need for tool and die manufacturers is to identify the best combination of steel chemical composition together with thermal and surface treatments in order to achieve the best thermomechanical shock and wear resistance. It is well known that mechanical and thermal stresses act in different combinations for cutting or forging tools and die-casting dies. Therefore, in general, under heavy operating conditions, these mechanical parts should be able to cope with two opposite industrial needs: the good product quality, as far as tolerances and surface roughness are concerned, and the long life of the tool or of die parts in contact with the component to be manufactured. The use of surface treatments which allow increased surface hardness and lower friction coefficient to be obtained, is a common industrial practice in forging tools and dies. Such treatments should imply a correct balance between hardness and toughness in order to achieve suitable strength with a limited crack susceptibility. The use of PVD (Physical Vapour Deposition) coatings revealed to be of particular interest since the wear resistance can be fully supplied by the external layer and thus the steel can be treated in its best structural condition. The present paper deals with the results of a research work on the current uses of PVD coatings technology in aluminium die-casting and steel precision forging. The choice of such a wide range of industrial applications allowed to examine different problems involved in the use of surface coatings. Amongst these, erosion and soldering of aluminium alloy on the die (brought about by the repeated injection cycles) are of great importance in die-casting dies. Mechanical strokes and thermomechanical shocks are the main influencing factors to be taken into consideration in steel cold and hot forging tools, respectively. The behaviour of PVD coatings in aluminium die-casting was studied by investigating three series of core pins coated with different chemical compositions and obtained by the same Balinit PVD technology. A PUSK PVD process was used to coat three punches for cold, warm and hot steel forging. The chemical compositions of the coatings were in this case chosen according to Teksid's industrial practice. Previous experiences had in fact revealed them to be the most suitable coatings for each process.

MATERIALS

For aluminium die-casting application field, three series of seven core pins on the gate side of a die-cast die for the production of a clutch casing were PVD coated with CrN, CrC or TiAlN. The core pins were made of Cr-Mo-V steel QRO 90 HT (Uddeholm designation). Alutek industrial practice revealed this steel to have a better behaviour in the above die parts with respect to H11 steel, widely used for the production of die-cast dies [1]. The chemical composition of the QRO 90 steel is labelled as A in Table 1. The Balinit PVD coating technique [2] was used for the present investigation.

TABLE 1 - Chemical composition (wt.%) of the steels examined

	DIN	C	Si	Mn	Cr	Mo	V	W
A	-	0.40	0.3	0.7	2.6	2.3	0.9	-
B	1.3343	0.90	0.3	0.3	4.1	5.0	1.8	6.4
C	1.2367	0.39	0.25	0.30	5.0	2.9	0.55	-
D	1.2344	0.39	1.0	0.40	5.1	5.1	1.0	-

TABLE 2 - General properties of the PUSK processes used for the examined PVD coating of forming tols

	PUSK process	
Metal vapour source	Micropoints of molten metal on the solid surface of cathode	
Vaporisation medium	Ton flow	
Atmosphere for metal vaporisation	Void (0.1 Pa)	
Electrical potential of the source	Negative	
Magnetic field in vaporisation region	YES	
Magnetic field in ionisation region	YES	
Magnetic field in deposition region	NO	
Electric field in deposition zone	YES	
Particles emitted from source, corresponding amount (%) and energy (eV)	TiN Ions 70 20 Atoms 28 2 Microdrops 2 ~0	CrN Ions 80 20 Atoms 19 0.5 Microdrops 1 ~0
Temperature of the source	100-500 °C	100-500 °C
Temperature of the part being coated	300 - 320 °C	300 - 320 °C

The workpieces were manufactured with an Al-Si-Cu alloy (9% Si, 3% Cu). Core pins were chosen for the present study because, among die components, they are the most prone to erosion and alloy soldering [3, 4]. Their critical behaviour is due to the direct exposition to the flow of molten alloy and to the slow cooling in contact with aluminium. Further, the pins can be easily coated and extracted from the dies. Each series was intended to manufacture approximately 10000 workpieces. However, owing to the good performance and in order to avoid production shutdowns, each series of pins was replaced after longer service periods. The longer duration was recorded by the TiAlN coated pins and corresponded to 22000 shots. The general steel and Balinit coatings characteristics, together with the actual number of manufactured clutch casings is given in Table 3.

The second series of investigations was carried out on three extrusion punches for steel precision forging at low (B), middle (C) and high (D) temperature. The chemical compositions of the steels used are listed in Table 1. Only the hot forming tool (D) was gaseous nitrided after the heat treatment. The punches were coated with TiN for the cold forming and with CrN for the warm and hot forming processes. The PUSK process was used in this case for the PVD coatings. The process general features are listed in Table 2 while the main data on the punches are given in Table 4. During forming, the material to be plastically deformed reached the dies at temperatures of 20, 700 and 1100 °C for the low-, middle-and high-temperature processes, respectively. Even if the punches were cooled after each stroke, during the deformation stage the local temperatures (where prolonged contact with the workpiece occurred) reached about 150, 500 and 600°C, respectively.

TABLE 3 - Data on the series of core pins examined, all of them made of QRO 90 HT steel

Hardness of steel before service (HRC)	PVD coating	Coating thickness (μm)	Hardness of the coating (0.491N HV)	Number of shots during service life
40	CrN	1-4/10	1750	11200
40	CrC	1-5	1850	10990
40	TiAlN	1-4	2700	22000

TABLE 4 - Data on the examined forming punches

STEEL	Hardness of steel before service (HRC)	Nitriding	PVD coating	Coating thickness (μm)	Maximum temperature of the punch (°C)	Billet temperature before forging (°C)	Number of strokes during service life
B	58-60	NO	TiN	4-5	~150	200	87000
C	54-56	NO	CrN	10-15	~500	700	40000
D	46-48	gaseous	CrN	15-20	~600	1100	24000

EXPERIMENTAL OBSERVATIONS

Die casting core pins

Four core pins from each coated series were studied. Two of them were the nearest to, the other the farthest from the gate. The surface of each die-cast core pin was examined by means of both optical microscope and scanning electron microscope (SEM) in order to evaluate the surface conditions after service as far as erosion, scuffing and soldering of aluminium alloy are concerned. Since the general location of the highly eroded or soldered zones was found to be in front of the gate [4], each core was longitudinally sectioned along a diameter parallel to the flow direction of the injected molten alloy. Careful microstructural examinations and EDS microanalyses allowed to identify the coating and alloy layers and to determine their thickness and condition. A common industrial practice to evaluate the behaviour of coatings is the investigation of the region around a hardness indentation. Rockwell C and B hardness tests were therefore performed on zones of best and worse aspect conditions of each core in order to correlate the information obtained by this technique to those deduced from microstructural examinations.

Forging tools

The steel forging punch geometry is schematically represented in Figure 1. The working zones are limited to the punch heads and the area of heavy workpiece material flow is also located in a small belt below the front impact region. The observations by stereomicroscope on warm and hot forging punches revealed a net of longitudinal and circumferential scuffs or microcracks in this region, particularly where the workpiece/punch rubbing also took place during the extraction of the punch from the manufactured part. Only longitudinal scuffing in the lateral working region was noticed in the cold forming tool. To investigate the causes of such damage ruling the end of life of the punches (when the tolerances of the workpieces were no more respected), transversal sections on cold forming tool and longitudinal sections of the heads of the other punches were prepared for microstructural and microchemical investigations.

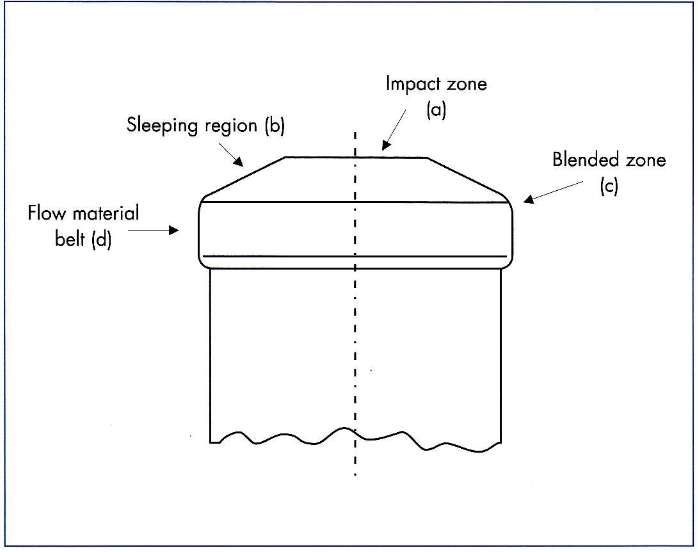

Figure 1: Schematic geometry of an extrusion punch

RESULTS

Die casting core pins

The observations of the core pins surfaces (see Figure 2, 3, 4) revealed that the Cr-C coating was the most critical as far as the soldering of aluminium was concerned. As a matter of fact, three out of four pins were extensively covered with aluminium regions concentrated on the surface directly exposed to the injected molten flow. Aluminium alloy was also found, even if in lower amount, on the surfaces of Cr-N and TiAlN coatings. In these cases, also the thickness and the extension were limited with respect to those of the carbide coating. On the other hand, the CrC layer showed a lower tendency to be eroded. The pin coated by TiAlN was spot eroded; the coating was absent in limited areas but the steel was not heavily damaged. Heavily eroded zones were found in CrN-coated pins, where the exposed steel was deeply dug. Further, longitudinal scuffing marks were left on the surfaces of CrC and CrN pins in front of the gate. These marks, together with the eroded regions, were mainly located near the head of the cores, where the cooling of the aluminium alloy was slower. The differences between the three coatings were less evident when the operating conditions of the core pins became less severe and no noticeable difference was detectable with the naked eye amongst the covered pins farthest from the gate.

Figure 2: Surface features at the head of the CrN core pin in the most critical location after 11200 shots

The SEM examinations on longitudinal sections of CrN coated core pins highlighted the presence of microcavities and

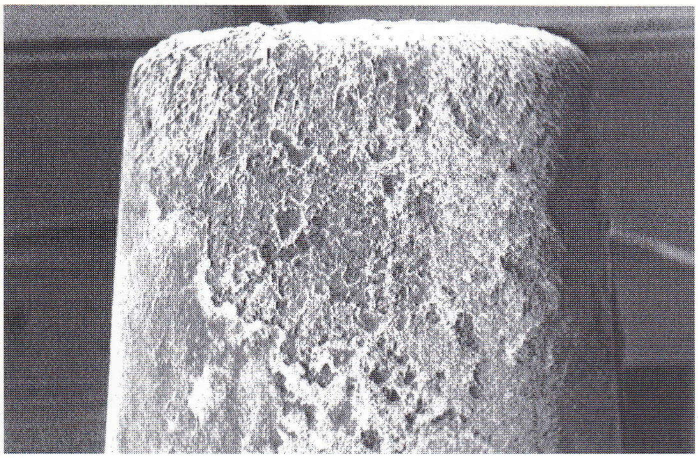

Figure 3: Surface features at the head of the CrC core pin in the most critical location after 10990 shots

Figure 4: Surface features at the head of the TiAlN core pin in the most critical location after 22000 shots

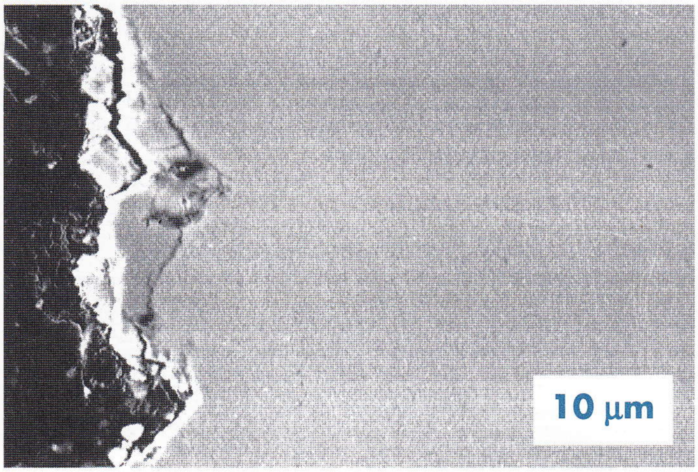

Figure 5: Typical features of CrN coated pins. SEM micrograph of a longitudinal section (the axis of the core pin is vertical)

microcracks at the coating/steel interface. Such discontinuities made easier in some regions the chipping off of the coating. In other zones the layer of CrN was covered with a thickness up to almost 20 µm of aluminium alloy. The thickness of the nitride layer was partly reduced by the wear action. Where present, it ranged from less than 1 to about 2 µm. When the CrN layer was lost, the contact of the steel with the injected molten alloy caused local surface damage leading to the formation of pits (see Figure 5). The formation of a brittle intermetallic phase made up of Fe, Si and Al was proposed in literature as a cause for similar surface damage [4-6]. In the present case, EDS qualitative microanalyses did not revealed differences in chemical composition between the regions of early damage and the bulk material. Further investigations are needed to clarify the formation of these pits.

Microstructural analyses on longitudinal sections did not evidenced discontinuities at the steel/CrC-coating interface. The layer of carbides was almost continuous even if in some regions it became very thin because of partial scaling off (see Figure 6). The average thickness of the coating was of about 1 µm near the head of the core pins, and it increased up to 5 µm towards the non-working region of the pins. SEM analyses on longitudinal sections confirmed the presence of extended regions covered by aluminium alloy. An alloy layer thinner than the deposited CrC covered almost all the pins and it appeared to protect the inner coating from damaging. The thickness of the aluminium alloy increased up to 150 µm because of the formation of multiple layers in the most critical regions.

In the TiAlN coated core pins the presence of a double layer brought about by the deposition process was observed (see Figure 7). The external layer of nitrides appeared to be affected by circumferential cracks which extended from the interface with the inner layer to the external surface. These defects were probably brought about by the thermal cycles and they were mainly located far from the heads of the pins. Sometimes these cracks propagated into the inner layer and then into the steel. A certain amount of the external nitride layer had thus been easily chipped off in critical regions. Despite the local absence of the external layer and a certain number of microcavities mainly located next to the external microcracks, the inner layer was almost continuous with a constant thickness of about 0.5 µm. Its presence was not observed only when large extension of the external layer were absent. In these cases the pre-existing microcavities seemed to be the initial sites for erosion of steel. The total thickness of the coating, where present, was about 5 µm, independently on its location on the pin. Further, a thin layer of soldered aluminium alloy, up to 15 µm in thickness, was sometimes found on the coating of the pins more exposed to the flow of molten alloy.

The observations of the indentated regions left by the Rockwell C hardness before service gave an indication of the adhesion of the deposited layer to the steel. The adhesion is thought to decrease as the circumferential crazing increases or the coating regions flake off around the indentation [7]. Prior to service, the CrC and TiAlN coatings around the hardness indentations were circumferentially crazed but no flaked zone was detected, thus showing a good adhesion to the steel. After service, this simple tests (which evidently makes not sense where the coating is absent) gave different results for either the different coatings or for the aluminium covered or free zones. Extended flaking areas were observed around Rocwell B indentations on the CrC coated core pin in both regions. Limited rings of uncovered steel next to the indentation were found also in less critical cores coated with TiAlN. Here, the size of these areas was less extended where an aluminium layer was present. Finally, CrN coating adhered better to the inner material, since the flaked areas, where present, were of limited size. Further, some spots of CrN coating were sometimes found even on the indentation surface.

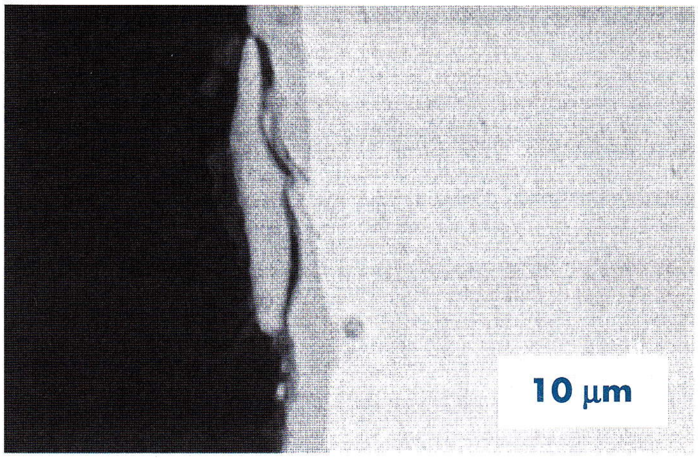

Figure 6: Partial scaling off of the CrC layer in a critical core pin. SEM micrograph pf a longitudinal section (the axis of the core pin is vertical)

Forging tools

The TiN cold-forming extrusion punch was examined after a service life of 87000 strokes. The tool was removed from service because of longitudinal marks in relief detected on the hole of the workpieces. Even if the punch featured generally good surface conditions as far as roughness was concerned, a number of longitudinal surface scratches corresponding to the above marks were observed. Frequently the scratches on the lateral belt of the tool only partially removed the titanium nitride coating. Sometime inside the grooves, the external layer was completely taken away. Here the unprotected steel was subjected to an easier damage as confirmed by the widened uncoated areas depicted by the micrograph in Figure 8. An extended uncoated circumferential region was also detected. The top impact area was observed to be richer of surface scratches interesting only the TiN layer that in this region featured a thickness of about 1.8 µm. Although more detailed information should be needed, it is supposed that hard particles furrowed the surface of the tool, their action being enhanced by the heavy flow, pressure and, in the working lateral regions, even by double rubbing cycles due to the extraction of manufactured parts. Warm forging tool showed similar features. Again, the impact zone was characterised by radial scuffing which interested only the external CrN layer, about 2 µm thick. Only small areas of coating and extensive radial scratching in the steel were observed in the sloping region at the top of the tool. In this location, the limited material flow was combined with high mechanical pressures. On the contrary, in blended regions, where extensive material flow took place, a greater surface roughness and deeper longitudinal scratches, even in lower amount, were observed (see Figure 9). SEM examinations on a longitudinal section also pointed out the presence of circumferential cracks that nucleated inside the zones of steel overlapping related to the extensive material flow under high

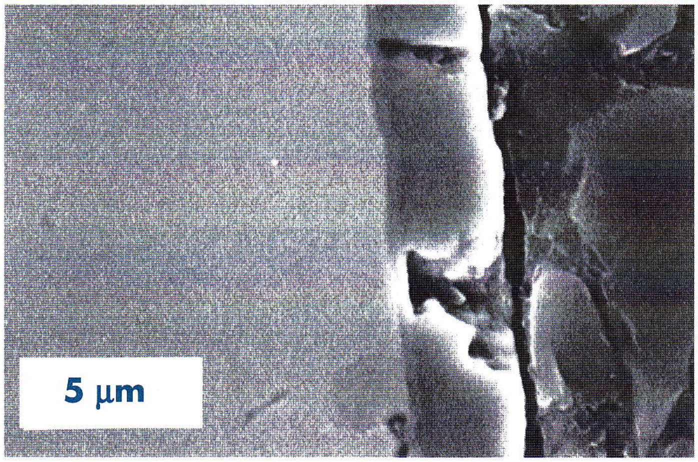

Figure 7: Typical features of an examined TiAlN coated core pin after a service life of 22000 shots. SEM micrograph of a longitudinal section (the axis of the core pin is vertical)

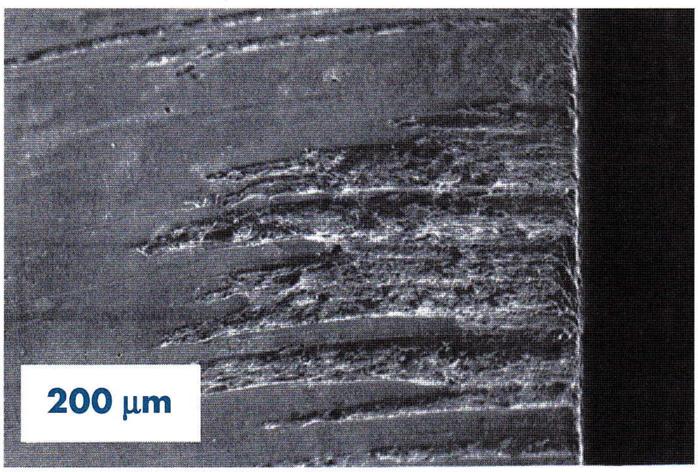

Figure 8: Typical damage on the lateral belt of the TiN coated cool forging tool. SEM micrograph of the surface near the transversal section; longitudinal axis of the punch: horizontal

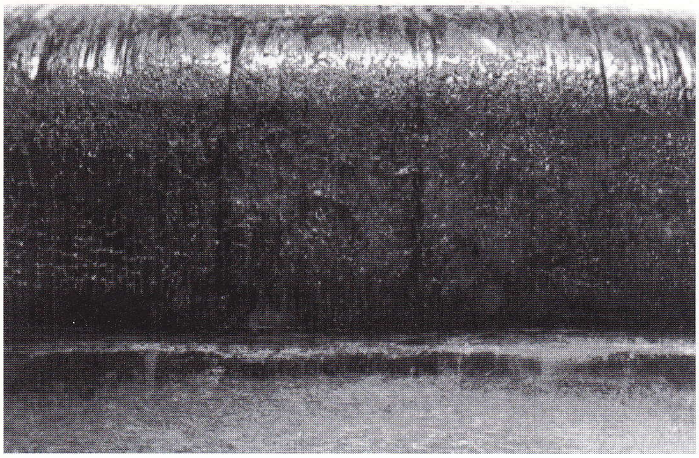

Figure 9: Blended and belt regions of the examined extrusion punch for warm forging after 40000 strokes. The axis of the tool is vertical

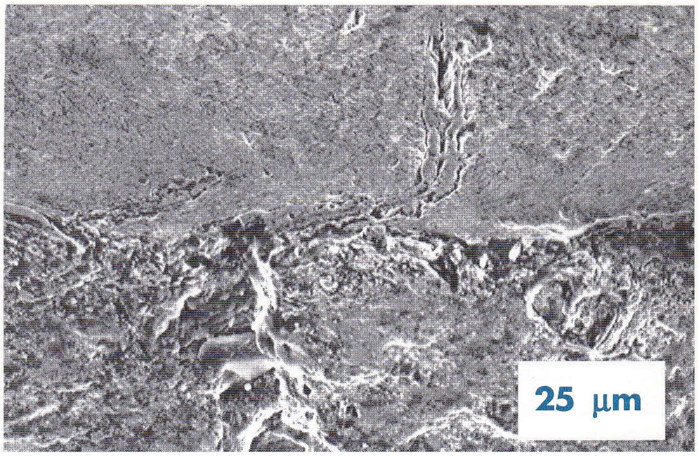

Figure 10: SEM micrograph showing both the lateral surface and longitudinal section (bottom and upper parts, respectively) of the warm forming tool in a region where a circumferentially oriented crack was present

pressures and tangential friction stresses. Early cracks, not traceable by surface observations, lay parallel to the surface. Longer fissures then turned to a radial orientation, presumably because of thermomechanical effects (see Figure 10). Both on the above blended region and on the flow material belt no more coated areas were detected. Below the blended zones, a net of longitudinal and circumferential cracks was observed. SEM examinations attributed to longitudinal ridges, circumferential laps and to high roughness, the nucleation of cracks having features similar to those observed in the blended regions. Moreover, below a certain zone, the opposite direction of the tangential stresses acting on the tool surface during the extraction of the workpiece changed the orientation of the overlapping effect. Thus, the first stage of the crack propagation was reversed in an intermediate circumferential belt where early nucleated cracks lay normally to the surface. Apart from the working head of the punch, no more crack nor extensive surface depletion were observed. Hot forming on the investigated oval-shaped pre-piercing punch enhanced the damage effects already observed on the previously examined tool. In this case, the entire working region was subjected to rubbing and heavy pressures together with high operating temperatures. Deep ridges and laps of flown material created on the surface the characteristic pattern depicted in Figure 11. No more coating was observed on this tool. As in the previously examined punch, material overlapping originated cracks which, during their growth, turned to a direction perpendicular to the surface. Additionally, radial scratches acted as nucleation sites for longer cracks. The surface of the tool and the edges of cracks were heavily oxidised.

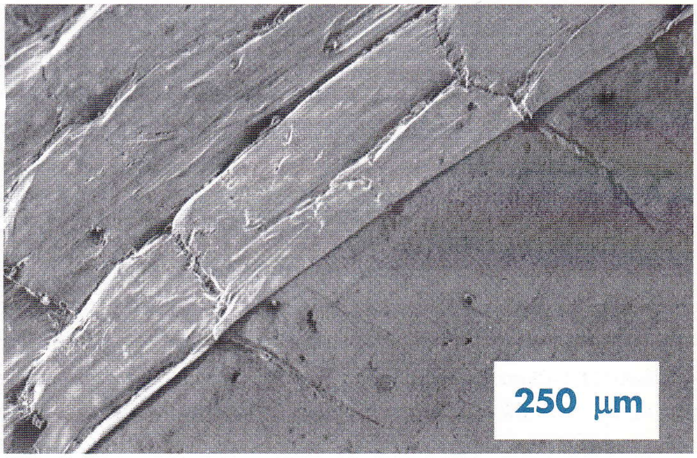

Figure 11: SEM micrograph showing the typical surface and the corresponding longitudinal section (right-bottom and left-upper sides, respectively) in the heavy flow region of the hot forming tool

DISCUSSION AND CONCLUSIONS

The analyses carried out on CrC coated core pins after 10990 shots showed a great tendency to the formation of multiple Al alloy layers. Even if it appeared that a layer of aluminium could better protect die-parts from wear, erosion and washout, the soldering of aluminium was detrimental for the surface quality of manufactured parts. TiAlN coating was prone to be particularly resistant to wear and to aluminium soldering. In fact, its thickness remained constant and thin layers of aluminium alloy were only occasionally observed. It should be noted that the TiAlN coating was subjected to cracking due to thermal effects. Limited soldering was observed on CrN pins, and discontinuities at the steel/coating interface made easy the removal of this layer and thus the wash out of steel. This is the main reason to be accounted for the worst erosion of these pins.

Results of hardness indentations were difficult to relate to microstructural observations. The former analysis gave positive results for CrN coated pins while the latter showed voids at the steel/coating interface and extended eroded regions where the coating was lost. On the contrary, CrC layer extensively flaked off while no interface discontinuities and an almost continuous CrC layer covered by aluminum alloy were found when examining longitudinal sections. Thus, it seems that the crazing and flaking off the coating is affected by several factors in addition to the adhesion of the coating to its substrate.

A proper discussion on the chemical composition of the most suitable coatings for aluminium die-cast application should take into consideration the commonly used surface treatments for die-cast dies [1, 8]. Comparisons have been made with another set of core pins (Tenifer QPQ treatment). In this case, after 9600 shots, a noticeable amount of soldered aluminium, comparable to that found on CrC coated pins, was observed together with significant wear of the steel and to evident extraction marks. As traditional heat treatments, CrC coating revealed to be prone to aluminium soldering. The set of pins coated by TiAlN, subjected to a number of shots double with respect to the others (probably examined almost at the end of their service life) demonstrated to be most suitable for use in aluminium die-cast dies. The latest coating (CrN), could be industrially used without any problem of aluminium soldering only for a shorter service life which appears to be limited by the accelerated steel erosion as soon as the coating is lost.

A general trend in the evolution of surface damage of PVD coated forging tools can be drawn by the observations of growing critical regions of the examined extrusion punches. The first depletion of surface characteristics corresponded to the formation of surface scuffing, which locally reduced the thickness of coatings. As the material flow and pressures increased, surface scratches reached the steel under the external layer. The above features were mainly observed in the cold forming tool. In addition, in punches for warm and hot forging, a number of cracks nucleated from the above radial and longitudinal ridges due to heavy thermomechanical cycles were detected. A further surface degradation took place in the areas of heavy rubbing. From the extensively deformed steel, laps formed from which cracks grew firstly parallel to the surface and then turned perpendicular to it. The direction of material flow, related to the workpiece extrusion or extraction phases, was found to determine the early growth of the cracks, which later developed mainly by thermomechanical fatigue.

The present study confirmed the industrial observations that steel damage rapidly occurs as soon as the external protective layer (in the present case, the different PVD coatings) is lost. In order to better understand the mechanisms of microstructural degradation which lead to the loss of the external layer, careful examinations should be carried out after increasing service periods, an experimental practice that economical reasons very seldom allow to be put into practice in industrial plants. Therefore, due to the encouraging results of PVD coating in extending the life of the examined tools and die parts and to the good perspectives for the industrial applications of such coatings, additional tests and analyses are in progress aimed at investigating in a greater detail some of the aspects illustrated in the present paper.

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FIGURE CAPTIONS

Figure 1. Schematic geometry of an extrusion punch.

Figure 2. Surface features at the head of the CrN core pin in the most critical location after 11200 shots.

Figure 3. Surface features at the head of the CrC core pin in the most critical location after 10990 shots.

Figure 4. Surface features at the head of the TiAlN core pin in the most critical location after 22000 shots.

Figure 5. Typical features of CrN coated pins. SEM migrograph of a longitudinal section (the axis of the core pin is vertical).

Figure 6. Partial scaling off of the CrC layer in a critical core pin. SEM migrograph of a longitudinal section (the axis of the core pin is vertical).

Figure 7. Typical features of an examined TiAlN coated core pin after a service life of 22000 shots. SEM migrograph of a longitudinal section (the axis of the core pin is vertical).

Figure 8. Typical damage on the lateral belt of the TiN coated cool forging tool.

Figure 9. Blended and belt regions of the examined extrusion punch for warm forging after 40000 strokes. The axis of the tool is vertical.

Figure 10. SEM micrograph showing both the lateral surface and longitudinal section (bottom and upper parts, respectively) of the warm forming tool in a region where a circumferentially oriented crack was present.

Figure 11. SEM micrograph showing the typical surface and the corresponding longitudinal section (right-bottom and left-upper sides, respectively) in the heavy flow region of the hot forming tool.