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High temperature tribological behaviour of tool steels during sliding against aluminium

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ABSTRACT

Soldering and abrasive wear of die-casting tools are some of the biggest problems facing the aluminium die-casting industry. The understanding of the tribological behaviour is crucial to design new tool steels and tool steel-coating systems. The present study aims at investigating aluminium adhesion of aluminium/tool steel pair, performing sliding tests at high temperature with ball-on-disc configuration to reproduce solid/solid interaction. Different test conditions have been conducted in order to select the optimal test parameters to obtain aluminium adhesion on disc surface. Once the lab test has been designed, the high temperature tribological performance of different hot work tool steels (uncoated and coated by PVD) sliding against aluminium has been studied to allow proper die material design and selection.

1. Introduction

High-quality aluminium castings for automotive parts such as engine blocks, carburettor bodies, transmission cases and valve bodies are usually produced by high pressure die-casting (HPDC). HPDC is a single step process in which molten metal is injected into water or oil cooled metallic mould or die under high velocity and high pressure, allowing high volume production of uniform castings. When solidification is completed and die casting has cooled sufficiently, the die is opened and the part is ejected mechanically by activated pins. Dies have a high economic cost (often above $100,000) and a high incidence on the produced piece cost (about 20% in aluminium die casting), thus their longevity is of extreme importance. The harsh conditions during the casting operation (high temperatures, chemical attack by molten alloys, and high stresses) may cause premature damage in dies and markedly decrease the process efficiency [1,2]. Most common types of failure include: thermal fatigue (e.g. heat checks [3] and corner cracking [4]), die soldering (adhesion of the cast alloy to the die) [5,6] and washout (includes corrosion, erosion, cavitation and abrasive wear) [7]. Most of these damage types are due to wear phenomena acting during the exposure of the die surface to the liquid aluminium, the motion of the liquid aluminium and the solidification and ejection of the casting. Soldering of aluminium to the die is one the major causes of production interruption for die maintenance tasks. Such damage is not easy to repair, soldered layers are usually mechanically polished or, in severe cases, they are removed by chemical attack or by re-melting, which often affects the die surface integrity. Since the cast part sticks to the die when soldering occurs, it also leads to problems during ejection of the casting, as more force is needed to separate the casting, which can result in warped castings and bent ejector pins [6,7]. Die soldering can be subdivided in two categories: metallurgical/chemical and mechanical. Metallurgical/chemical soldering occurs at high surface temperatures and is associated with corrosion and growth of intermetallic layers. Mechanical soldering, in the other hand, does not require too high surface temperatures, it develops when high pressure is applied and promotes the sticking of the melt aluminium to the die. Both mechanical and chemical soldering occur simultaneously, resulting in a mixed type of soldering [6,8]. There are several works dealing with liquid/solid interaction between molten aluminium and different tool materials [2,5,9]. Lab scale casting machines and immersion tests were employed in these works to reproduce chemical interaction between materials. However, limited information is available about the solid/solid interaction between the aluminium and the tool material during HPDC.

In the present work solid/solid interaction is studied in order to reproduce aluminium adhesion phenomena on tool steel. The understanding of the tribological behaviour is crucial to develop new tool steel and tool steel-coating systems. The tribo-physico-chemical mechanisms during die/casting interaction at high temperature are very complex and could involve friction, wear, material transfer, oxidation and deformation simultaneously. Direct examination of industrial tools may provide information

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about the acting damaging mechanisms but this is tedious, time consuming and may be not feasible in some industrial applications (mainly due to the size of tools and their high cost that do not permit the use of destructive analyzing techniques). Thus, a lab scale test that reproduces the tribological behaviour of tools during HPDC will help to evaluate the applicability of different tool steels or hard coatings.

To our knowledge, very limited tribological investigations have been conducted for aluminium/steel pair and even less at high temperature, aimed at reproducing the tribological conditions acting in HPDC. Menezes et al. [10,11] used an inclined pin-on-plate sliding tester to study the effect of surface texture at RT while sliding a pure aluminium pin on EN8 (unalloyed medium carbon steel) plates with different roughness and directional grinding marks. It was observed that the coefficient of friction and transfer layer formation depends primarily on the directionality of the grinding marks of the harder mating surface. Ni et al. [12] investigated the tribological behaviour of non-hydrogenated and hydrogenated diamond-like-carbon (DLC) coatings against A319 aluminium alloy at 25, 120, 240 and 300 °C through pin-on-disc tests. At elevated temperature, aluminium stuck to non-hydrogenated DLC, while the hydrogenated DLC maintained its non-sticking nature although its wear resistance started to decrease when the temperature was higher than 120 °C due to graphitization. A block-on-cylinder [13] (AISI H13 as block and AA6063 Al-alloy as cylinder) wear resistance rig was used to elucidate the effect of an iron nitride compound layer on the wear resistance of nitrided dies used for hot extrusion of aluminium. Tests were conducted at 510 °C and it was found that the compound layer is comparatively more chemically stable against hot aluminium than the nitrided die material. A flat-on-flat test method was used to measure friction, wear and adhesion of AA5083 aluminium and AZ31B magnesium alloy sheets against tool steel (AISI P20) at RT and 450 °C [14]. This test allows to screening of the tool surface material coatings and lubricants.

In the current study, a lab scale test is designed to perform wear test at high temperature aimed at reproducing as close as possible the aluminium adhesion on tools during HPDC. A ball-on-disc test configuration where aluminium balls are used as a counterpart for sliding on hot work tool steel discs is chosen. With this test configuration it is expected to reproduce aluminium adhesion on HPDC tools, which is one of the main tool damaging mechanisms. Different test conditions are examined in order to select the optimal test parameters to obtain aluminium adhesion on disc surface. With the selected test parameters the tribological behaviour of different coated and uncoated tool steels grades is investigated in order to rank their applicability in HPDC dies.

2. Experimental

Two commercial hot work tool steels with hardness levels usually applied in hot forming tools, DIN 1.2344 (41 and 52 HRC), and HTCS-150 (52 HRC) and HTCS-170 (52 HRC) were used to prepare discs samples of 40 mm in diameter and 5 mm in thickness. The DIN 1.2344 is one of the most used tool steels in HPDC, meanwhile the HTCS steel grade is a recently developed tool steel characterized by the high values of thermal conductivity. The HTCS grades have been successfully applied to decrease the time cycle in HPDC [15]. Disc surfaces were grounded and polished following conventional metallographic procedures using diamond particles of 1 μm as a final polishing step. The resulting roughness is $R_a < 0.1$ μm. A CrN coating of 13 μm thickness with a roughness of $R_a = 0.6$ μm was deposited on discs of HTCS-150 using a commercial cathodic arc PVD reactor. Table 1 shows a brief description of these materials.

Table 1
Tool steel materials used in tribological tests.

Material	Description
DIN 1.2344	Reference material, k^a 28.4 W/mK (at 400 °C)
HTCS 150	Powder metallurgy alloyed tool steel, k^a up to over 66 W/mK
HTCS 170	Remelted alloyed tool steel, k^a up to over 53 W/mK
HTCS 150 + CrN	Commercial PVD deposition of a CrN coating of 13 μm, 0.6 μm R_a

[a] Thermal conductivity.

Table 2
Tribological tests performed on DIN 1.2344 (1400 cycles in each case).

Test ID	Hardness (HRC)	Speed (m/s)	Load (N)	Temperature (°C)
A	41	0.025	8	450
B	41	0.025	15	450
C	52	0.025	8	450
D	52	0.025	15	450
E	52	0.05	8	450
F	52	0.05	15	450
G	52	0.025	8	250

High temperature sliding tests were carried out in a CETR UMT-2 tribometer with ball-on-disc configuration. An aluminium ball (diameter 9.5 mm) of AA2017-T4 alloy was used as counterpart. Different test conditions varying sliding speed (0.025 and 0.05 m/s), load (8 and 15 N), temperature (250 and 450 °C) and disc hardness (41 and 52 HRC) were conducted on discs in order to select the optimal test parameters to obtain aluminium adhesion on disc surface. 1400 cycles were performed in all tests in order to obtain measurable and reproducible wear rates that allow computing an average value of the tribological behaviour.

Wear scars on disc surfaces were examined by means of optical confocal microscopy (Sensofar Plμ 2300), scanning electron microscope (SEM, ZEISS ULTRAplus) and energy dispersive X-ray analysis (EDX). The wear loss and stuck material volumes were calculated from the cross sectional area of the wear track obtained in 8 zones by optical confocal microscopy (200X) of the scar. By means of an image analysis software (SensoMap) an average profile of each image was used to calculate the negative and positive volumes. The normalized wear rate ($K_{negative}$, in mm^3/N m) was defined as the volume loss per sliding distance per normal load. An equivalent positive rate ($K_{positive}$) was calculated for stuck or piled up material with the same units.

3. Results and discussion

3.1. Tribological test parameter selection

In order to study the test parameters influence on the tribological behaviour of the aluminium/tool steel pair, several tribological tests were performed varying these parameters as indicated in Table 2.

Fig. 1 shows the normalized wear rates identified as negative (for volume loss) and as positive (for volume gain). It should be noticed that negative values may hide adhesion of material in the wear track, meanwhile positive values may include volume gain due to deformation of material, not only due to aluminium adhesion. However, the normalized wear rates show a tribological behaviour trend.

Fig. 2 shows the aluminium weight percentage measured by EDX mapping in disc wear scars with the same magnification for all samples (4 different zones of each sample were examined). These values complement the tribological trend observed in Fig. 1. Normalized $K_{negative}$ rate of tool steel discs shows a high material loss in tests B, E, F and G, indicating a predominant abrasive wear mechanism. $K_{positive}$ is higher in tests C and D that means transfer of material