Surface & Coatings Technology 307 (2016) 28–37

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

# Temperature effects on DLC coated micro moulds

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ARTICLE INFO

*Article history:*
Received 11 May 2016
Revised 28 July 2016
Accepted in revised form 15 August 2016
Available online 16 August 2016

*Keywords:*
Micro injection moulding
DLC
FEM
Polymer processing
Thermal stability
Micro fabrication

ABSTRACT

Microinjection moulding is a key enabling technology for replicating miniaturized components and parts with functional features at the micrometer and even sub-micrometer length scale. The micro moulding tools used in the process chain are critical for delivering high quality parts for the duration of the product life cycle, and recently tool coatings such as Diamond-like carbon (DLC) have been used to extend their use and enhance the performance. The micro injection moulding process has high injection speeds with cyclic heat transfer characteristics, and little is understood on how the localised heat transfer at the surface will influence the DLC surface coating delamination and cracking. In this research a microinjection moulding process using three different polymers, Polypropylene (PP), Acrylonitrile butadiene styrene (ABS) and Polyether ether ketone (PEEK) is studied. Finite element analysis (FEA) simulation is utilised to identify the process temperature factors that lead to tool thermal expansion and dimensional changes that directly impact the life cycle of the coating. The theoretical and FEA results show that the mould material and the two coatings experience a significantly different thermal expansion from each other. It has also been shown that at the micro scale heat loss at the tool surface is dominant, and the variation in heat has a significant influence on the different thermal expansion rates. In particular the DLC coated micro rib features are particularly susceptible to high variations in heat transfer. The research identifies areas of the tool surface that experience sudden heat variation across the part surface, and concludes that through process optimisation it is possible to reduce the potential for DLC coating delamination and cracking during service.



## 1. Introduction

The emerging capabilities within the micro manufacturing replication process of micro injection moulding (μ-IM) have enabled the mass production of lighter, thinner and smaller devices for demand led applications within the sectors of healthcare, automotive, communication and consumer electronics [1]. As a result, the technology faces new challenges with regards to the process optimisation, high productivity, advanced mould cavity engineering and precise process control [2,3]. To meet demand, injection mould machinery manufacturers have developed discrete machines specifically for micro component replication that have added functionality and simplified integration of ancillary processes such as product handling, inspection and packaging [4].

The process of μ-IM has the benefit of replicating a large variety of structured surfaces incorporating functional features within the micro and nano meter range [3]. However, the manufacture of the moulding tools that incorporate micro and nano features and enhance the replication fidelity (RF) at all scales remains a key enabling component of the process chain [3]. Micro moulding tools are manufactured through the innovative combination of complementary micro/nano machining and structuring technologies such as micro electrical discharge machining (μEDM), laser ablation, micro milling and focused ion beam machining [5–9]. The demand for micro/nano length scale integration features within injection moulding tools results in cavities being produced with technologies that combine so called top-down structuring with bottom-up technologies. The bottom-up technologies allow polymer based self-assembly technologies to deposit on the cavity surface. The deposition of features onto the cavity surface can be used for component surface functionalization or for processing enhancement.

The development of the underpinning micro tooling and subsequent μ-IM polymer replication has been implemented for applications within microfluidic, 'Lab-on-a-Chip' (LoC), inkjet printers, water purification systems, opto-fluidic microscopes, microelectronic cooling, micro chemical reactors and micro fuel cells systems [10]. The μ-IM process is highly suited for high volume manufacture of these devices which are inexpensive and light weight, and can be considered as disposable alternatives to ceramic platforms. To meet the growing demands within this area requires the key elements of tooling and process to adopt new technologies for higher reliability, higher accuracy and longer life with low maintenance costs. These requirements can be achieved, for

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http://dx.doi.org/10.1016/j.surfcoat.2016.08.034

example, by modifying the surface of machine elements by adding protective coatings on metal substrates. Thin films are also known as coatings, are layers of material(s) used to protect a part from premature wear resulting from the interaction of the processing environment.

In this paper, the deposition of an amorphous hydrogenated carbon (aC:H) coating on mould surfaces is modelled to determine the effect that cyclic heating and cooling have on the resulting thermal expansion of tooling coating. The paper is organised as follows. The next section reviews surface treatment technologies utilised in tool-making and the functionalities that can be introduced by their application. The subsequent section introduces the theory of thermal expansion. Then, the experimental set-up used to investigate the effects of the μ-IM process on coated mould tools is described. Finally, the experimental results of the simulations are presented and the capabilities of surface treatment of μ-IM tools is analysed.

## 2. Tooling surface technologies

Traditionally, improving the wear resistance of moulding surfaces was achieved through the application of advanced steels, ranging from ingot cast martensitic matrix steels to advanced powder metallurgy tool steels with a high content of hard carbide particles [11]. However, more recently coating technologies for structured/engineering surfaces have been applied to increase wear resistance and also to functionalise surfaces [12,13–15]. Different manufacturing technologies can be applied to structures and engineering surfaces and they include a broad range of processes. These include sand blasting, innovative grinding systems, focus ion beam, nano-imprint lithography, chemical texturing and laser machining [13,14,16,17].

### 2.1. Coated surfaces

Diamond like carbon (DLC) coatings belonged to the amorphous hydrogenated carbon (aC:H) group and are used for the coating of plastic injection moulding inserts [3]. DLC coatings improve the replication performance of the micro and nano structured masters [12]. This is achieved through a combination of superior tribological and mechanical properties such as low friction, low wear and high hardness when compared to traditional tool materials [18–20].

The low friction coefficient that results in low wear surface characteristic can be explained with the high ratio between the hardness and Young's modulus and the low ratio between the surface energy and hardness [21]. Typically, the surface treatment of inserts using pulsed laser deposition (PLD) of DLC coatings yields surface hardness of up to 70 GPa with friction coefficients in the range of 0.05–0.2, an order of magnitude lower than that of ceramic coatings [22]. Further investigations of DLC coatings where special attention was paid to the inhibiting role of gas–surface interactions, showed that duty cycles with control variables of time and speed resulted in super low friction coefficients of 0.003–0.008 [23]. In the research conducted by Saha et al. the effect of surface properties of micro structured masters on the hot embossing process was investigated by using nitrogen (N) and nickel (Ni) doped diamond like carbon (N:DLC:Ni) coated and uncoated silicon (Si) micro moulds. The results demonstrated that even with high friction and adhesion characteristics of this replication process the N:DLC:Ni coated Si masters successfully increased the mould lifetime by 3–18 times when compared against uncoated moulds [24].

Bremond et al. studied the tribological behaviour of DLC-coated 100C6 when subjected to a temperature increase from a room temperature to 400 °C. The DLC coatings belonged to the amorphous hydrogenated carbon coatings' group. The results have shown that when used at temperatures higher than 200 °C the coating damage increases significantly due to stiffness reduction of the 100C6-steel substrate [25].

Sasaki et al. investigated the ejection force ($F_e$) with a consideration of the tool surface roughness and the tool surface coatings [26]. The experimental results demonstrated that when moulding PP and PET a reduced $F_e$ and product deformation were achieved when the surface roughness of the inserts was in the range of Ra 0.212 to 0.026. The PMMA samples required a lower $F_e$ when surface roughness was Ra 0.092. Also, the results showed that any $F_e$ reductions were dependent both on the optimised surface roughness and the polymer material used in the moulding trials. In addition, it was concluded that the PVD WC/C carbon coating was the most effective in reducing Fe [26].

In micro injection moulding, large surface area to volume ratios are typical and result in high adhesion forces between mouldings and the tool surfaces [24]. However, it was reported that by treating the mould surfaces with DLC coatings when moulding PC and ABS polymers a $F_e$ reduction of 40% and 16%, respectively, was achieved in comparison with untreated surfaces [12]. The benefits from using DLC coatings in micro replication processes are proven [24].

### 2.2. The effects of polymer materials on coating delamination

The ability to predict the interfacial delamination of coatings has a major technical significance with regards to lifetime assessment of products under service conditions. In a study by Di Leo et al. the delamination properties of thermal barrier coatings (TBC) was simulated to determine the relevant material parameters appearing in a traction-separation-type law. The methodology developed in the research is used to determine the material parameters for TBC systems [27]. Kang et al., investigated the delamination of DLC films on titanium alloys. The research concluded that by depositing a TiCN interlayer between the Ti-6Al-4V ELI alloy and the DLC film an improvement in hardness, elastic modulus and interfacial bonding can be achieved. In addition the resulting coefficient to friction was 0.03 ($°C^{-1}$) [28]. Escudeiro et al., studied the wear properties of UHMWPE and PEEK when in contact DLC and Zr-DLC coatings. In the study each material was subjected for 2 million cycles (Mc). The research concluded that Zr-DLC delaminates after 1.2 Mc. The delamination was caused by synergetic stress-induced corrosion which introduces interface fatigue [29].

In a study by Zhang et al., the application of DLC on enhancing the life cycle of artificial joint was investigated when using different substrate materials. In particular, stainless steel, CoCrMo alloy and titanium alloy substrates were used. In the research it was found that the failure mode of DLC coatings on 316 stainless steel and CoCrMo alloy through friction testing was coating delamination. Finally, the report also concluded that DLC coating on Ti6Al4V has superior wear resistance in addition to better stability in immersion and electrochemical tests [30].

## 3. Thermal expansion

In addition to mechanical interactions such as injection pressure, shear stress, clamping force and friction between the resulting mould surface and polymer melt, the filling (heating) and cooling stages of the process result in cyclical temperature gradients. Delamination of coatings can occur during the transient change of temperature and the thermal expansion variation between the tool and the coating substrate.

### 3.1. Linear thermal expansion

The change in length that takes place when a solid body is subjected to a change in temperatures depends on the original length of the body and the temperature change over which it is heated or cooled. The relationship between these factors is known as the average coefficient of linear thermal expansion ($\propto_{t_2}^{t_1}$) defined by Eq. (1) the as:

$$\propto_{t_2}^{t_1} = \frac{L_2 - L_1}{L_R(t_2 - t_1)} \tag{1}$$

where ($t_1$) and ($t_2$) are the initial and final temperatures, ($L_1$) and ($L_2$) are the initial and final lengths, respectively, and ($L_R$) is the length at a reference temperature.