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Surface finishing of intricate metal mould structures by large-area electron beam irradiation

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ABSTRACT

The advancement of polymer moulding tools is increasingly focused on imparting not only form but also surface texture for functionality to the surfaces of parts that are created. Furthermore, the increasing demand for inexpensive and higher quality micro-components means that tools for replication processes must take advantage of advanced manufacturing techniques. Tools created by processes such as micro-investment casting, as in this case, may often suffer from excessive surface roughness, malformed edges and general deformation. This results in higher de-moulding forces and a reduction in fidelity of moulded parts to design intent. In this study, large-area electron beam irradiation (EB) is shown to be an effective technique for improving these metrics. For the first time, large population, high aspect ratio micro-features are subject to this process and the mechanisms of smoothing and key enhancement phenomena are demonstrated. The possibility of including EB irradiation in an integrated process chain for arriving at net shape is also discussed.

Surfaces of protruding features are shown to have surface roughness reduced significantly from 126 to 22 nm Ra value, with bottom substrate also similarly improving from 150 to 27 nm Ra. Bottoms of recessed features are also observed to have much improved surface finishes. 'Doming' of tops of column features is also demonstrated, further enhancing form. These features would be far too fragile to be polished by any other mechanical method.

1. Introduction

The ability of replication/moulding techniques, to create micro-components and micro featured components is continually improving. This is largely driven by consumer demands for plastic components with enhanced performance or functionality [1]. Surface microstructures can affect the properties of a surface, including tribological characteristics such as coefficient of friction and wear [2], appearance and optical characteristics [3], heat transfer coefficient during boiling and condensation [4], and water repellency [5–9]. Micromoulding is a scalable route to manufacturing microstructured surfaces [10–12]. The requirements for scaling micromoulding tools to high volume applications are that the moulding tools must be made of durable metal such as steel and be of low cost.

Increasing pressure is being placed on suppliers to produce so called 'micro' components or indeed larger components which include microstructures. For such components or features on components to be produced in large volumes and within the customer price expectation replication technologies are the only viable methodology. Recent moulding technologies have been increasingly focused upon designing intricate microstructures in metal moulds [13–15] in order to impart enhanced surface properties upon the final polymer part such as increased hydrophobicity [14,16] Metal microstructures and nanostructures are attractive for micro-manufacturing moulds [17] as they can be reused many times more than moulds composed of traditional microfabrication materials such as silicon or quartz. Embossing, moulding, rolling, and stamping can produce microstructures at 1/1000 the cost of conventional fabrication techniques such as silicon microfabrication, micro-milling, or laser micromachining. Unlike paint, spray, or plasma-based surface finishes, micromoulding can fabricate lithographically defined and ordered three dimensional microstructures [10–12].

With increasing demands for higher form accuracy and lower surface roughness of produced parts, technologies for the finishing of mould tools have been the subject of much research [18]. A rapid and predictable ejection mechanism during mechanical separation at the end of the moulding process is also vital to the repeatability of the operation and the quality of the finished part and it is known that higher surface roughness increases friction coefficients and the

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required de-moulding forces between tool and moulded part [19]. The surface finishing of intricate, precision components is therefore highly important.

For flat surfaces, ultrasonic polishing, an adaptation of ultrasonic machining has been demonstrated using an abrasive slurry and a CNC tool [20,21], with an Ry roughness of 7 nm achievable, although the size of the tool and abrasive nature of the process limits this from being applied to intricate, non-flat surfaces. Laser polishing has also been applied to the finishing of both flat milled tool steel [22] and structured moulds [18] since it is a non-mechanical polishing process, although a roughness of approximately 0,5 μm was achieved, much higher than that from abrasive techniques on flat surfaces. Laser polishing also requires a focused beam and its rastering across the surface, and a significant remelted and heat-affected zone is produced. Electro-chemical polishing (ECP) [23] has also been demonstrated as a potential technique for the process, although it is not desirable since it is time consuming, asperity dependent and incurs an environmental burden. Effluent resulting from ECP presents a significant disposal challenge.

Large-area electron beam irradiation has been demonstrated as a highly efficient method of polishing metal mould surfaces, and is capable of finishing surfaces machined by laser beam [24] and EDM [25,26] with improved corrosion behaviour observed. Since it is a pulsed process and the heating/cooling cycle usually occurs in under 10 μs, repetition of the irradiation process is used to gradually achieve the finish, and a large remelted/recrystallised zone is not produced. Because of this, the process is suited to the polishing of intricate structures for which their intended form must be retained. The process is also clean with no material wastage, requires no precise set-up procedure and takes place in a vacuum, eliminating the possibility of oxidation. In this work we apply for the first time the electron irradiation technique to the polishing of highly intricate and high-aspect ratio metal mould structures. This paper reports an investigation into the application of electron beam parameters to the change in form and surface roughness of metal mould structures. X-ray diffraction (XRD) is also used to interrogate the surface microstructure and expose any phase or crystallographic texture changes induced by the process.

Table 1
Specimens subjected to electron beam irradiation.

Sample designation	Material	Description	Dimensions (μm)
a	17-4PHA	Rods, circular	Ø80
b	17-4PHA	Holes, circular	Ø80
c	17-4PHA	Holes, circular	Ø40
d	17-4PHA	Holes, circular	Ø20
e	17-4PHA	Rods, square	25 × 25
f	17-4PHA	Rods, circular	Ø100

2. Experimental

2.1. Metal mould structures

In this study six micro-structured specimens were investigated to understand the effect of electron beam irradiation upon varying morphology. These structures have been specifically designed to introduce texture and surface functionality into plastic moulded components. A breakdown of the microstructures with dimensions can be seen in Table 1, and SEM images of each surface are presented in Fig. 1. The material used for all tests was AISI 630, [17-4PHA]. It is a precipitation hardening martensitic stainless steel with composition: Cr 15–17.5%, Ni 3–5%, Cu 3–5%, Mn, P, S, Si, Ta, Nb < 1%, C 0,07%, and Fe balance.

Typical features produced via the investment casting method were selected. This process chain begins with a rapid prototyped polymer part onto which a silicon rubber is cast. A ceramic is then cast to the microstructured rubber, after which metal is cast to the structured ceramic, resulting in a microstructured mould used to impart features on to a final polymer part.

2.2. Electron irradiation experiments

A Sodick PF32A EBM machine was used for electron beam irradiation experiments (schematic in Fig. 2). The irradiation process is carried out in an air-tight chamber into which an inert gas, Argon at a pressure of 0,05 Pa is supplied, after an initial 10 min vacuum cycle time. This Argon gas is used as the medium for plasma build up required for the electron generation and beam propagation. The

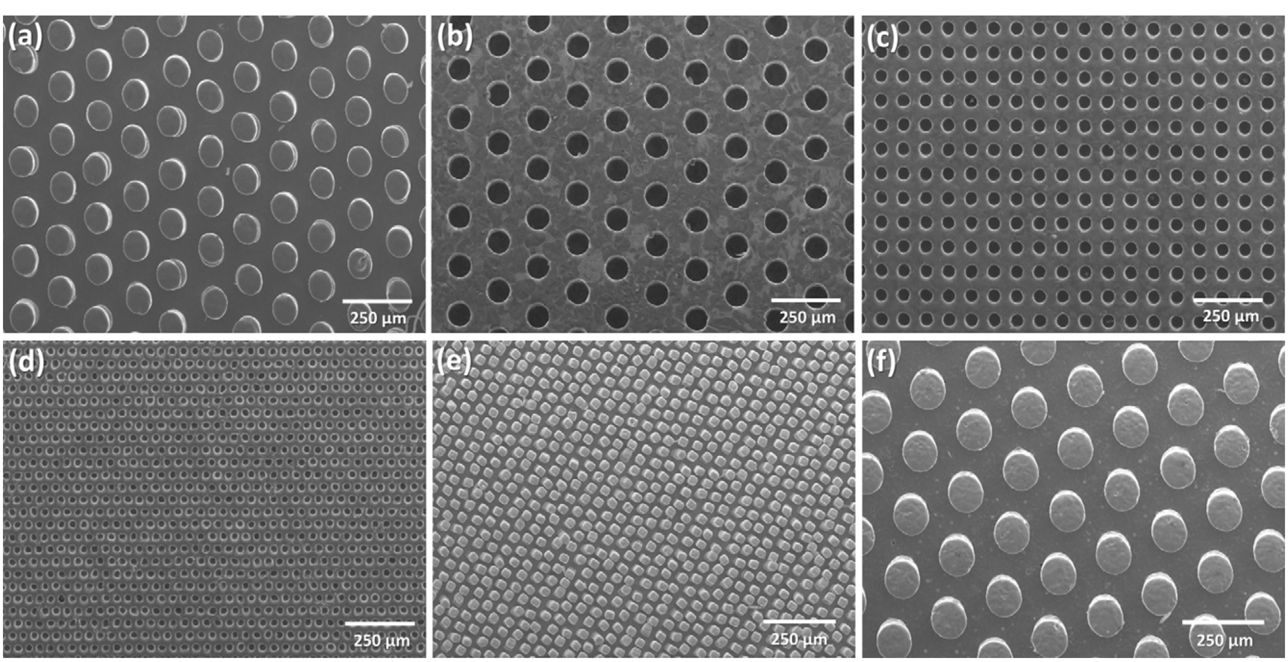

Fig. 1. Array of mould structures used in this study. Figure label corresponds to designation in Table 1.