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Effect of curing parameters and configuration on the efficacy of ultraviolet light curing self-adhesive masks used for abrasive jet micro-machining

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ABSTRACT

Abrasive jet micro-machining (AJM) uses a high speed jet of particles to mechanically etch features such as micro-channels into a wide variety of target materials. Since the resulting air-particle jet is divergent, erosion resistant masks are required for patterning. Because of their ease of application, 50 and 100 μm thick commercially available ultraviolet (UV) light curing self-adhesive masks are potentially very useful in AJM. However, optimum curing parameters have until now been specified in terms of a curing time for a specific recommended curing unit, making extrapolation to other curing units impossible. Using masks to create straight 250–600 μm wide reference channels in borofloat glass, this paper quantified the optimum curing UV light energy density, and investigated the effect of differing UV exposure units (flat and cylindrical-backed), UV light energy densities, and mask configuration during curing, on the pattern transfer accuracy (before AJM), and the eroded micro-channel feature size. As expected, as long as the masks were cured at the same energy density, the pattern transfer accuracy did not depend on the curing unit. The most accurate pattern transfer to the mask film (widths within 5–7% of design) corresponded to energy densities between 516–774 and 387–516 mJ/cm^2 for the thick (100 μm) and thin (50 μm) masks, respectively. Under these conditions and for both exposure units, the average widths of the eroded channels after AJM were found to be within 3–9% of the intended design. Curing the masks outside this range resulted in eroded features that were approximately 15–20% and ~5% larger than intended, for the thick and thin masks, respectively. The orientations of the channel patterns with respect to the curing cylinder axis did not affect the pattern transfer. However, when compared to the cylinder ends, curing at the midpoint along the cylinder length improved the pattern accuracy by approximately 3%, resulting in eroded features that were 10–20% closer to the design width. Finally, it was found that patterning multiple layers of masks improved the erosion resistance without compromising the feature width, enabling the AJM of higher aspect ratio features.

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1. Introduction

Abrasive jet micro-machining (AJM) uses a jet of particles, directed through a patterned erosion-resistant mask, to etch features for the micro-fabrication of a wide variety of devices. For instance, Schlautmann et al. [1] reported fabricating electrophoresis capillaries, Belloy et al. [2] fabricated glass inertial sensors, Park et al. [3] etched micro-molds in steel, Yamahata et al. [4] machined ball valve micro pumps in glass, and Ghobeity et al. [5] generated microfluidic chips in glass.

There have been a number of studies related to micro-device fabrication using AJM with patterned masks made from various metallic and polymeric materials. For example, Wensink et al. [6] examined two polymers that could be structured lithographically on glass, and studied the use of electroplated copper as a mask attached to a glass substrate over a titanium binding film. The study showed that the resulting copper mask had high erosion resistance, and channels as small as 50 μm in width could be fabricated in glass. Liao and Chen [7] fabricated 240–575 μm microgrooves and holes on brittle silicon wafers using AJM with lithography. First, the substrate was preheated at 80 °C and coated with a water-soluble resin, a mixture of polyvinyl alcohol and polyvinyl acetate. After drying the first layer, they formed a second layer using a combination of urethane acrylate oligomer, photopolymerization, and an initiator with strong adhesion to the first layer and strong resis-

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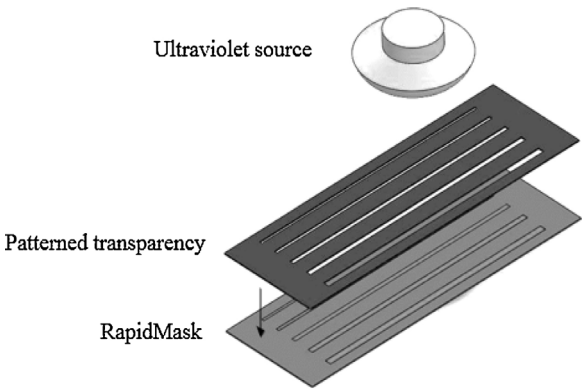

Fig. 1. Procedure to cure the RM using a patterned transparency that allows UV light from the source to pass through the transparent patterns of the photomask. The UV light is transferred onto the photosensitive RM film.

tance to AJM. After the layers were formed, photo-etching was used to achieve desired patterns which were then machined using AJM. Pawlowski et al. [8] used epoxy and polydimethylsiloxane (PDMS) masks attached to glass substrates, in conjunction with lithography techniques, to achieve feature sizes of 20–30 μm after blasting the glass with 10 μm diameter aluminum oxide particles. Lomas et al. [9] used PDMS and SU-8 as masks on stainless steel to make a precision hot embossing metal mold. Park et al. [10] reported using AJM to fabricate microgrooves as small as 80 μm on glass using an ultraviolet (UV) light hardening polyurethane mask, BF405. Preparation of the masks, however, required a complex a multi-step process. Belloy et al. [11] reported creating complex microstructures in glass with aspect ratios between 5 and 10, by using steel masks attached to the glass, and rotating the specimen while machining at both normal and oblique incidence. Yagyu et al. [12] presented a rapid prototyping method to fabricate a glass chip using AJM and direct laser patterning of a polymer, AuPU4, as a mask coating on a glass substrate.

A number of authors have compared the performance of different mask materials in AJM applications. For example, Slikkerveer and Touwslager [13] investigated the use of three different elastomeric coatings as AJM mask materials, a 100 μm laminate dry-film resist (Ordyl BF410), a flexographic printing material (LF55G1), and ab aliphatic urethane diacrylate oligomer film (Ebecryl 270), and found that the maximum erosion occurred at oblique angles in all three cases. All three materials were polyurethane (PU) acrylate based, suitable for photolithography, and it was found that the LF55G1 was the most erosion resistant. Achtsnick et al. [14] studied the erosion resistance and pattern transfer accuracy of a variety of metal, elastomer and photoresist AJM mask materials. They reported that metal masks were generally more suitable for high particle velocities and fast production processes, but that the minimum achievable feature width was limited to 300 μm. For electroplated copper masks, the achievable mask thickness was limited to 10–30 μm. Electro-formed zinc was found to be a good alternative because it could be applied in thicknesses of 1 mm or higher, resulting in a large erosion resistance, albeit at the expense of a larger minimum achievable feature size. They also studied four types of self-adhesive elastomer foils and concluded that they were suitable for more complex pattern transfers, but did not perform well under higher air pressures due to their elastic behavior. They found that the epoxy-based photoresist SU-8 was a good compromise to use in order achieve improved accuracy, although the equipment to prepare the mask was relatively expensive.

Self-adhesive masks are of particular interest in AJM applications because, in contrast to the multi-step procedures described above that involve masks applied as coatings, self-adhesive masks can be patterned very easily, dry-processed, and easily adhered to the target. The technique used for self-adhesive masks is straightforward if a proper halftone image and a suitable ultraviolet (UV) light exposing unit are used. As shown in Fig. 1, the desired pattern is first printed on a clear acetate transparency sheet. The sheet is then laid over the unexposed mask material and subjected to a dose of UV radiation. The areas below the black portions of the acetate sheet are not exposed to UV light, and remain erosion resistant, while portions below the clear areas cure, becoming brittle and thus easily eroded. The self-adhesive mask is then attached to the target substrate and blasted using AJM to fabricate the desired patterns shown in Fig. 2. For example, Ghobeity et al. [5] used a high tack self-adhesive RapidMask® (RM) (IKONICS Imaging, Duluth, MN, USA) to create microfluidic chips, and achieved feature sizes from 50 to 300 μm. Burzynski and Papini [15] compared the performance of two types of RM with steel contact masks on a glass substrate, and reported that, because of its higher erosion rate, the aspect ratio, defined as the channel depth divided by its width, was limited to 1 using RM, as opposed as 3 using the steel. They used the measured erosion rate to construct a level-set based surface evolution model that could predict the shape of both the eroded channel cross sections, and also the eroded mask.

Although self-adhesive UV curing masks such as RM have been used in AJM applications [5,10,14,15], there is a lack of information regarding the optimum curing conditions. Such masks were originally developed for the much larger-scale application of sand-carving artistic patterns, where the demands regarding the pattern transfer accuracy and mask durability are not as stringent as they

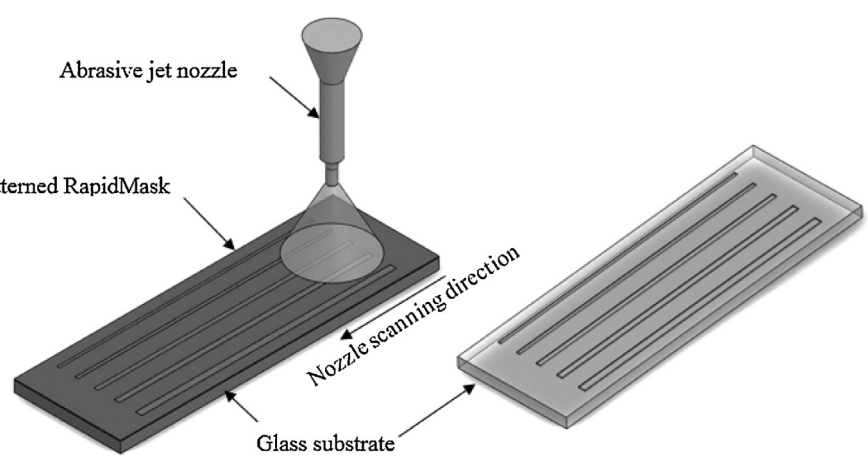

Fig. 2. Procedure to etch the surface of the glass. The patterned RM is attached to the glass, and AJM is used to transfer the pattern to the glass substrate.

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