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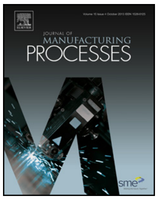

Full length article

A study of the micro-hole geometry evolution on glass by abrasive air-jet micromachining

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ABSTRACT

Abrasive air-jet (AAJ) micromachining has become an attractive technology for the fabrication of micro-structures on a wide range of engineering materials. However, problems specific to effective mould construction still remain challenging. This paper presents a study on the evolution of micro and blind holes on glass during abrasive air-jet machining. Experiments were conducted under different practical settings of air pressure, particle mass flow rate and drilling time. A 3D laser measurement microscope was used to characterize the machined hole profiles. It was found that there was a clear evolution of the profiles of the hole bottom surfaces. Three types of hole surface contours, i.e., convex, flat, and concave (reverse bell-shaped), were obtained within the operating range used, in which the first two types have rarely been reported in literature. The profile variation took place along with the setting parameters of particle flow rate and air pressure, which indicated that the particles distribution density across the cross section of a cylindrical nozzle also varied with the setting parameters. At a low flow rate, the hole bottom was formed with a convex shape, which might be attributed to the fact that the distribution of particles at the nozzle centre was less than that around the brim. As the particle flow rate increased, the bottom surface evolved from convex to flat or even concave. With a proper setting, AAJ can therefore be used to fabricate a micro hole with a desired bottom surface profile. The variation of abrasive particle distribution in the jet in the AAJ micromachining might be attributed to the flow bounce back and stagnation effects when the jet impacts on a target workpiece.

1. Introduction

Current techniques for micromachining of difficult-to-machine materials, such as laser machining and electrical discharge machining (EDM), essentially require large energy generated from complex heat-sourced machines to thermally destroy and remove unwanted materials. Owing to its distinct features of thermal damage free and flexibility in machine setup, abrasive air-jet (AAJ) machining, also known as abrasive jet micromachining (AJM), has become an energy-efficient and attractive method for micromachining components made from advanced but difficult-to-machine materials, including glass, ceramics, quartz and silicon which are increasingly selected for constructing modern micro-featured devices, such as electronic components and micro-fluidic channels [1,2].

In AJM, materials are eroded by an air jet with abrasive particles. An AJM system typically consists of a high-pressure air supplier, a mixing chamber where abrasives are mixed with air, a nozzle, and a positioning system for the nozzle or cutting head. The abrasive particles are accelerated to a high velocity by applying pressurized air in a fine nozzle, and the nozzle moves relative to the work substrate in order to produce the desired structure [3]. By transferring the momentum from the pressurized air onto the abrasive particles, the AAJ is capable of eroding the target material to generate the required part features by means of micro-plastic deformation and/or brittle fracture through the impact of the high velocity abrasives [3,4]. For particular hard and brittle materials, brittle fracture becomes dominant. In this fracture mode, upon the impact of a particle, a fragmentation zone that consists of a complex network of cracks with random sizes and locations is formed, and localised cracks are generated at the work surface due to the impact force of the abrasive particles. The continuous motion of particle penetrating into the zone causes a propagation of cracks. Fragments loosen from the cracks can be immediately generated upon that impact or

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by the impact of other following particles in the vicinity of the generated fragmentation zone. The loose fragments are finally taken away from the zone by the air jet flow, which causes the removal of the target material [1,4].

The features formed on the target material, such as groove width and depth, kerf geometry, hole shapes, surface integrity, etc., are a result of a combination of multiple impact of a number of particles through an abrasive-laden air jet ejected from a nozzle. It is noted that not all the particles within an air jet are evenly distributed and have the same velocity. This in fact depends on various process parameters, such as nozzle type and size, air pressure, particle size and flow rate related to the nozzle size, and processing time [3,5]. There have been several studies to characterize the AAJ process. However, the major parameters that govern the process in forming the profile of feature machined are controversial. Achtsnick et al. [6] in an analysis of the micro-abrasive blasting process showed that the particle dispersion depends on the nozzle type, and cylindrical nozzles generate an axis symmetrical normal distribution. Under such circumstance, it seems that a feature with flat bottom may not be obtained by a cylindrical nozzle, but by a line shaped Laval nozzle where the particle flow can be spread evenly on the target surface. In another separate study conducted by Balasubramaniam et al. [7], it was found that the machined surfaces are of reverse-bell shape. They therefore believed that the abrasive concentration was highest at the centre line of the jet and reduced as approaching to the periphery. Ghobeity et al. [8] on the other hand, pointed out the importance of particle sizes, which are varied across the nozzle section, and this distribution can significantly influence the depth and shape of resultant profiles. A computer simulation reported in [9] illustrates that there are collisions between incoming and rebounding particles. Burzynski and Papini [10] suggested that, apart from the non-uniform incident particle spatial distribution and velocity, there is also a variation in particle spacing along the jet axis. In a study to understand the microscopic erosion mechanisms of monocrystalline silicon under the impacts of microsolid particles, Li et al. [11] found that the majority of the particles bounced away from the target surface without sliding or rolling during the impact. An analytical approach for predicting the surface profile of micro-channels machined using air driven abrasive jets for brittle materials had been proposed in [12], which was mainly for masked erosion of glass by powder blasting. A method to estimate the profiles of holes and micro-channels fabricated in glass using a jet of abrasive slurry was presented in [13]. Jafar et al. [14,15] studied the effects of particle size, kinetic energy, and attack angles on the rough micro-channels using AJM. They found that in order to decrease the AAJ machined surface roughness of the fabricated channels, it is effective to do post-blasting using abrasive jet with low kinetic energy.

In spite of the research efforts in recent years, the effects of different parameters on the shape of the resultant surface using AJM are not widely investigated. Nouraei et al. [16] compared abrasive slurry jet micro-machining (ASJM) with abrasive air jet micro-machining, and confirmed that the erosion mechanisms in ASJM and AJM were similar with a borosilicate glass. They found that the holes machined using ASJM were with relatively steep sidewalls and flat bottoms while those machined using masked AJM were more “V” shaped. Wang et al. [17] reported that during the microhole formation on brittle glasses by an abrasive slurry jet, the hole cross section is characterized by a “W” shape, which can be mainly attributed to the fluid diversion characteristics when a jet impacts a material surface. Due to the existence of a stagnation zone upon the jet impingement, the particle impact velocities and angles at the centre of the jet and at the edge of the jet are different [18,19]. The stagnation zone can apply great drag on the abrasive particles thus decrease the erosion rate. Fan et al. [20] investigated the velocity distributions and particle behaviors of the free jet and impinging jet in and out of the nozzle for a micro abrasive water jet (MAWJ) process, and showed that a W-shaped contour is formed in the microhole machining due to a secondary erosion process caused by the expansion of the viscous jet flow along the target surface in the wall jet region. On the other hand, for the microhole formation using AJM, only reverse bell shaped or “U” shaped contours have been reported in almost all available literatures so far. In the AJM process, a stagnation zone should also exist which can vary the particle impact velocities and angles. A further examination of the micro-hole contour evolution on glass by abrasive air-jet micromachining will help to understand the mechanisms in the process which can facilitate process planning and optimization.

Fig. 1. Experimental setup.

This paper presents an experimental study on the micro-hole shape evolution in abrasive jet micromachining of glass. Experiments are conducted under different air pressures and abrasive mass flow rates for fabricating blind holes on the workpiece. A 3D laser scanning measurement microscope is used to characterize the machined surface profile. The influences of key process parameters, including air pressure and abrasive mass flow rate, on the surface profile evolution are analysed and discussed.

2. Experimental methods

Experiments were conducted using an Airbrasive Model K Series II air jet machine as shown in Fig. 1. This machine allows the adjustment of air pressure and abrasive flow according to the experimental needs. A Roland MDX-40 two-axis motion stage with a closed chamber was used to hold and move the jet nozzle for AJM operation. A dust collector was incorporated in the Roland MDX-40 machine. The machine received user command from a control PC through an input notepad and translated it into nozzle movement. The transverse or scanning speed and the distance to move were adjustable by changing the control program code. The nozzle was a cylindrical type with an inner diameter of 0.28 mm. The abrasive powder was aluminium oxide with a nominal diameter of 27 μm. An image of the abrasive particles is shown in Fig. 2. The abrasive powder was fed into the powder container of the abrasive jet machine and its flow rate was calibrated for precision supply. The workpiece material was lime glass which is commonly used to manufacture glass container, window panes, and micro-channels. The lime glass was in a dimension of 50 mm × 50 mm × 5 mm.

In the experiments, a nozzle standoff distance of 0.5 mm and jet impact angle of 90° were considered. Different abrasive flow rate, air pressure, and drilling time were used to investigate their effects on the hole evolution. Some pilot experiments were carried out to determine the parameter settings. The air pressures used were 0.427, 0.517, and 0.600 MPa (or 62, 75 and 87 psi respectively); the abrasive flow rates were 0.02, 0.04, 0.07, and 0.09 g/s; and the drilling time was 7, 10, and 15 s. A Keyence model VK-