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Short communication

Reduction of particle embedding in solid particle erosion of polymers

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ABSTRACT

Particle embedding can be an unwanted consequence of abrasive jet micromachining (AJM) of polymeric materials. The embedding of aluminum oxide particles into acrylonitrile butadiene styrene (ABS), polytetrafluoroethylene (PTFE), polydimethylsiloxane (PMDS) and polymethylmethacrylate (PMMA) was studied under cryogenic and room temperature conditions. Scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDX) showed the fractional area coverage by embedded Al_2O_3 particles after room temperature AJM to be: 16% (ABS), 19% (PTFE), 25% (PDMS) and 3.2% (PMMA). Under cryogenic conditions, however, the fractional area coverage of embedded Al_2O_3 was found to be significantly reduced: 10% (ABS), 0.8% (PTFE), and 1.6% (PDMS). For PMMA, it was demonstrated that the surface was shielded by the embedded particles, resulting in an erosion rate that decreased with increasing embedded particle coverage.

Several methods for the removal of embedded particles were also studied. A first step of blasting with spherical glass beads dislodged some of the Al_2O_3 particles embedded during AJM so that the fractional area coverage by embedded Al_2O_3 particles was reduced to 1.1% from 3.2% for PMMA. After this glass bead blasting, a further reduction in embedded particles could not be achieved by ultrasonic cleaning the PMMA samples with distilled water or with NaOH. However, more embedded particles could be removed using a freezing technique where the samples were first dipped in NaOH mixed with detergent or distilled water and then frozen by immersion in liquid nitrogen for 5 min after which the samples were allowed to warm to room temperature. For samples machined under cryogenic conditions, this freezing technique applied after the preliminary glass bead blast, reduced the area coverage of Al_2O_3 to 4% for ABS, 0.5% for PDMS and to almost 0% for PTFE. Finally, for PMMA machined at room temperature, using either the freezing method or an adhesive tape to pull out the embedded particles resulted in less than 0.5% embedded Al_2O_3 coverage. Since it was effective for all the studied polymers, it is recommended that glass bead blasting at 45° followed by the freezing technique be used to substantially reduce particle embedding after AJM.

1. Introduction

Polymeric materials are attractive for micro-fabrication because of their desirable physical and chemical properties, and relatively low cost [1–4]. Abrasive jet micromachining (AJM) has been used to create holes and micro-fluidic channels in polymers such as polymethylmethacrylate (PMMA) at room temperature and polydimethylsiloxane (PMDS) at cryogenic temperatures [5–8]. However, sharp abrasive particles such as Al_2O_3 can become embedded during AJM [5–8], contaminating the machined surfaces, and possibly affecting the performance of devices such as micro-fluidic chips [9].

A number of studies have reported the occurrence of particle embedding during the solid particle erosion of polymers. For example, Walley and Field [10] have noted that sand particles blasted at 36 ± 6 m/s embedded into polyethylene targets during the initial incubation period of erosion testing. They reported that the maximum size of the embedded particles (50 μm) was much less than that of the originally blasted sand particles (300–600 μm). It was not known whether the breakage occurred on initial impact or due to being struck by subsequent impacts. Friedrich reported seeing embedded steel particles in polyethylene targets at −35 °C and in polybutene-1 at room temperature after launching 500 μm steel balls at 57 m/s [11]. The embedded particles were found to be much smaller than the originally launched particles [11]. Because it was unlikely that the steel balls fragmented upon impact, the author

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concluded that the erodent material contained broken irregular-shaped steel particles besides the steel balls. Using EDX analysis, Sari found fractured and embedded particles in a polyphenylene sulfide (PPS) composite when impacted by 150–212 μm angular aluminum oxide particles launched at 1.57 m/s [12]. Lathabai et al. [13] launched 10 μm SiO_2 particles at 3.5 m/s and found embedded particles in a 500 μm thick flame sprayed Nylon 11 coating, using SEM in backscattered mode and EDX analysis. The authors suggested that the embedded particles may contribute to a shielding effect.

In machining and surface preparation applications, particle embedding is usually undesirable since it reduces the erosion rate and surface quality. For example, Zu et al. [14] reported that embedded silica particles reduced the erosion rate of an aluminum alloy. Kim [15] also attributed a decrease in the erosion rate of high purity reaction-bonded silicon nitride discs to the embedding of 100 μm silicon carbide particles blasted at 900 °C. Zhou and Bahadur [16] reported that embedded silicon carbide particles may prevent the removal of a chip from a Ti–6Al–4V substrate by blocking the cutting action of an impacting particle. Brown et al. [17] attributed the initial weight gain they saw during the incubation period in a solid particle erosion test to the embedding of angular fragments of 210 μm angular quartz into an 1100 Aluminum alloy target.

For applications where erosion resistance is required, some researchers have suggested that embedded eroding particles can be viewed as an effective barrier to erosion. For example, daCosta and Vilar [18] proposed that erosion resistant materials could be selected taking into account the possibility of using embedding as an erosion resistance mechanism.

Particle embedding has been reported to interfere with the effectiveness of grit blasting of metal surfaces to improve the adhesion of plasma and ceramic coatings [19–21]. Day et al. [19] found that the grit contamination of Hastelloy® X (nickel–chromium–iron–molybdenum alloy) sheet by fused alumina increased with increasing grit size, blasting pressure, impact angle and number of blasting passes. In contrast, Harris and Beevers [21] reported that using smaller alumina particles increased embedding on mild steel and aluminum.

The quantification of embedding can be complicated by the difficulty in distinguishing small embedded particles from the surrounding rough target surface. Momber et al. [20] reviewed problems associated with grit contamination and the resulting adhesion problems on hot-rolled low-carbon steel containing different alloying elements. They used scanning electron microscopy (SEM) and image analysis to quantify embedding, finding that embedded 165 μm aluminum oxide particles covered approximately 8% of the surface of a steel alloy after 300 s of blasting. Amada et al. [22] used an electron probe micro-analyzer (EPMA) and image analysis to determine that up to 10% of the surface area of grit-blasted steel was covered by Al_2O_3 and ZrO_2. Grübl et al. [23] used SEM and X-ray microanalysis techniques to count embedded alumina particles on titanium-aluminum alloy hip implants after grit blasting, measuring 154 per mm^2 in the size range 15–95 μm.

Particle embedding in the surface of semiconductor wafers after polishing has been a concern in the microelectronics industry. Negri et al. [24] conducted experiments in a flow chamber to investigate the effects of chemical solutions on the detachment of 0.3 μm and 3 μm alumina particles embedded in GaAs wafers after mechanical polishing. They found that an ammonia solution gave the best particle removal rate (80%). Toscano and Ahmadi [25] developed theoretical models for the detachment (sliding, rolling and lifting) of embedded particles when impacted by CO_2 pellets in a carrier gas, based on the hydrodynamic and impact conditions to determine the corresponding embedded particle removal conditions such as the critical velocity of the impacting CO_2 pellets. They found that the removal of very small embedded particles required correspondingly small CO_2 pellets, and that the effectiveness of the surface cleaning increased as the nozzle-substrate angle decreased; i.e. as the tangential component of the impact velocity increased.

The present work examined particle embedding in acrylonitrile butadiene styrene (ABS), polytetrafluoroethylene (PTFE), polydimethylsiloxane (PMDS) and polymethylmethacrylate (PMMA) under process conditions typical of abrasive jet machining applications. Various techniques for particle removal were investigated, as was the minimization of embedding by the use of cryogenic AJM (CAJM).

2. Experiments

2.1. Materials

Particle embedding was investigated on the following target materials:

(1) 1.6 mm thick PMMA sheet (Acrylic FF sheet, CYRO Industries, Rockaway, NJ, USA)
(2) 2 mm thick PDMS samples (Sylgard® 184 Silicone elastomer, Ellsworth Adhesives, Germantown, WI, USA) which were cured in a vacuum oven for 4 h at 75 °C.
(3) 3 mm thick ABS sheet (McMaster-Carr, 200 Aurora Industrial Pkwy., Aurora, OH, USA)
(4) 2 mm thick PTFE sheet (McMaster-Carr, 200 Aurora Industrial Pkwy., Aurora, OH, USA)

2.2. Machining experiments

A commercial microblaster (MB 1005 Microblaster, Comco, Inc., Burbank, CA, USA), incorporating a mixing device in order to prevent particle bed compaction and thus ensure good repeatability [26], was used in all machining experiments. The embedding experiments were performed with nominally 25 μm Al_2O_3 which, when measured with an optical particle size analyser (Clemex PS3 Research System, Clemex Technologies Inc., Longueuil, Quebec, Canada) were found to have a log-normal size distribution with a mean spherical diameter of 31.5 μm with a standard deviation of 7 μm.

Use of a 200 kPa blasting pressure and a 760 μm inner diameter round nozzle resulted in an average particle velocity in the range of 100–115 m/s [26]. Two different types of experiments were performed in order to investigate particle embedding:

(a) Single and multi-pass unmasked channels were machined at 90° impact angle using a 0.5 mm/s scan speed in PMMA, ABS, PTFE and PDMS using 25 μm Al_2O_3. The particle mass flow rate was measured to be 2.83 g/min (standard deviation of 0.12 g/min) by weighing (mass balance with accuracy of 0.1 mg) the amount of powder blasted into sealed container with a particulate filter for 2 min prior to each machining experiment.The effect of cryogenic AJM on embedding was investigated in a similar experiment using ABS, PTFE and PDMS.
(b) While scanning at a constant velocity in one direction, the PMMA samples were simultaneously oscillated at 5 Hz in the direction perpendicular to the scan direction to create a 10 mm wide band of preconditioned surface with an approximately uniform coverage of embedded particles. The number of embedded particles was controlled by varying the scan speed between 0.5 mm/s and 3 mm/s. Unmasked channels were then machined into the preconditioned samples using a constant scan speed of 0.5 mm/s in order to determine the effect that the varying degrees of particle embedding had on the material removal rate (Section 3.1.1).