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Wet blasting as a deburring process for aluminum

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ABSTRACT

Light weight aluminum has shown high applicability in the automobile industry for high fuel efficiency. However, the manufacturing of aluminum is limited by the deburring process owing to the difficulty in employing wet blasting. In this paper, we present experimental and computational studies on the deburring process of wet blasting for aluminum. The process conditions are analyzed to achieve high deburring performance that minimizes the surface damage. Parameters of wet blasting with a significant influence on the deburring process are investigated and a promising deburring technique for aluminum is proposed.

1. Introduction

General machine parts undergo cutting processes such as milling or drilling. These processes lead to chips or burrs in the machine parts. Thus, the focus of research in the manufacturing industry has been centered on developing a deburring process to enhance the quality of products. During the machining of hard materials, various kinds of burrs are generated at the machined surface or edge at a rate related to the wear rate and machining velocity. Biermann and Heilmann (2010) investigated the generation rate of burrs on machining process and Kim et al. (2001) focused on the generation of burrs during drilling process. Various deburring processes have been developed based on mechanical, chemical, or thermal methods, which are listed by Aurich et al. (2009). Among these, a method known as wet blasting, which is one of the most efficient mechanical deburring processes, is extensively employed for its rapidity and accuracy. In this deburring or peening method, small particles of abrasive materials are mixed with water, and the mixture is then injected into a target. By mixing water, more momentum is transferred to the abrasive materials in wet blasting than in sand blasting as presented by Appleman and Bruno (Jr.) (1985). Through this process, the burrs and rust are minimized and removed. Wet blasting requires simple equipment and can be completed within a very short time compared with other mechanical deburring processes; this in turn guarantees low cost and a high production rate. Recently, wet blasting has also been employed in micro peening and etching processes for brittle materials by Horsch et al. (2006), and improved surface roughness at certain injection pressures by Mineta et al. (2009). Although wet blasting shows effective deburring performance for hard materials, it may diminish the surface quality of soft metals (e.g., aluminum) adjacent to burrs. For this reason, the application of wet blasting to aluminum, which is widely employed in various automobile components to achieve high fuel efficiency, is currently limited.

In this study, we design a deburring process of wet blasting for aluminum. The process conditions are analyzed to achieve optimal deburring performance without loss of surface quality. Dominant parameters of the process conditions are selected and their influence on the deburring process is investigated. Owing to the many parameters involved in the design of a wet blast process, a numerical simulation is first attempted to test these parameters, and hence to find the proper operational conditions of wet blasting. On the basis of the findings from the numerical simulation, experiments are performed to study the effectiveness of wet blasting on the deburring of machined aluminum.

2. Numerical analysis

The simulation proceeds according to an iterative procedure. To simulate the flow of the mixture in the wet blasting process, the conservations of continuity and momentum are applied. The transient conservation equations for the incompressible mass and momentum are as follows:

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

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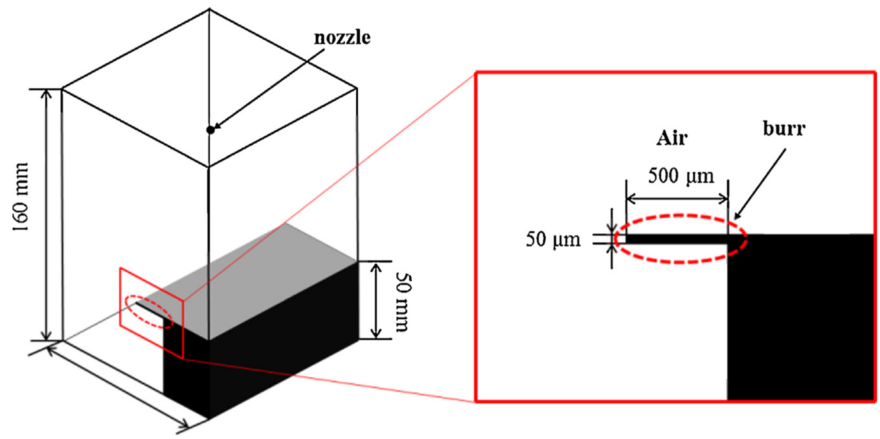

Fig. 1. Computational model and detailed geometry of a burr.

$$\frac{\partial u_i}{\partial t}+\frac{\partial u_i u_j}{\partial x_i}=-\frac{\partial (p/\rho)}{\partial x_i}+\frac{\partial (\tau_{ij}/\rho)}{\partial x_j}+g_i\left(1-\frac{\rho_0}{\rho}\right)c, \tag{2}$$

where ρ is the density of the mixture, t is the processing time, x_i is a Cartesian coordinate, u_i is a velocity component, τ_{ij} is a stress tensor component, and p is pressure. The last term in the momentum equation represents the buoyancy force, where g_i is the gravitational acceleration vector and ρ_0 is the reference density. The behavior of abrasive particles and water droplets is numerically simulated by using a Lagrangian multiphase model. The time-dependent position and velocity of a droplet are calculated as

$$\frac{\partial x_{d,i}}{\partial t}=u_{d,i}, \tag{3}$$

$$m_d\frac{\partial u_{d,i}}{\partial t}=F_{dr,i}+F_{p,i}+F_{am,i}+F_{b,i}, \tag{4}$$

where $x_{d,i}$ and $u_{d,i}$ are the position and velocity of the droplet, respectively; and m_d is the mass of the droplet. The right side of Eq. (4) incorporates the forces acting on the droplet, where $F_{dr,i}$ is the drag force, $F_{p,i}$ is the force induced by pressure, $F_{am,i}$ is the virtual mass force, and $F_{b,i}$ is the body force of the droplet. The drag force and pressure force on the droplet are defined as

$$F_{dr,i}=\frac{1}{2}C_d\rho A_d\left|u_i-u_{d,i}\right|(u_i-u_{d,i}), \tag{5}$$

$$F_{p,i}=-V_d\frac{\partial p}{\partial x_i}, \tag{6}$$

where u_i and $u_{d,i}$ are the velocities of the flow and droplet, respectively. C_d and V_d are the drag coefficient and volume, respectively, of the droplet. In addition, the virtual mass force and body force on the droplet are defined as

$$F_{am,i}=-C_{am}\rho V_d\frac{\partial (u_i-u_{d,i})}{\partial t}, \tag{7}$$

$$F_{b,i}=-m_d g_i, \tag{8}$$

where C_{am} is the virtual mass coefficient and m_d is the mass of the droplet. To calculate the effect of the droplet, the impulse on the burr is considered as

$$E=\frac{1}{2}m_d u_n^2, \tag{9}$$

where u_n is the velocity component of the normal direction of the burr. The deburring performance is evaluated with E.

The computational domain and detailed geometry of a burr are shown in Fig. 1. The injection nozzle is located at the center of the computational domain, which is 80 mm from the burr. The height and width of the modeled burr are 50 and 500 μm, respectively.

3. Experiment

The experimental setup is shown in Fig. 2. The diameter of the nozzle is 8 mm, and the air-compressor provides air pressure in the range of 0–5 bar. A kneading machine is installed to obtain a uniform mixture of abrasive materials and water in a reservoir. Glass beads (GB 9; size, 125–180 μm) and aluminum oxide (Al_2O_3: alumina) are tested as the abrasive materials for deburring the target material Al. The hardness of the glass bead is about 5.5 Mohs, which is higher than that of Al (3 Mohs); the hardness of alumina is 9 Mohs. Al blocks are drilled to generate burrs around the cross-drilled holes. The burrs are located within 100 mm of a nozzle gun. The height of the generated burrs is in the range of 0.15–1.50 mm. The high injection pressure (~4–4.5 bar) is presumably maintained for a distance of around 100 mm owing to the very low air drag. The concentration of the mixture is set to 25 wt% when the effects of pressure and processing time are investigated, and the effect of

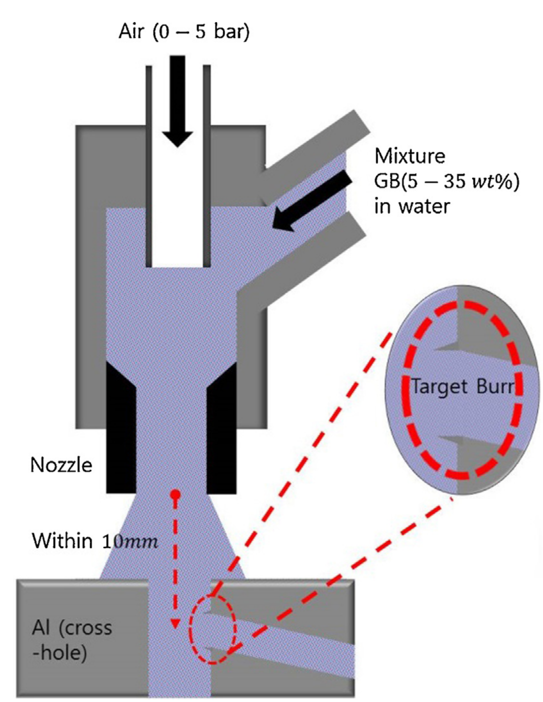

Fig. 2. Schematic drawing of wet blast equipment.

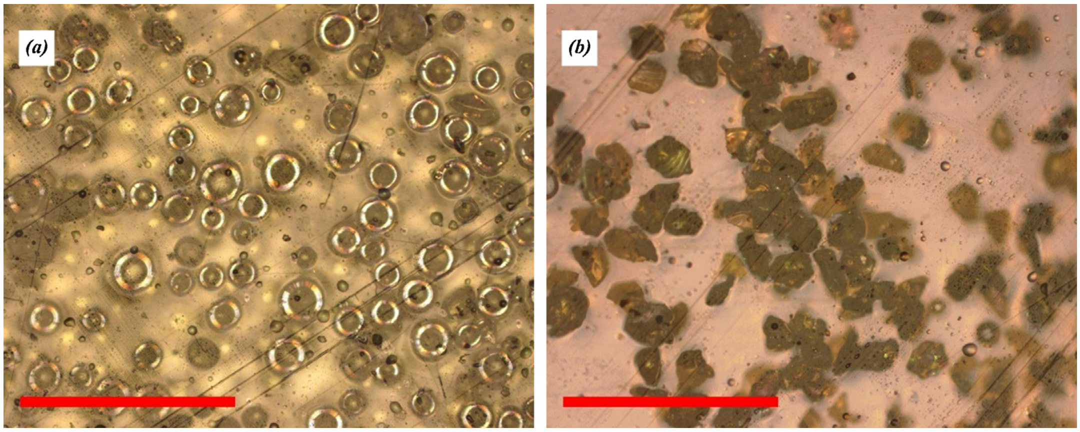

Fig. 3. Microscopic images of the abrasive materials: (a) glass beads (GB 9) and (b) aluminum oxide (Al_2O_3). The scale bar is 1 mm.

the mixture concentration is analyzed in the range of 5–35 wt%. A flow rate of 0–100 ml/s is considered for the mixture. An endoscope with a resolution of 640 × 480 pixels is employed to examine the burr around the cross-drilled holes. Deburring performance is estimated from the reduction in burr size as determined from endoscopic images (Fig. 3).

4. Results and discussion

4.1. Simulation results for deburring performance of abrasive materials

The simulated wet blasting process is presented in Fig. 4. The abrasive particles are set to have a partially elastic bouncing condition of 70% upon impacting a rigid surface. When liquid droplets impact the rigid wall, the impinging droplets can adhere to the wall, spread out along the wall, or break up into smaller droplets and rebound from the wallowing to the combined effect of the momentum and surface tension of the droplets, impact angle, and wall conditions. To recognize the regime criteria in the numerical simulation, various models such as the Obermeier and Chaves (1991), MPI, Bai and Gosman (1995), Satoh et al. (2000), and Rosa et al. (2006), ONERA models have been proposed and used in the literature. The MPI and Satoh models were appropriately applicable to sticking and spreading conditions such as when oil droplets form a film. The ONERA model was proposed to describe the vaporization of droplets at the wall with high temperature. The Bai model excels at predicting splashing, especially post-impingement quantities such as secondary droplet size and velocity. In the wet blasting process, water droplets with high pressure, upon impacting the solid wall, break up into smaller drops and rebound—a phenomenon that is plausibly simulated with the Bai model. Thus, the behavior of droplets impacting the solid surface was modeled with the Bai model that describes the detailed characteristics of impacting droplets during the wet blasting process. The interactions between particles were neglected. To identify a suitable abrasive particle, three such particles widely used in the industry were simulated with the same operating conditions. Specifically, glass beads (GB 9), ceramic beads, and urea were compared in terms of deburring performance.

The time course of impulses and cumulative impulses for different types of abrasive particles is shown in Fig. 5. Owing to the random injection of particles during the simulations, the impulses on the burr show fluctuations in time. As indicated by simulations of the operating time, the impulses on the burr with urea are fewer than those with glass or ceramic beads. Thus, we selected glass beads as the abrasive particles because they are technically more effective than urea and economically superior to ceramic beads.

To investigate the deburring performance with respect to the operating pressure, impulses on the burr with different injection pressures were calculated as shown in Fig. 6. The simulated pressure ranges from 1 to 10 bar. The cumulative impulses increase by about 7% as the injection pressure increases by 1 bar. The linear increment in the cumulative impulses is induced by the increase in the amount of abrasive particles and injection velocity due to the increased operating pressure. The simulated deburring performance shows a linear increase without any saturation because an

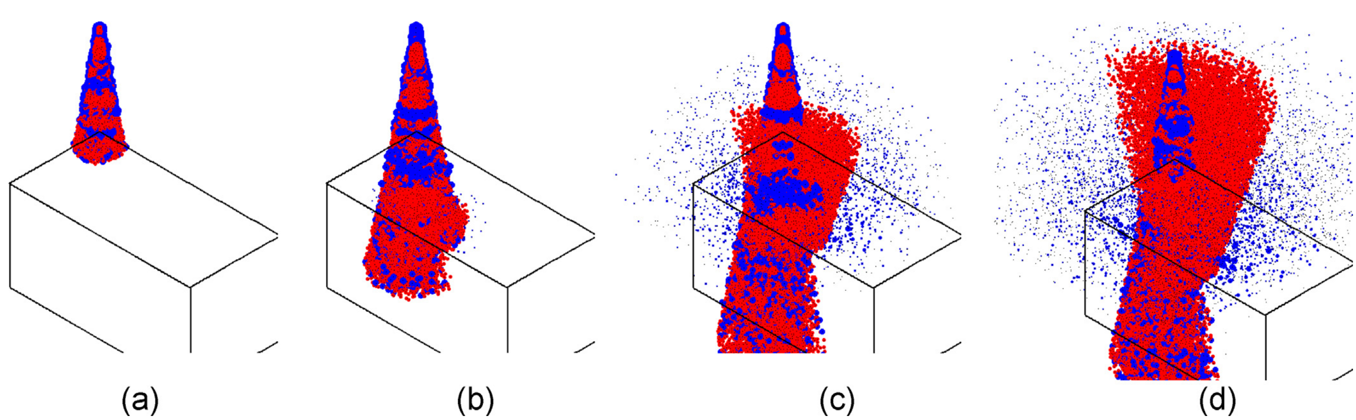

Fig. 4. Simulation of injected particles in the wet blasting process. The abrasive particles and water droplets are shown in red and blue, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

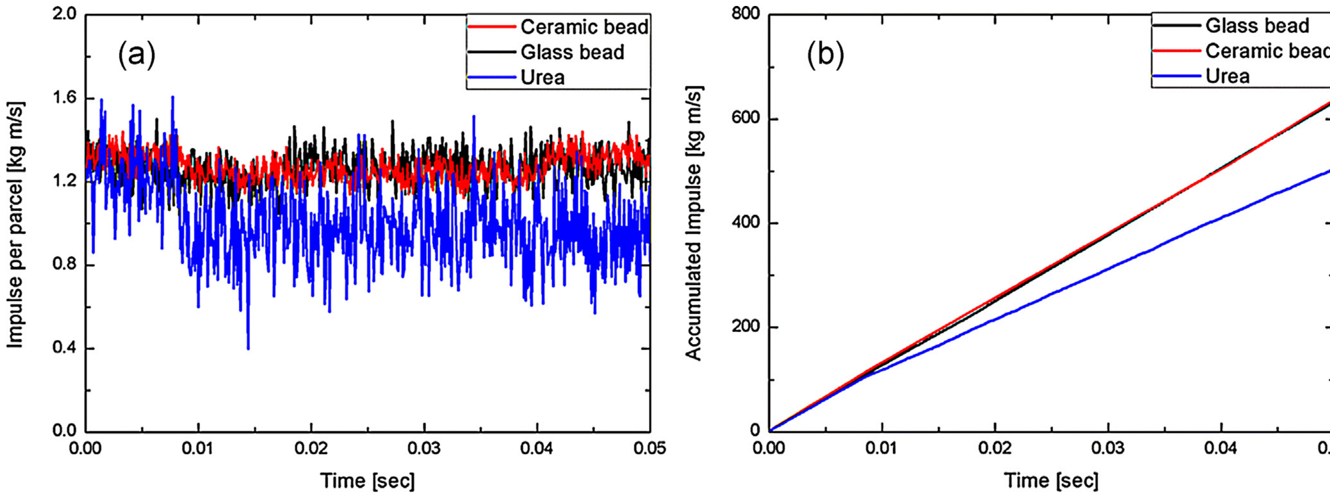

Fig. 5. Time course of (a) impulses and (b) cumulative impulses for different abrasive particles.

ideal wet blasting condition without any loss is assumed for simplicity. Thus, an experimental study was conducted to thoroughly investigate wet blasting performance by analyzing the simulated results.

4.2. Effect of processing time and pressure on deburring

From the simulated results, the glass beads were expected to be the best abrasives in wet blasting for aluminum, showing high abrasive performance at a reasonable price. Accordingly, experiments were carried out with glass beads. Moreover, as indicated by the simulations, increasing the injection pressure in wet blasting from 2 to 10 bar proportionally increases deburring performance. In most industries, an injection pressure of 5 bar is typically used in wet blasting processes with abrasives. Thus, experiments were performed with injection pressures from 2 to 5 bar to find the most efficient deburring conditions based on simulated results.

In the industry, aluminum oxide (Al_2O_3: alumina) has been widely used as the abrasive material of wet blasting processes. Alumina is generally harder than glass beads and has been shown to exhibit better abrasive performance than glass beads by Possart et al. (2002). Although alumina shows effective deburring and surface finishing of metals with high toughness, it is difficult to apply to soft metals such as Al because it induces surface defects during the deburring process. Thus, we conducted preliminary experiments with Al plates to investigate the compatibility of Al.

The mean particle sizes of the alumina and glass beads are 100 and 125 μm, respectively. Embedded alumina particles on the surface of an Al block are observed after the wet blasting process (Fig. 7, dotted circle). No defects on the processed surface, however, are found when glass beads are used as the abrasive material. Embedded particles diminish the surface quality and may even cause components to fail. After wet blasting with alumina, the Al surface is roughly damaged, whereas the Al surface processed with glass beads shows a uniformly dimpled surface. Because the glass bead is softer than alumina and the former is regularly spherical in shape, the cleanliness of the process is guaranteed with glass beads as the abrasive material. We have tested other materials such as ceramics and plastic media. Although the simulations predict reduced deburring performance for plastic media, experimentally, these materials show levels of performance similar to those of glass beads. Thus, we chose glass beads and ceramics as the abrasive materials for wet blasting Al. Ultimately, we selected glass beads from a practical and economic point of view.

Experiments were carried out to examine the effects of pressure and injection time on the deburring performance. The heights of the remaining burrs after deburring with 25 wt% glass beads (GB9) were measured at different pressures and injection times. As shown in Fig. 8, the deburring capability is closely related to the injection

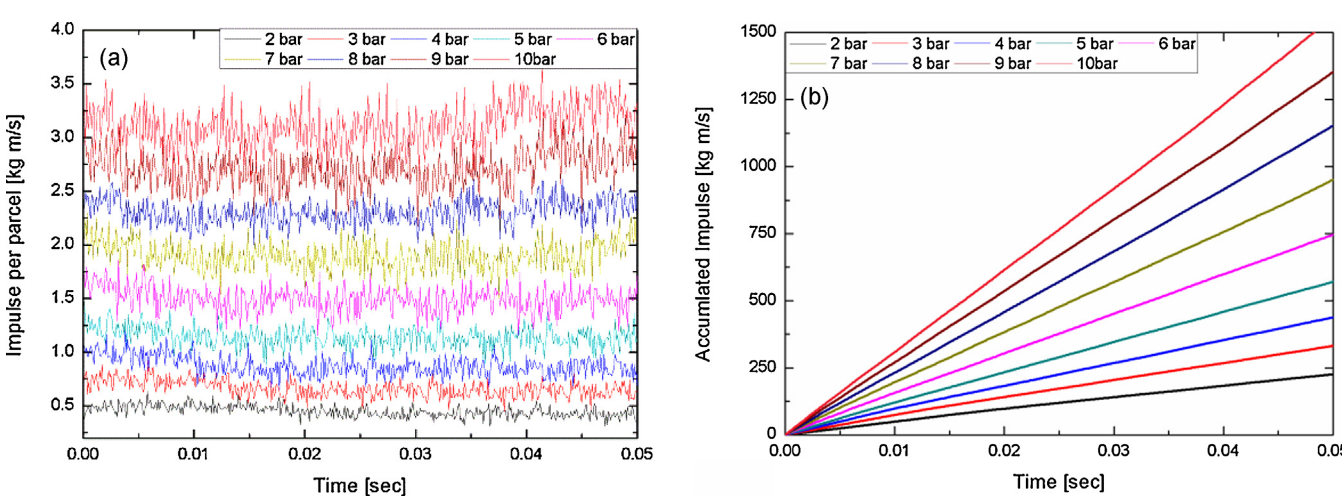

Fig. 6. Time course of (a) impulses and (b) cumulative impulses at various injection pressures. The pressure range is 1–10 bar.

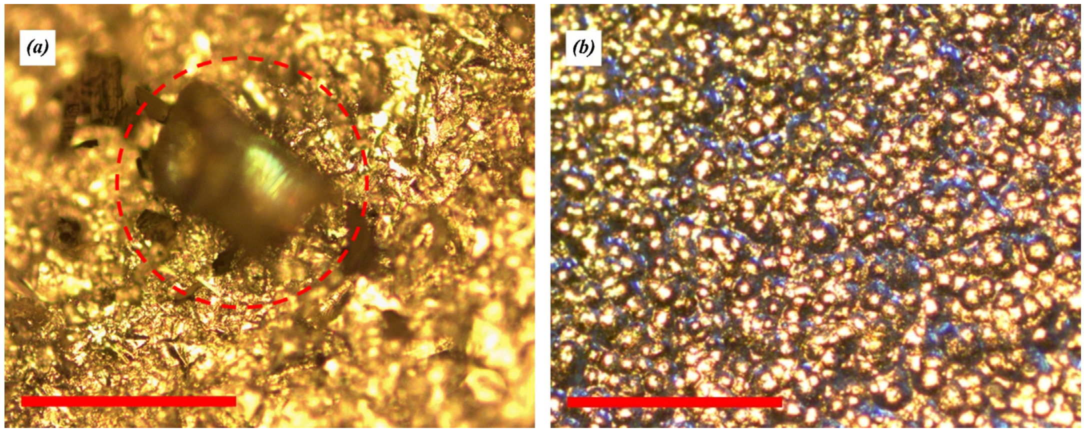

Fig. 7. Microscopic images of target surface after wet blasting. The scale bar is 0.25 mm. A pressure of 4.5 bar is applied for 10 s. The mixed abrasive materials are (a) aluminum oxide (Al_2O_3) and (b) glass beads (GB 9).

pressure, which was specifically investigated in the simulations. The height of the remaining burr decreases as the injection pressure is increased. The deburring performance, however, saturates when the injection pressure is increased above ~4 bar. Furthermore, the deburring capability is not guaranteed to increase with the injection time. From these experimental results, guidelines for the injection pressure and time that provide sufficient deburring effects were determined for experiments to further analyze the two process conditions: an injection time of 9 s at a pressure of 4 bar, and an injection time of 7 s at a pressure of 4.5 bar.

4.3. Flow rate and concentration of abrasive materials

Because the shapes of the burrs generated for the experiments varied in height and thickness, the resultant burr heights are shown with deviations. Under the pre-determined pressure and injection time, the effects of flow rate and concentration of glass beads (GB 9) on the deburring performance were investigated. Experimental results for different flow rates with a glass bead concentration of 25 wt% in water are shown in Fig. 9. When the flow rate is larger than ~1 ml/s mm^2, the height of the remaining burrs decreases to less than 0.4 mm, with a concomitant reduction in the deviation. The reduction in the height of the remaining burr by increasing the flow rate is approximately within 0.1 mm even though the deburring capability is increased by the increased flow rate. These results provide the minimum flow rate that guarantees the expected level of deburring performance with the determined process conditions. The deburring performance with respect to the concentration of the abrasive material is shown in Fig. 10. The flow rate is about 2 ml/s mm^2. The heights of remaining burrs after deburring with different concentrations do not show considerable

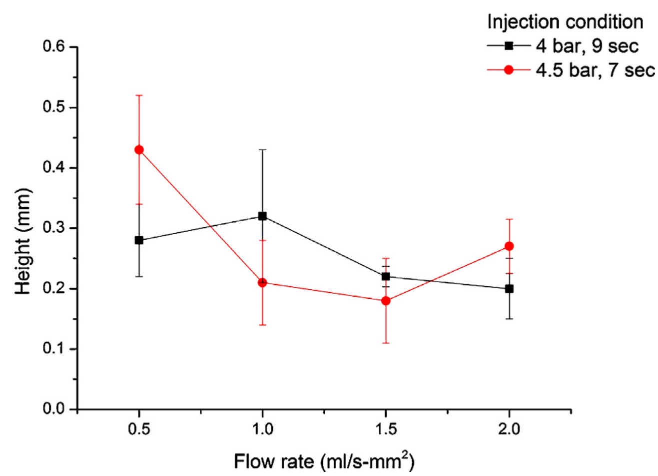

Fig. 9. Height of remaining burr after deburring at various flow rates under selected injection conditions of pressure and time.

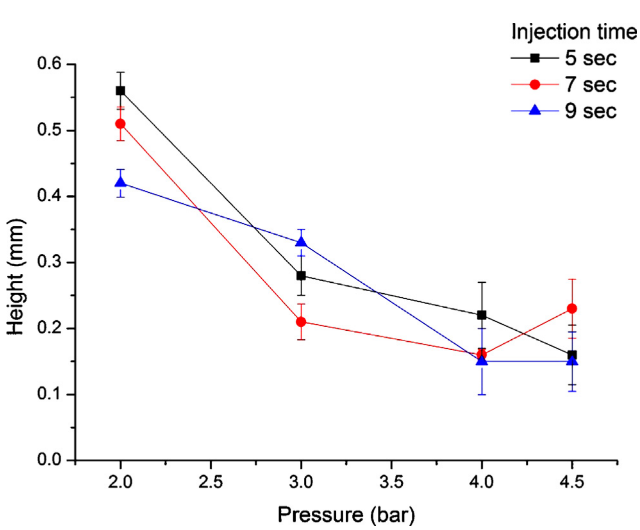

Fig. 8. Heights of remaining burr at various pressures and injection times.

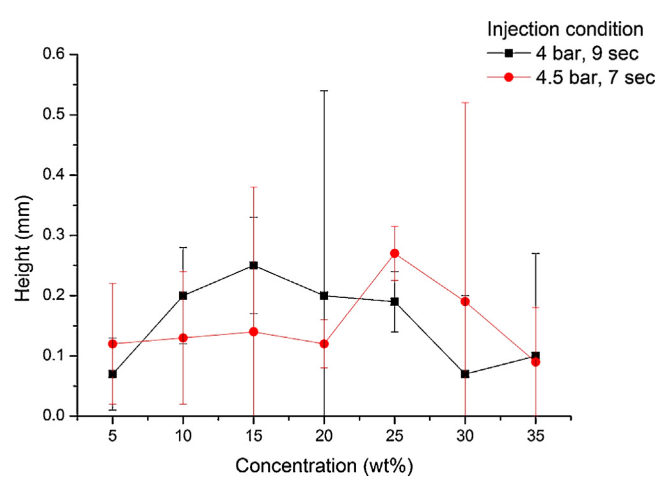

Fig. 10. Relation between concentration (wt%) and height of remaining burr under selected injection conditions of pressure and time.

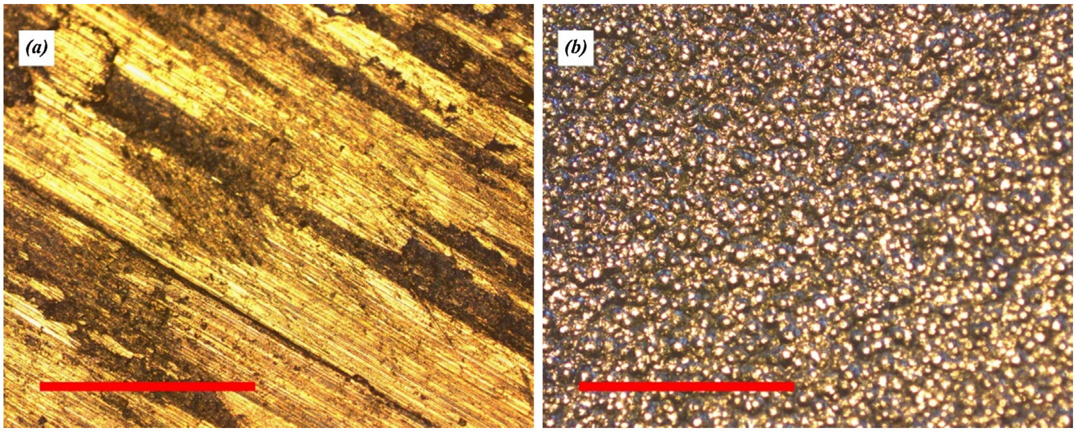

Fig. 11. Microscopic images of aluminum surface: (a) before blasting and (b) after blasting. The scale bar is 1 mm.

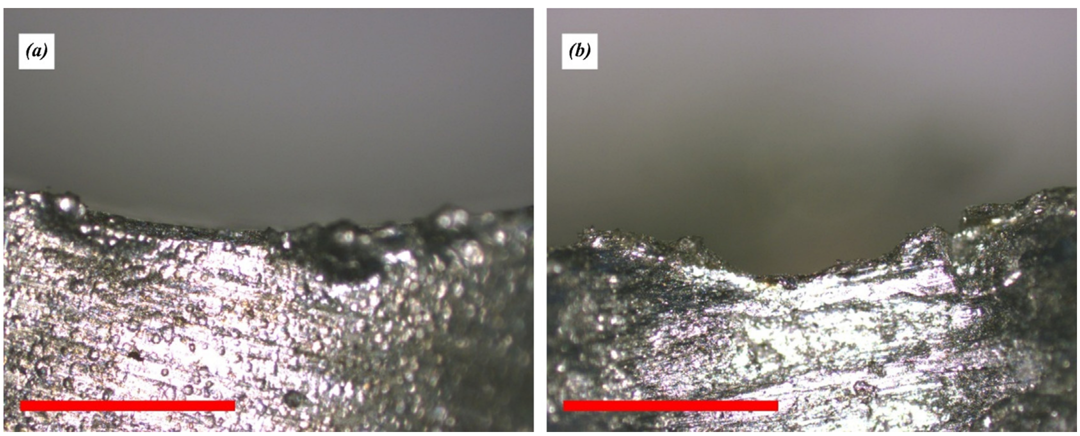

Fig. 12. Microscopic images of cross-drilled holes after wet blasting under selected injection conditions of pressure and time: (a) [4 bar, 9 s] and (b) [4.5 bar, 7 s]. The scale bar is 1 mm.

variation and are generally less than the adequately processed size. Under the selected injection conditions of pressure and time, the deburring performance is not significantly influenced by the concentration of abrasive materials relative to other processing conditions. A higher concentration may induce more interactions among the abrasive particles, which cannot generate more enhanced impulses on the burr.

4.4. Surface damages of Al block with wet blasting process

A wet blasting process with high deburring performance may cause surface damage and residual stress of the target materials, which is observed by Horsch et al. (2006) and Sridhar et al. (1992). Although the additional residual stress on the surface can increase the strength of the materials, the surface roughness would be critical for specific parts that require high precision. Here, the surface condition was investigated after wet blasting with the developed processing conditions. The surface damage was evaluated by the changed surface roughness due to the deburring process. Preliminary tests were performed with a flat plate specimen to observe the surface change (Fig. 11). Specimens were closely positioned at about 20 mm from the injection nozzle. The applied injection pressure and injection time are 4.5 bar and 30 s, respectively. The small dimpled shapes are induced by the spherical glass beads under severe conditions. For practical analyses, the surface roughness was analyzed after deburring on the Al block with cross-drilled holes. As shown in Fig. 12, a microscopic image of the surface near the cross-drilled holes shows no noticeable change, as in results with plate specimens. The initial surface roughness is on average $\sim R_a$ 0.17 μm. During a 9-s period after wet blasting at an injecting pressure of 4.0 bar, the roughness changes to R_a 0.81 μm. The roughness increases to R_a 0.51 μm as the injection time is reduced to 7 s, even at the increased pressure of 4.5 bar. The flow rates and concentrations of the two cases are 2 ml/s mm^2 and 25 wt%, respectively. The roughness changes are equivalent to less than the precision-machined range of grade N7 (R_a 1.6).

5. Conclusions

In this study, we demonstrated the promising capabilities of wet blasting as an effective deburring technique for aluminum. Cross-drilled holes with a diameter of 8–12 mm were prepared in aluminum blocks and wet blasting was performed. On the basis of the results of the computational and experimental investigations, the following conclusions can be drawn:

1. The process parameters of wet blasting with a dominant influence on the deburring process are the type of abrasive material, its concentration, the flow rate, injection pressure, and injection time.
2. Glass beads (GB 9) about 125–180 μm in size show high deburring performance without severe loss of surface quality as an abrasive material.
3. The size of the burr is reduced to below 0.3 mm within 10 s of blasting at the blasting pressure of 4.0 bar. The derived pressure and time of wet blasting applicable to the deburring process provide adaptable guidelines for the time and pressure of injection under different deburring requirements.

4. Considering the guideline conditions for the pressure and time of wet blasting, the flow rate required to assure deburring performance is over 1 ml/s mm^2. However, the concentration of abrasive materials in water does not significantly influence the final deburring performance.
5. The experimental and computational analyses presented herein are expected to guarantee the high capability of wet blasting in deburring ductile materials.

Acknowledgements

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