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ORIGINAL ARTICLE

Formability and fracture of metallic sheet materials in microscale punching processes using laser-accelerated flyer impact

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Abstract
Laser-accelerated metallic flyers can be used in microscale manufacturing processes by providing high-speed impact and shockwave to target materials. This study conducted microscale punching experiments using a laser-accelerated flyer for various mold sizes, workpiece thicknesses, and flyer thicknesses to investigate performance and failure characteristics of the punching process. In the case of a single flyer impact, punching was successful when the ratio of mold diameter to workpiece thickness exceeded 3. High-speed punching advantages, which improve punching quality as the shear zone increases and burrs become smaller, were validated. When flyer thickness was significantly reduced, punching performance deteriorated although higher speed could be realized, because the thinner flyer was difficult to maintain flatness during acceleration, resulting in inefficient forming pressure transfer to the workpiece. When the ratio of mold diameter to workpiece thickness was less than 3, punching was achieved through multiple flyer impacts. However, pressure transfer efficiency from the flyer to the workpiece was further reduced. Thus, punching performance could be improved by reducing the relative size of the flyer to the mold diameter.

Keywords Microscale punching · Laser-accelerated flyer · Flyer impact · High-speed punching

1 Introduction

Since weight reduction and component miniaturization has become more important, interest in microscale manufacturing is increasing. The technology of processing microscale holes and features in thin metallic materials is also increasingly required in many industrial fields, such as electronics, medical, and biotechnology [1–3]. Microscale holes typically have been fabricated by mechanical punching, drilling, wire electrical discharge machining (WEDM), and chemical etching. Mechanical punching process using die and punch has advantages in terms of cost and productivity compared to other processes. However, it is costly to manufacture small die and punch sets for small holes, and the machined tools are not sufficiently strong, causing buckling and breakage problems [4]. Die and punch alignment also becomes more critical, which hinders achieving the desired level of accuracy for microscale punching [5].

Many processes have been proposed to solve these problems. Murata et al. [4] proposed punching by replacing the metal punches with ultra-high pressure gas. They were able to punch holes with hardly any burrs and cracks without considering the clearance between punch and die. However, there were several disadvantages, such as large shearing drop resulting from bulging deformation, and the quality deterioration on the pressured area. Watari et al. [6] proposed punching sheet metal by applying an impact load to a urethane sheet with a metal punch. They were able to fabricate features of various shapes and sizes on SUS304, Al050, and PBP2 materials. However, an additional study is required to find optimal process conditions, since punching performance was significantly influenced by the hardness of urethane, metal punch radius, and die hole size. With the development of laser technology, punching using a laser-induced shockwave has attracted much attention. When a high-intensity pulsed laser beam irradiates an energy-transforming medium, high-temperature and high-pressure plasma can be generated by ablating the thin portion of material, which then absorbs the

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remaining laser energy. This plasma propagates the shockwave to the workpiece and deforms it to the desired shape when the shockwave maximum pressure exceeds the material dynamic yield strength. Since the shockwave duration is typically less than 40 ns, the strain rate of the deforming material is very high, up to 10^7 s^{-1}, and this high-speed processing is well known to be superior to conventional processes in terms of formability, spring back, and wrinkling. This process also has the advantage of increasing workpiece fatigue resistance, because it generates compressive residual stress on the workpiece surface through the high-speed impact energy [7, 8].

Many studies have investigated fabricating microscale features on metallic materials using laser-induced shockwaves. Liu et al. [9] irradiated the ablation material to generate high-temperature and high-pressure plasma and performed forming by propagating impact to the workpiece with the plasma. They successfully produced 250-μm-diameter holes in 10-μm copper foil. The process feasibility was further investigated through finite element analysis. Wang et al. [10] experimentally investigated accelerating the sheet metal flyer to high speed through plasma expansion, to manufacture microscale features using the flyer kinetic energy. To increase laser energy absorption when generating plasma, they used a multilayered flyer and confirmed that higher forming pressure and formability could be achieved using the multilayered flyer compared to single-layered flyers. Curtis et al. [11] measured the velocity of the accelerated flyer using photon Doppler velocimetry (PDV) and studied the effects of laser beam shape, thickness of confinement layer, and laser beam diameter on flyer acceleration characteristics. They showed that flyer velocity of approximately 4 km/s could be achieved with a 700-μm focused laser beam onto a 25-μm-thick flyer.

Thus, previous studies have confirmed that laser-induced shockwave is an efficient method to fabricate microscale features and components. However, punching and embossing processes using laser-induced shockwave were only applied to very thin workpieces with thicknesses of several tens of micrometers to verify the process. Although it is likely that microscale features can be manufactured for thicker and hard-to-form materials by optimization of the process, there are no current studies focusing on forming performance, changes in deformation mechanism and fracture characteristics, and factors affecting manufacturing quality.

Therefore, this study conducted experiments to accelerate a flyer using laser-induced plasma and punch or emboss microscale features on metallic materials. The effects of various process parameters on manufacturing performance were investigated, such as mold size, workpiece thickness, and flyer thickness. Improved punching quality, i.e., increased shear zone and decreased burr size compared to conventional mechanical punching, was confirmed by a scanning electron microscope (SEM). Flyer planarity during acceleration and flyer velocity were identified as crucial factors for punch quality. When the ratio of mold diameter to workpiece thickness was reduced, Al foil could be successfully punched using multiple flyer impacts. Efficiency and punching performance for multiple flyer impacts could be improved by reducing the relative size of the flyer to the mold diameter.

2 Experimental procedure

Figure 1 shows the microscale punching experiment using laser-accelerated flyer impact. A Q-switched 1064-nm Nd:YAG laser with 10-ns pulse width was used as an energy source. The laser beam passes through reflectors and focusing lens (focal length = 19 cm), then impacts on the flyer surface. High-temperature and high-pressure plasma is generated by ablating a thin portion of the flyer. The plasma accelerates the flyer by absorbing the remaining laser energy and expanding rapidly. The ablated area on the flyer surface can be controlled by adjusting the distance between the focusing lens and the flyer surface. The accelerated flyer impacts the workpiece at a very high speed, generating a pressure wave and forcing the workpiece into the mold shape.

The flyers in this study were fabricated from pure aluminum using mechanical punching and subsequent rolling with 2.5 mm diameter and 50 and 300 μm thicknesses. The laser beam focal size on the flyer surface was 2 mm, i.e., smaller than the flyer diameter, to ensure that the working fluid from ablation distributes the pressure to the flyer surface and to prevent the fluid from escaping radially. However, since the laser beam is of Gaussian shape, there was a limitation in applying uniform pressure to the flyer [12]. A confinement

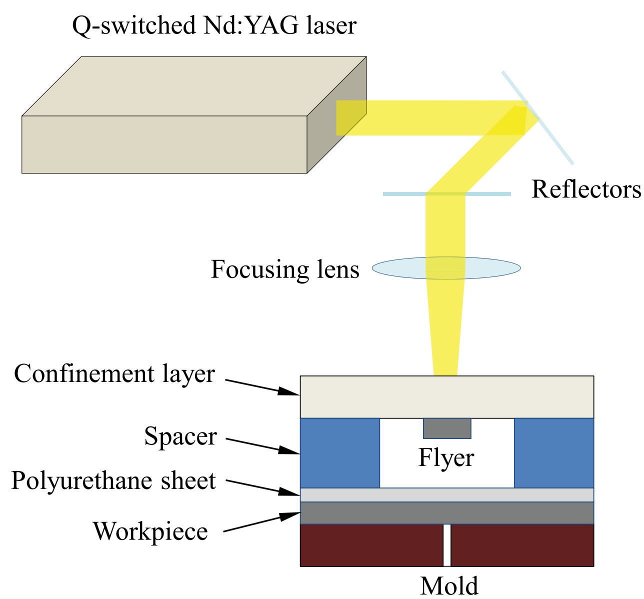

Fig. 1 Experimental setup for microscale punching using laser-accelerated flyer

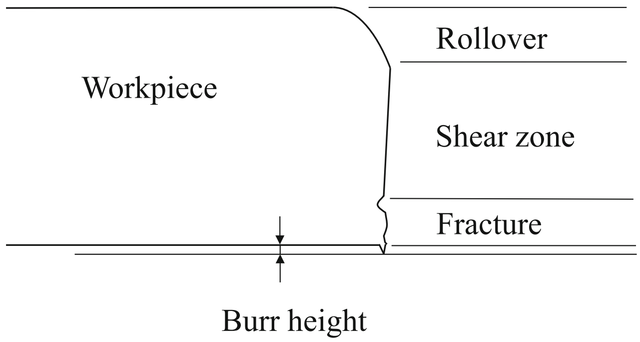

Fig. 2 Typical edge profile of punched hole

layer fixed to the entire mold system to confine the laser generated plasma in one direction and transmit strong pressure to the flyer as the plasma expanded. Soda lime glass was used for the confinement layer, since it has excellent transparency to 1064 nm. Flyers were attached to the confinement layer using water. A spacer was placed between the flyer and the workpiece to allow the flyer to accelerate sufficiently before impact. A polyurethane sheet was placed on the workpiece to prevent the plasma from directly contacting the workpiece and causing thermal damage. The workpieces were also aluminum with thicknesses of 50, 100, and 200 μm. Single 394- and 600-μm-diameter holes were fabricated on the mold by WEDM. The mold material was D2 steel.

In the punching process, when the material flows into the die cavity, it deforms plastically until the deformation zone reaches the material shear strength. Since stresses are concentrated near the edge of the die surface, fracture occurs from the lower surface of the workpiece and spreads to the top surface. After punching, the edge profile is generally characterized by rollover, shear zone, fracture, and burr as shown in Fig. 2. Punching using laser-accelerated flyer impact is a very high-speed deformation process. Therefore, it was expected that deformation and fracture characteristics would be significantly different from typical mechanical punching. Fracture characteristics were observed with an optical microscope (HS-300U) and a SEM (Tescan Vega3). The height of the workpiece in the case of embossing was measured using a three-dimensional shape measuring instrument (Nano3D) to check the degree of formability in different process conditions.

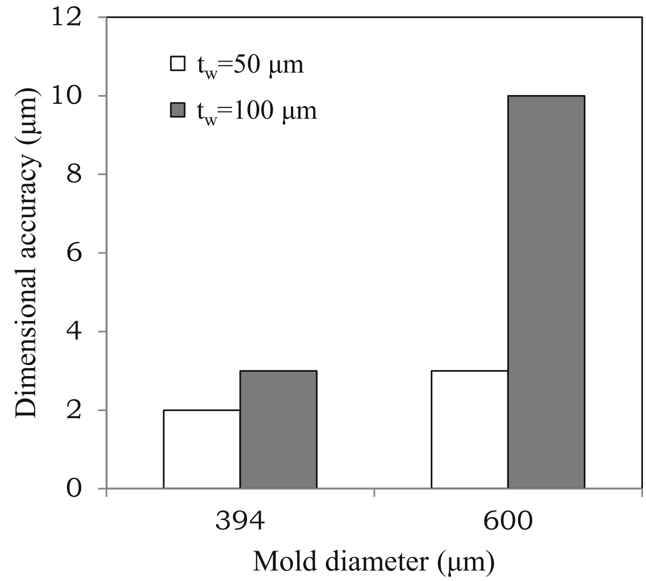

Fig. 4 Dimensional accuracy of punched holes for different workpiece thicknesses (t_w) and mold diameters (d_m) for 300-μm-thick flyer

3 Results and discussion

3.1 Thick flyer punching

Figure 3 shows the punching results for 600- and 394-μm holes using the 300-μm-thick flyer and laser intensity of 6.3 GW/cm^2. Punching was successful when the workpiece thicknesses $t_w = 50$ and 100 μm. However, when $t_w = 200$ μm, an embossed shape resulted on the workpiece without

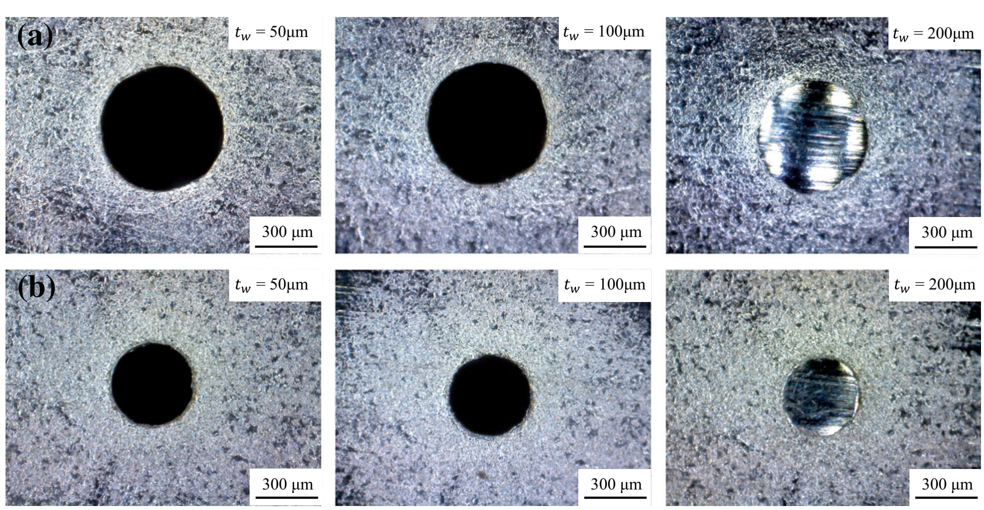

Fig. 3 Optical microscope images of punched and embossed workpieces by 300-μm-thick flyer impact for different workpiece thicknesses (t_w) and mold diameters (d_m): **a** d_m = 600 μm and **b** d_m = 394 μm

punching through. Thus, punching capability of the process was established as $d_m/t_w > 3$, where d_m is the mold diameter.

Punched hole accuracy was assessed by comparing the mold and punched hole (d_p) diameters,

$$\Delta d = d_m - d_p \quad (1)$$

where Δd is the index of dimensional error in the punched holes.

Figure 4 shows that when $t_w = 50$ μm, $\Delta d = 2$ and 3 μm for $d_m = 394$ and 600 μm, respectively. When $t_w = 100$ μm, $\Delta d =$ 3 and 10 μm, respectively: slightly increased, still small. Generally, material flowing into the die cavity increases as workpiece thickness increases, increasing rollover and degrading punching dimensional accuracy. However, this effect was not significant for the process conditions here, and the mold microscale hole was transferred to the workpiece very accurately.

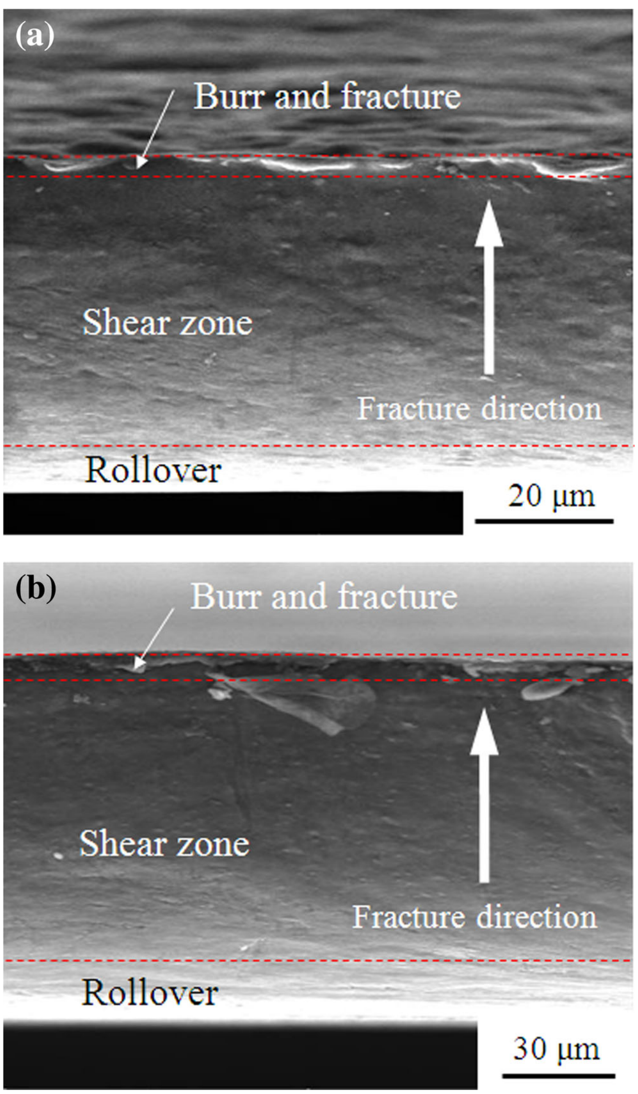

Fig. 5 SEM images of punched surfaces for 300-μm-thick flyer impact at different workpiece thicknesses (t_w): **a** $t_w = 50$ μm and **b** $t_w = 100$ μm

To investigate material fracture characteristics in detail, the fractured surface of the punched hole was observed using SEM, as shown in Fig. 5. Figure 5a shows that the fractured surface when punching 600-μm-diameter hole in the $t_w =$ 50-μm workpiece was quite smooth and clean. Ratios of rollover, shear, and fracture and burr zones = 16, 78, and 6%, respectively, and burr height at the hole exit was about 2.2 μm. Figure 5b shows the punched profile for 394-μm-diameter hole in the $t_w = 100$-μm workpiece. Ratios of rollover, shear, and fracture burr zones = 18, 75, and 7%, respectively, and burr height was 4 μm. There was no significant difference to Fig. 5a, with large relative shear zone and good punched hole quality. Thus, the effect of workpiece thickness and mold diameter was minimized under these high-speed punching conditions.

Decreased rollover and burr height and increased shear zone are regarded as improved punched hole quality. This can be achieved in high-speed forming processes, such as the current method, since the material experiences high local shear strain under high-speed deformation, and the material shear effect is increased by the narrow shear band, causing rapid temperature increase and material softening. Since the

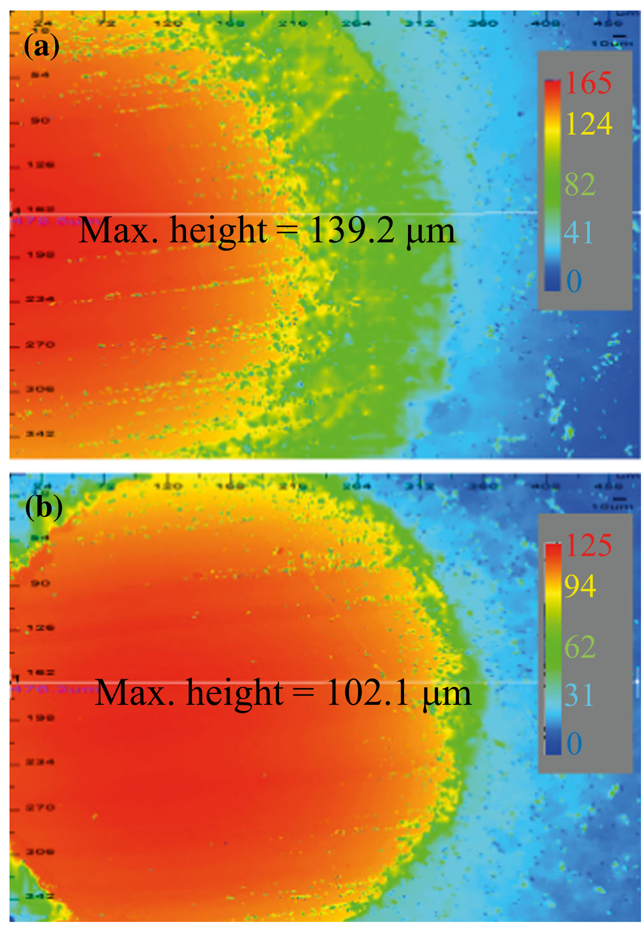

Fig. 6 Workpiece embossed features and maximum height for **a** mold diameter $d_m = 600$ μm and **b** $d_m = 394$ μm with 300-μm-thick flyer

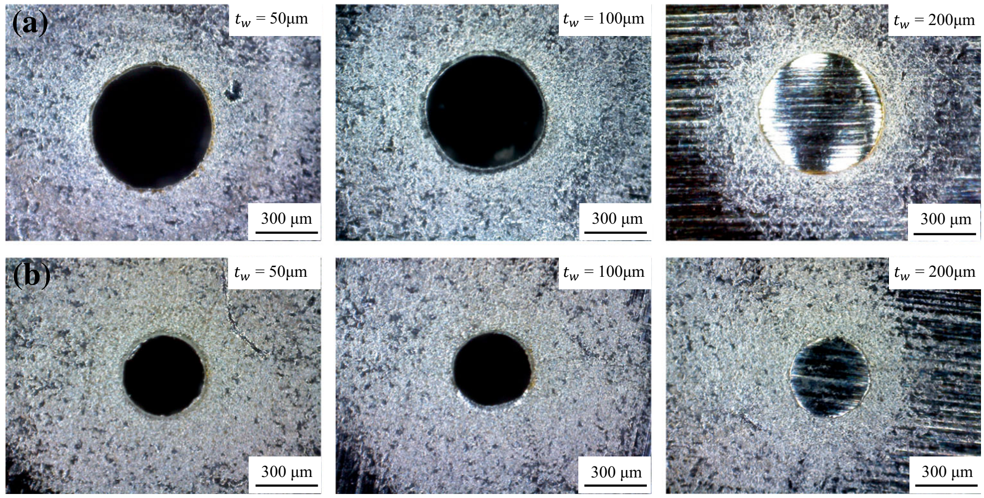

Fig. 7 Optical microscope images of punched and embossed workpieces by 50-μm-thick flyer impact for different workpiece thicknesses (t_w) and mold diameters (d_m): **a** $d_m = 600$ μm and **b** $d_m = 394$ μm

laser-induced plasma accelerated the flyer to between several hundreds of meters per second and several kilometers per second, punching using laser-accelerated flyer impact causes local shear deformation at high strain rate in the workpiece and produces good quality punched hole.

Another difference between punching using laser-accelerated flyer impact and conventional mechanical process is the clearance between the die and punch. This is one of the most important factors affecting forming quality. In the proposed laser-based process, the flyer is larger than the hole diameter, which can be considered similar to mechanical punching with negative clearance. The workpiece experiences three-dimensional compressive stress, which improves material plasticity, and since drawing stress is reduced, cracks are less common and the shear zone is enlarged. Consequently, the workpiece quality is improved and rollover, and fracture and burr zones are reduced [13].

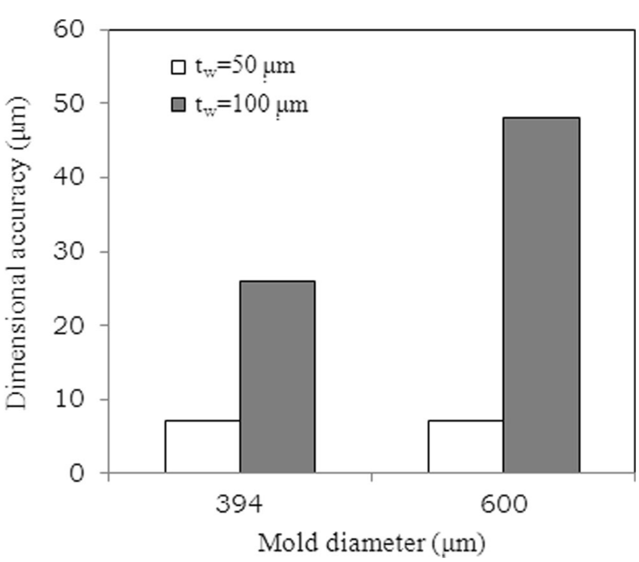

Fig. 8 Dimensional accuracy of punched holes for different workpiece thicknesses (t_w) and mold diameters (d_m) for 50-μm-thick flyer

Figure 3 shows that when $t_w = 200$ μm, the workpiece was embossed rather than being punched due to the workpiece thickness. Figure 6 shows the measured embossed feature

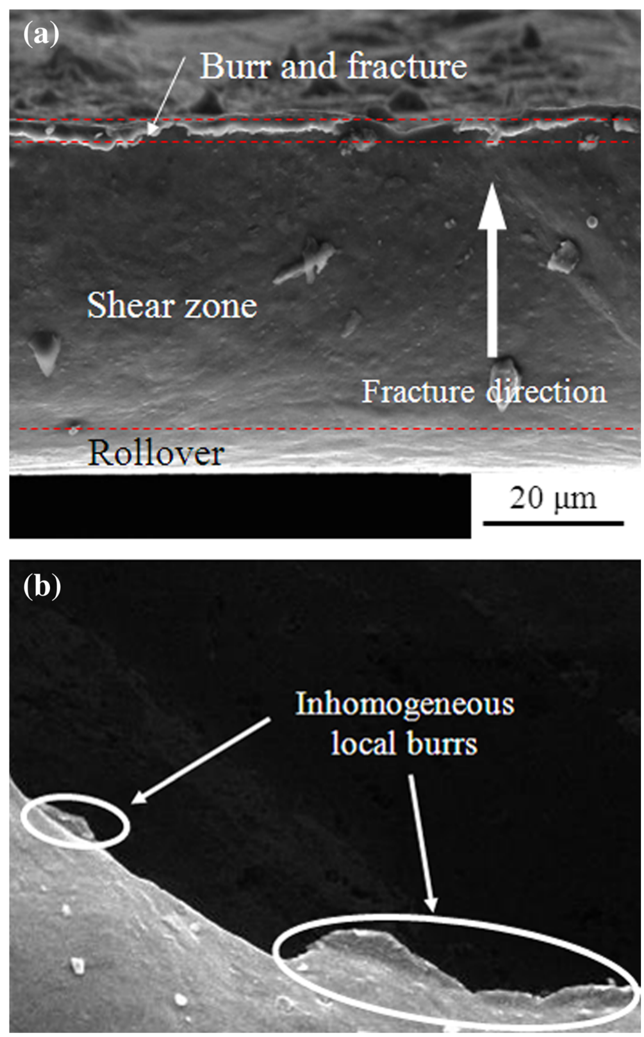

Fig. 9 SEM images of punched hole using 50-μm flyer and mold diameter $d_m = 600$ μm: **a** punched surface and **b** top view

height. When $d_m = 600$ μm, maximum embossed height (h_e) = 139.2 μm. When $d_m = 394$ μm, $h_e = 102.1$ μm. It is reasonable that h_e increases as d_m increases, because the area of the workpiece contacting the mold surface reduces as d_m increases. The ratio $h_e/d_m = 0.232$ and 0.259 for $d_m = 600$ and 394 μm, respectively, i.e., the embossing ratios were similar.

3.2 Thin flyer punching

To investigate the effect of flyer velocity on punching quality, we used a thin 50-μm-thick flyer. Aside from the flyer thickness, other process conditions were the same as in Section 3.1. Flyer mass decreases with decreasing flyer thickness; hence, flyer velocity at impact increases, due to being accelerated by the laser-induced plasma under the same energy conditions.

Figure 7 shows optical microscope images of punching with 50-μm flyer for various workpiece thicknesses ($t_w = 50$, 100, and 200 μm) and mold diameters ($d_m = 600$ and 394 μm). Similar to the case where $t_f = 300$ μm (see Fig. 3), punching was successful when $t_w = 50$ and 100 μm, but when $t_w = 200$ μm, the workpiece was only embossed rather than punched. Thus, punching was achieved when $d_m/t_w > 3$, similar to Section 3.1. However, a few burrs occurred in the periphery of successfully punched holes, and punching performance was somewhat deteriorated.

Figure 8 shows the dimensional accuracy using Eq. (1). When $t_w = 50$ μm, $\Delta d = 7$ μm for both $d_m = 600$ and $d_m = 394$ μm, which is slightly increased compared to Fig. 4. When $t_w = 100$ μm, dimensional accuracy decreased sharply, $\Delta d = 48$ and 26 μm, respectively. Thus, forming performance is degraded when t_f is small, and this effect becomes more prominent as t_w becomes thicker.

Figure 9 shows SEM images of punched holes to investigate material deformation characteristics and changes in the fracture surface. Figure 9a shows that the fracture surface has typical characteristics of high-speed forming, with a relatively wide area of shear zone. Ratios of rollover, shear, and fracture and burr zones = 15, 79, and 6%, and burr height was 3.3 μm. Compared to the case $t_f = 300$ μm, shear zone decreased and burr increased slightly, but not significantly. However, as shown in Fig. 9b, large burrs occurred locally around the punched hole surface, and the entire punched surface was

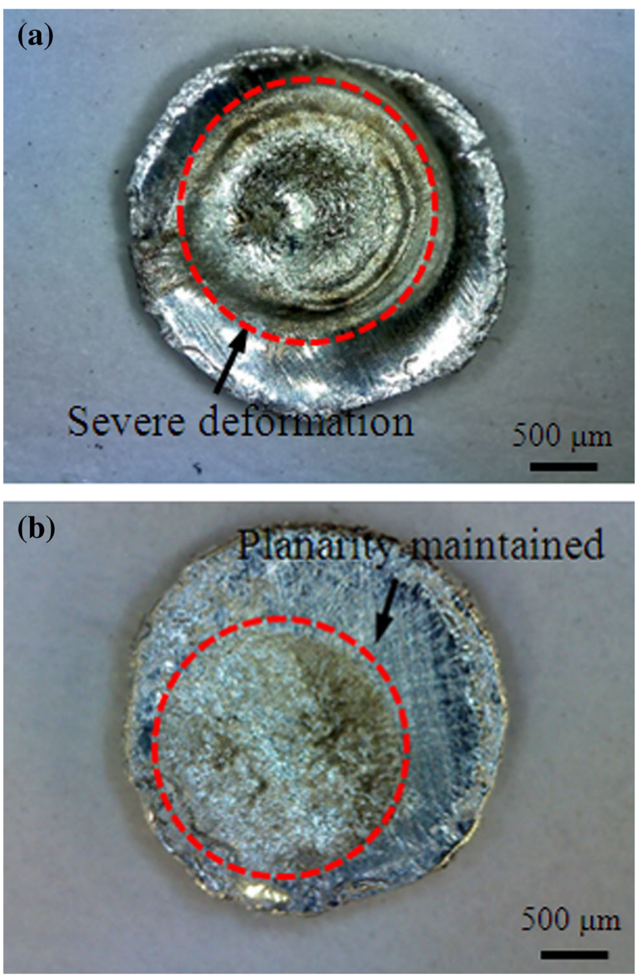

Fig. 10 Deformed flyer after laser-induced launching for **a** flyer thickness $t_f = 50$ μm and **b** $t_f = 300$ μm

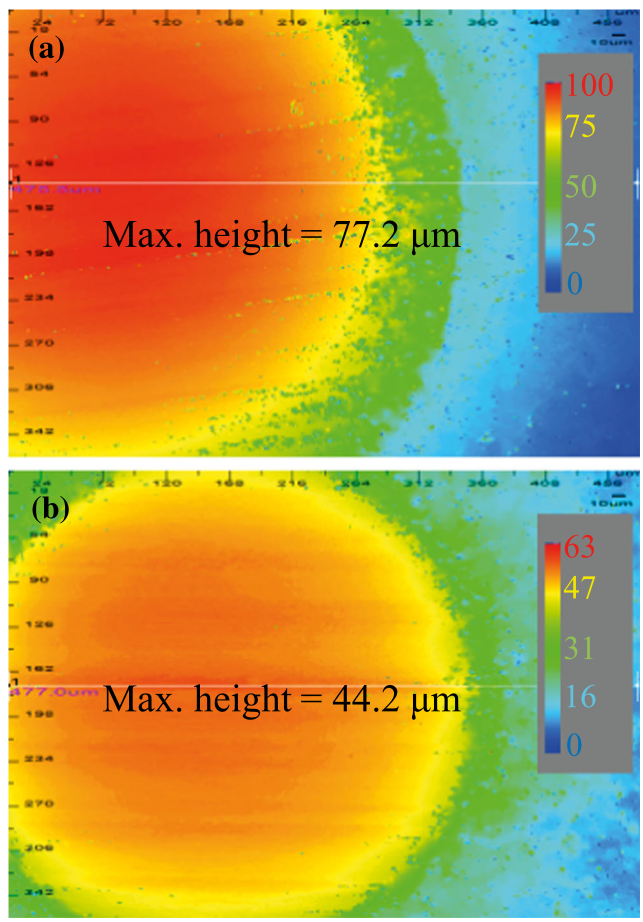

Fig. 11 Workpiece embossed features and maximum height for **a** mold diameter $d_m = 600$ μm and **b** $d_m = 394$ μm with 50-μm-thick flyer

somewhat inhomogeneous, i.e., the pressure applied to the workpiece by the flyer impact varied along the edge of the mold.

When flyer kinetic energy is transferred to the workpiece, the approximate relationship between flyer velocity, V_i, and impact pressure, P, can be expressed as [14]:

$$P = \frac{\rho_1 \rho_2 C_1 C_2}{\rho_1 \rho_2 + C_1 C_2} V_{\mathrm{i}} \tag{2}$$

where subscripts 1 and 2 represent a flyer and a workpiece, respectively; ρ is the material density; and C is the material longitudinal wave velocity,

$$C = \sqrt{\frac{3K(1-\nu)}{\rho(1+\nu)}} \tag{3}$$

where K represents the bulk modulus, and ν represents Poisson's ratio.

From Eq. (2), impact pressure transmitted by the flyer to the workpiece increases with increasing flyer velocity. The workpiece deforms plastically when the pressure transferred to the workpiece exceeds the dynamic yield stress of the workpiece. Therefore, higher flyer velocity, i.e., higher workpiece pressure, promotes improved formability and surface quality. However, using the thin flyer did not appear to provide the full benefits of the high-speed punching, as shown in Figs. 7 and 8.

The reason appears to be related to the failure of the flyer to maintain planar shape impacting the workpiece. Figure 10 shows the deformed flyer after launching for flyer thickness = 50 and 300 μm. Thin flyer shape was significantly affected. Large deformation was particularly evident in the middle of the flyer where the laser energy was focused. However, the thick flyer largely maintained planarity. When $t_f = 50$ μm, the flyer lost flatness during acceleration, the flyer could not impact flat upon the workpiece, and the plasma pressure could not be evenly transmitted to the workpiece. On the other hand, when $t_f = 300$ μm, even when insufficiently accelerated compared to the 50-μm flyer case, workpiece quality was improved because flatness was maintained and a flat impact was applied to the workpiece. Thus, not only flyer velocity but also planarity during acceleration is a crucial factor for punched hole quality.

This degradation of forming performance and loss of transmitted pressure was verified from h_e when $t_w = 200$ μm, as shown in Fig. 11. Embossed heights $h_e = 77.2$ and 44.2 μm for $d_m = 600$ and 394 μm, respectively. Larger h_e for $d_m = 600$ μm was due to the smaller area of contact with the mold surface. Relative formability was similar, $h_e/d_m = 0.14$ and 0.13,

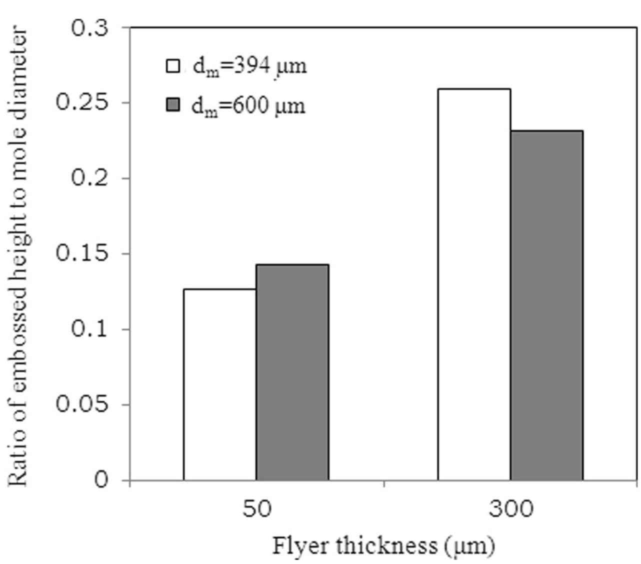

Fig. 12 Ratio of embossed height to mold diameter at different flyer thicknesses (t_f) and mold diameters (d_m)

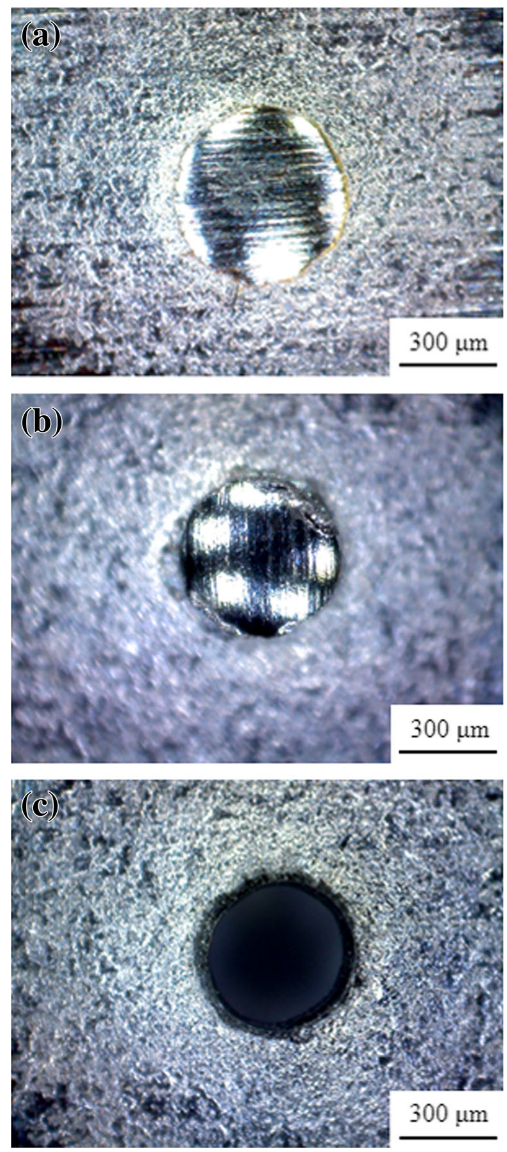

Fig. 13 Optical microscope images of punched and embossed workpieces after **a** two, **b** three, and **c** four 2.5-mm-diameter flyer impacts

respectively, but significantly decreased from the thick flyer cases (Fig. 12) by approximately 44 and 56%, respectively. Thus, punching capability was degraded for the thinner flyer case.

Since a faster flyer in principle is more likely to provide better formability, further research is required to find a suitable method to accelerate thinner flyers while maintaining their shape to improve formability and punching capability.

3.3 Multiple flyer impact punching

Successful punching was not achieved in the experiments of Sections 3.1 and 3.2 when $d_m/t_w \leq 3$. Therefore, we investigated expanding the punching capability by impacting more than one flyer on the same workpiece. Workpiece of thickness 200 μm was embossed when attempting to punch a 600-μm hole impacting with a 300-μm flyer as shown in Fig. 3. Figure 13 shows that when flyers impacted the workpiece two and three times, the embossed height increased to 169 and 267 μm, respectively. Finally, when the flyer impacted the workpiece four times, the disk-shaped scrap was separated and punching was successful.

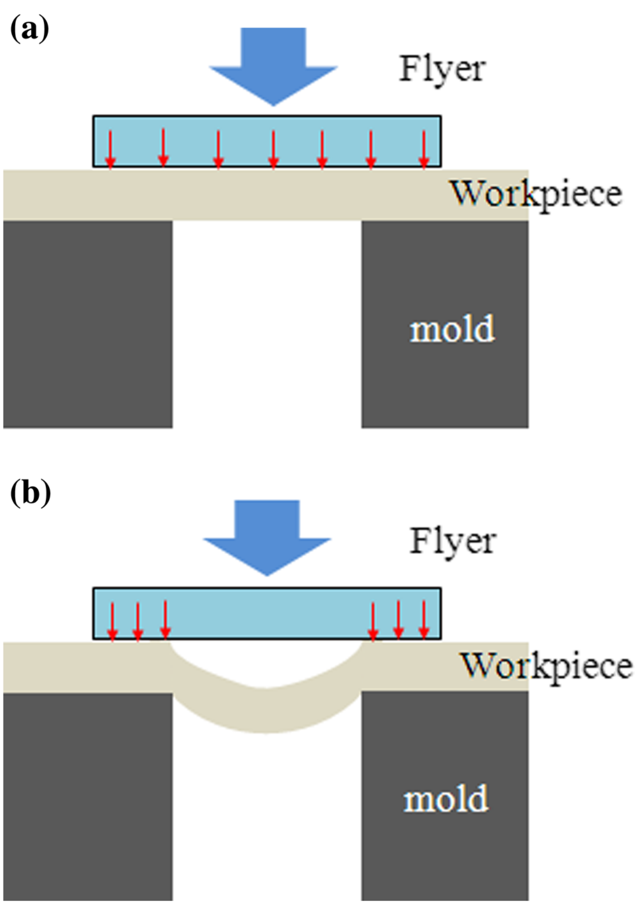

Fig. 14 Impact pressure transfer from the flyer to workpiece for **a** single and **b** multiple flyer impacts

However, accuracy was significantly degraded compared to single flyer impact case (Fig. 4): $\Delta d = 153$ μm. The reason is that as workpiece thickness increases, the amount of rollover into the mold hole increases, and on subsequent impacts, flyer kinetic energy is inefficiently transferred because the workpiece is already embossed after the first flyer impact. Figure 14 shows that pressure is more uniformly delivered to the nondeformed workpiece. When impacting on an already embossed workpiece, significant energy is consumed in the flange portion contacting the flyer, and only once the flyer plastically deforms does it contact the embossed area of the workpiece to transfer the deformation force. Thus, transmission efficiency of multiple flyer impacts is inherently lower than single flyer impact.

Figure 15 shows SEM images of the fracture surface for multiple flyer impacts. Rollover ratio for the fracture surface parallel to the flyer moving direction was significantly increased due to increased workpiece thickness. Although the shear zone occupied most of the area, which is a characteristic of high-speed forming with smooth surfaces, the back side of the workpiece shows that the flyer pressure was not efficiently

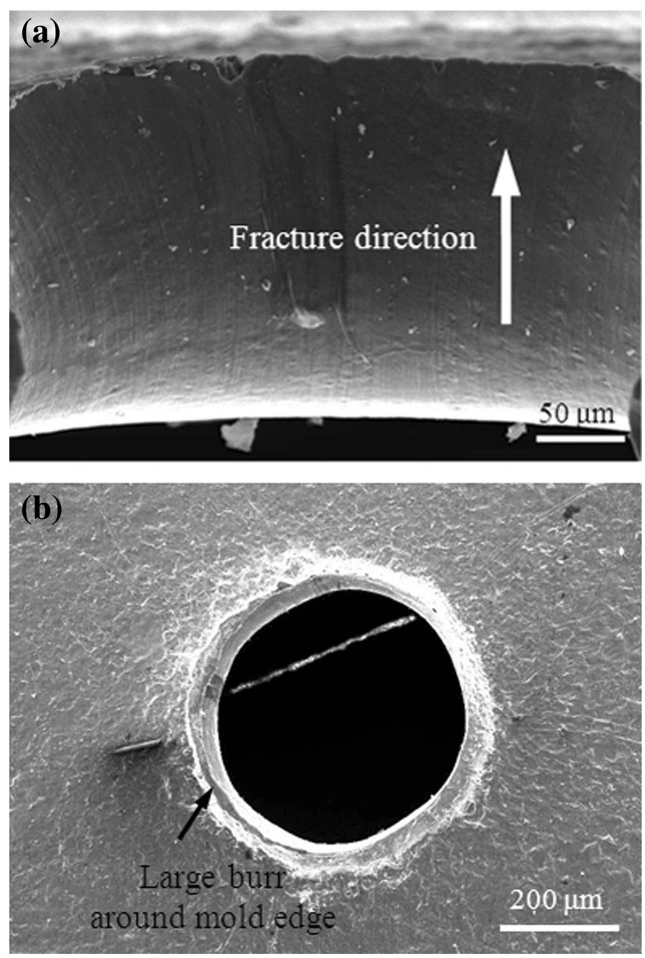

Fig. 15 SEM images of punched hole from multiple flyer impacts for 200-μm-thick workpiece, 300-μm-thick flyer, and 600-μm mold diameter: **a** punched surface and **b** bottom view with large burr area

transmitted, generating a large burr. If the flyer pressure is not smoothly transmitted to the mold vicinity and workpiece, shear decreases and tensile stress due to the bending moment increases. Therefore, cracks generated at the upper and lower ends of the workpiece do not coincide, consequently generating a large burr. This phenomenon is similar to using a punch with large die clearance in conventional punching.

Therefore, it is very important to increase flyer energy transfer efficiency when using multiple flyer impacts. This study considered the ratio of the flyer to mold diameter was an important variable to determine formability for the multiple flyer impact case. When this ratio is reduced, the contact region between the flyer and workpiece in the flange decreases. This will enable the flyer to target the die cavity more effectively, and improve pressure transfer from the flyer to the workpiece.

Figure 16 shows that embossed and punched workpieces by multiple flyer impacts with flyer and laser diameters were reduced to 2 and 1.6 mm, respectively, maintaining the ratio flyer/laser diameter = 80%. Workpiece deformed height was increased, $h_e = 210$ μm after two flyer impacts, and there was an increase of approximately 24% compared to the case of Fig. 13a. Fracture occurred in some regions of the mold periphery, although the scrap was not completely separated, after three flyer impacts (Fig. 16b). Scrap was completely removed and punching completed after four impacts (Fig. 16c).

Figure 17 shows that the ratio of flyer to mold size is an important factor in determining punching capability of this process. Formability was improved by reducing flyer diameter, hence improving energy transfer efficiency from the flyer for multiple flyer impacts. However, no significant improvement in dimensional accuracy of the punched parts was evident when flyer diameter was reduced (compare Figs. 13c and 16c). Apparently, more intense pressure localized around the edge of the mold is required to improve dimensional accuracy. Further research is required to find the optimal ratio of flyer to mold size and investigate the effects of flyer diameter and beam size on formability and punching capability. In addition, the Bayesian method or analysis of variance (ANOVA) [15] will be applied to investigate the relative importance of various factors and their correlation effects.

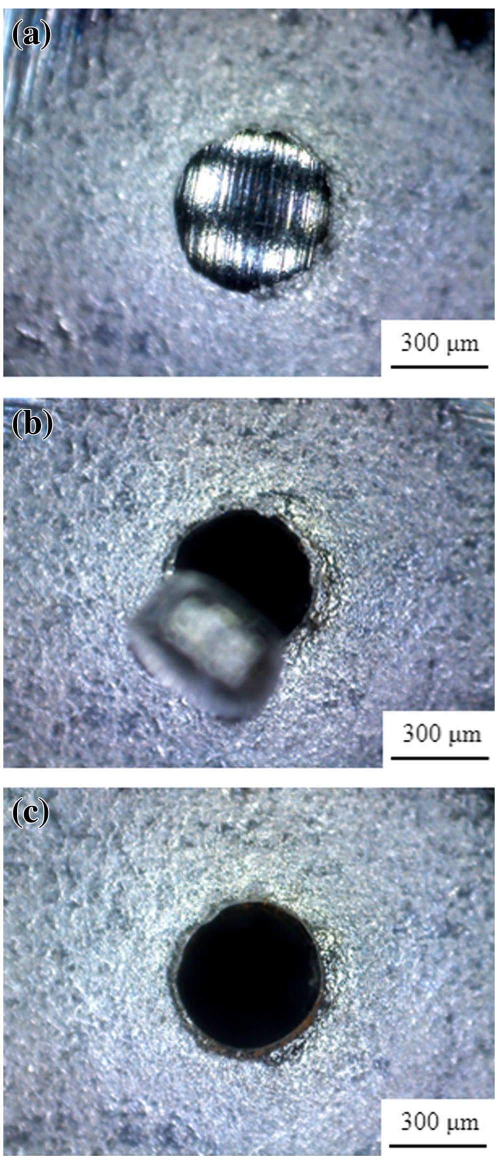

Fig. 16 Optical microscope images of punched and embossed workpieces after **a** two, **b** three, and **c** four 2-mm-diameter flyer impacts

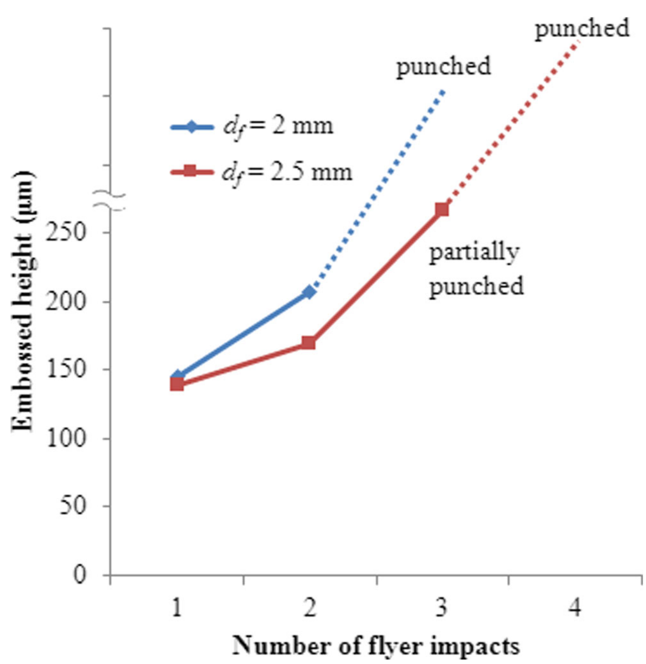

Fig. 17 Workpiece embossed feature height and failure after multiple impacts from flyers with different diameters

4 Conclusions

This study investigated high-speed laser-accelerated flyer impact to determine processing capability for microscale punching and to identify the deformation mechanism and fracture characteristics. The following conclusions can be drawn:

1. Single flyer impact punching of 394- and 600-μm-diameter holes was successfully achieved for 50- and 100-μm-thick Al foil. However, when $d_m/t_w \leq 3$, the workpiece was embossed rather than completely punched.
2. The shear zone was relatively wide, and the fracture and burr were narrow, which confirmed improved punching quality and the advantage of high-speed processing. This is because the shear effect increases as the material receives locally high shear strain in the high-speed forming process, and punching with negative clearance was realized because the size of the flyer that pressurized the workpiece was larger than the hole diameter.
3. Although the thin flyer was able to impact the workpiece at higher velocity than the thicker flyer, workpiece dimensional accuracy and embossed height were reduced. The reason could be that the thin flyer lost flatness while accelerating, and could not deliver the impact force evenly to the workpiece. High-speed flyer impact should increase forming performance by increasing workpiece pressure, and further research is required to identify optimal conditions for accelerating flyers while maintaining their planar shape, and hence retaining transfer efficiency.
4. Punching was successful on 200-μm Al foil when $d_m/t_w \leq 3$ using multiple flyer impacts. However, dimensional accuracy was significantly degraded and large burrs were generated on the back side of the workpiece. Workpiece embossed height and formability could be enhanced for multiple flyer impacts by reducing the ratio of flyer to mold diameter. Further research is required to apply localized intensive pressure around the edge of the mold to maximize formability and process capability.

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