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Optimizing Drilling Conditions for AZ61A Magnesium Alloy

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For magnesium alloys, optimizing the machining conditions is necessary to prevent ignition of chips. In this study, effects of point angles of drill bits and drilling parameters on surface roughness and cutting resistance forces were measured and studied. Surface roughness and cutting resistance forces are increased following the increase of point angle and material removal rate. Point angle ($2p$) descends from 118° to 55° producing the smoothest machined surface and minimum variance in the measured roughness. In addition, effect of drilling operation on varying microstructure of AZ61A was also investigated in this study. The drilled sample showed a minimum extent of deformation twinning layer, when the drill bit adopted a point angle of 55°. The drilled sample developed a superior surface roughness and a short extent of twinning layer generated on the matrix of machined sample, if a 5%NaOH solution was used as lubricant and a 55° point angle was used.

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1. Introduction

Drilling process is one of the most important cutting processes and has been widely investigated by numerous researchers. In fact, drilling operation is not considered as a very crucial factor to influence the quality of machine parts with a good machinability like magnesium alloys. Many researchers have investigated effects of drill bit's geometrical parameters on the quality of machine parts. Chen *et al.*[1)] used a split-point drill to develop a force model incorporating the splitting parameters for the drilling process. They optimized drill-point geometry to minimize the thrust force and torque during drilling. Chen and Tsao[2)] indicated that drills with different coatings performed differently on the drill life and quality of drilled hole. Haas *et al.*[3)] investigated effects of different profiles on the functions of drills. They measured torque produced from varying drilling conditions: cutting speed, feed, on/off in running cutting fluid. They concluded that cutting fluid is a significant factor in producing drilling hole's profile. Besides, cutting fluid affected the amount of BUE (Built-Up Edge) depending on the efficiency for cutting fluid removing heat from cutting workpiece.

Moreover, researchers also focused theoretically on drilling process and conducted some more drilling experiments. Wiriyacosol and Armarego[4)] used the tractable metals and developed empirical expressions for estimating torque and thrust force during drilling process. They indicated that increasing the point angle of drill reduced torque but increased the thrust force. The above information indicates that geometrical factors of drill bits and processing parameters greatly affect the performances of drilling operation.

Magnesium (Mg) alloy is one of the popular lightweight materials. Magnesium alloy has been widely applied for structural material due to a high strength-density ratio, vibration absorbing and unique physical properties. In addition, high EMI (Electromagnetic Interference) and good thermal conductivity also promote the application of magnesium alloy as a substitute for plastic in 3C business. However, drilling process is a necessary step for making parts. So far, most researchers are trying to prevent the ignition of magnesium scraps through modified the geometry of machining scraps and machining handbooks[5–8)] recommend that drill bit of 70°–118° point angle is suitable for drilling magnesium and magnesium alloys. This study, however, investigated not only the operation parameters, like cutting speed, feed rate and point angle of drill bits on the quality of drilling hole, but also the dynamic effects of drilling operation on microstructure of AZ61.

2. Experimental Procedure

A vertical type and numerical-controlled milling machine was used in this study, Fig. 1. The sample material is commonly used wrought AZ61A (6.5%Al, 0.8%Zn). Samples prepared from an extruded rod, 40 mm in diameter. Each sample has 40 mm in thickness. The cylinder specimen was tightly fixed on the pallet of the vertical milling machine through a clamp and drilled at different parameters to get drilled holes. Surface roughness of each drilled hole was measured and microstructure at the subsurface of drilled hole was observed by optical microscope. Another cylindrical specimen with 200 mm in diameter and 50 mm in height was prepared and fixed tightly on the 3-axial drilling dynamometer and set on the pallet of the vertical milling machine. This cylindrical sample was used to measure the cutting resistant forces during drilling process. The cutting force and thrust force during drilling process were decomposed into X, Y and Z axial cutting resistant forces by the dynamometer. Those

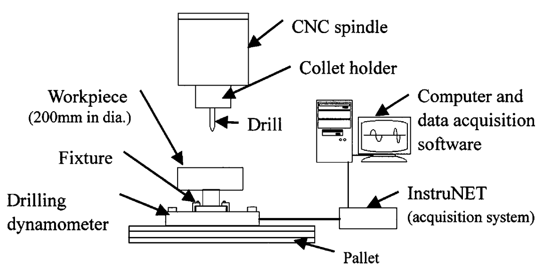

Fig. 1 Layout of dynamic acquisition system in drilling process.

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signals of the 3 axial cutting resistant forces were recorded respectively by a data acquisition system.

A standard twist drill was used to drill a pilot hole of 5 mm in diameter with 30 mm in depth under the condition of 405 rev·min^{-1} and 0.1 mm/rev. Then, two-flutes drill bits (HSS, 13 mm in diameter, 8°–12° in clearance angle, 30° in helix angle) with a modified point angle ($2p$) from 35° to 118° were used to drill holes, 30 mm in depth under two spindle speeds (405 rev·min^{-1} and 890 rev·min^{-1}) and three feeds (0.1, 0.2 and 0.3 mm/rev). This experiment was designed to investigate the effect of point angle of drills on the qualities of drilled holes.

In the second experiment, different lubricants were adopted during drilling, including water-insolvable metalworking oil (Shell VALVATA® Oil J460, flash point 278°C), 5% sodium hydroxide (NaOH) solution and compressed air (70.6 N/mm^2 in pressure) used as reference. Cylindrical specimens of AZ61A alloys were totally immersed into the lubricants and drilled under the specific drilling condition. This experiment was set to compare effects of lubricants on the qualities of drilled holes.

3. Results and Discussion

3.1 Effect of point angle on surface roughness

Figures 2(a) and (b) show the relation of surface roughness (*Ra*) versus point angle of drill bit at a given feed 0.3 mm/rev but with rotational speed 405 and 890 rev·min^{-1}, respectively. When the point angle ($2p$) of the drill is less than 55°, the surface roughness of the drilled hole increases following the decrease of point angle. Cutting lips become longer since the point angle decreases and therefore the contact area of cutting edge increases. For a given feed, discontinuous chips removed from workpiece produced a large extent of shear zone ahead of cutting edge. Heat generated from the shearing action of chips accumulated at the interface of chips and tool. Part of chips might partially melt or re-melt and re-solidify near the cutting edge and promoted the formation of built-up edge (BUE) along helix slots as shown in Fig. 3(a). The adhesive blocky chips became solder and tore alternately at cutting edge. Sometimes cutting edge rubs magnesium alloy creating a burnished surface, Fig. 3(b). The surface finish of the drilled hole is greatly deteriorated and the measured surface roughness shows a remarkable scatter. BUE becomes very apparent and serious if the drill bit has a small point angle ($< 55°$) and drills at a great feed rate. If the drilled hole concerns merely on the measured surface roughness, the optimum point angle of drill bit lies at or greater than 55° for drilling without using lubricant.

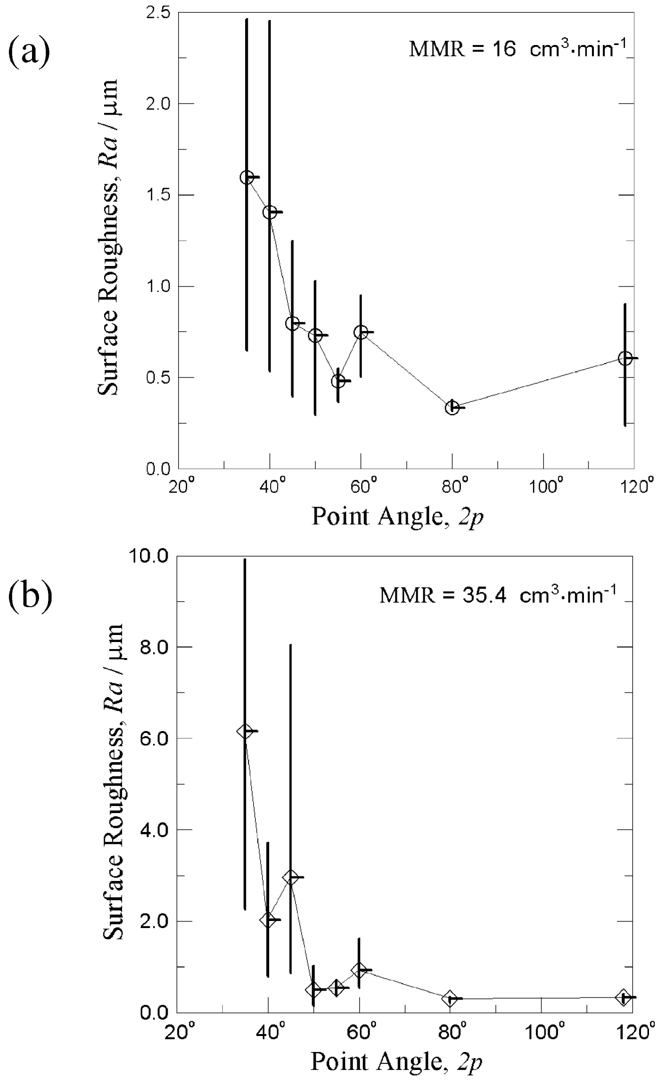


Fig. 2 The range and average of surface roughness (*Ra*) versus point angle of drill bit at material removal rate, MMR (a) 16 cm^3/min (rotation speed: 405 rev·min^{-1}) and (b) 35.4 cm^3/min (rotation speed: 890 rev·min^{-1}).

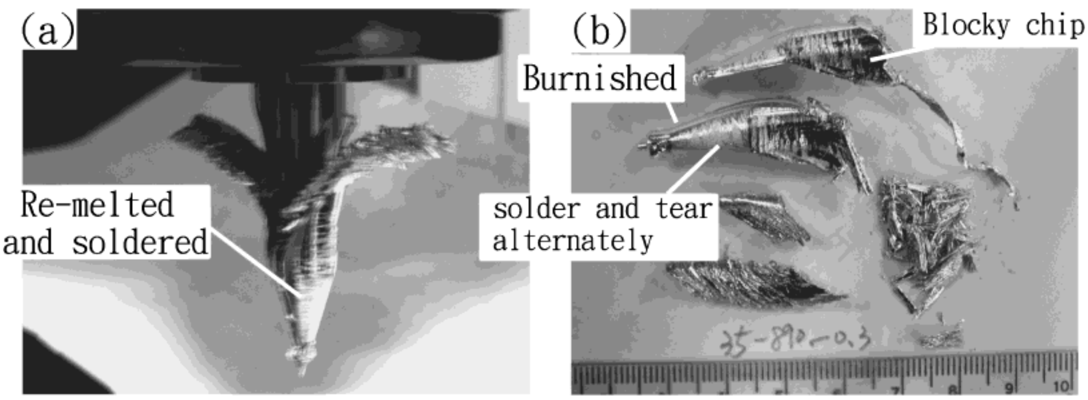


Fig. 3 BUE produced from a drill bit with a sharp point angle (35 degree).

3.2 Effect of cutting velocity on surface roughness and cutting resistant force

Figures 4(a)–(f) demonstrate the effect of material removal rates (MMRs, MMR $= \pi \times (D^2/4) \times f \times N$) on the quality of drilled surface when the point angle varying from 35° to 60° where π is the constant, 3.1416, D is the diameter of drill bit, f is a feed rate (mm/rev) and N is a spindle rotation (rev·min^{-1}). The MMRs were set from 5.3 to 35.4 cm^3/min in this study. When the point angle is less than 55°, increasing MMR lifts up the measured surface roughness of drilled hole and enlarges its deviation as well. Using a higher MMR intensifies the cutting pressure and generates a great amount of heat forming a severe BUE during drilling.

The surface temperature of the drilled specimen was measured during drilling. K-type thermo-couples, a diameter of 0.6 mm, were installed to the top surface of specimens away from the wall of drilled hole about 2 mm. The peak temperatures obtained are affected by taking different MMRs, as recorded in Fig. 5. These data agree with the previous discussions on that when the point angle is less than 55°–60°, increasing the MMR generates a great amount of heat forming BUE readily during drilling and then increases the resistant force from removing chips concurrently. The melting point of AZ61A alloys is about 650°C and the melting temperature of the precipitate, $Mg_{17}Al_{12}$, in AZ61A is about 460°C which is far lower than AZ61A.[9)] The heat accumulated at the interface between chips and cutting lip partly re-melts the chips and afterward solidifies. Formation of BUE greatly deteriorates the quality of surface finish even forming burnish.

The force and energy dissipated in drilling process has been measured and calculated in this study. Relations of work (Joule) versus different MMRs under different point angles are shown in Figs. 6(a) and (b) at rotational speed 405 and 890 rev·min^{-1}, respectively. Despite of the rotational speed of the spindle, drilling operation consumes minor work when the point angle is at or greater than 55°. For a given size of a drilled hole, increasing the feed rate definitely increases the energy needed to conduct the drilling.

Summarily speaking, decreasing point angle increases the length of cutting lip and/or taking a higher MMR produce a greater amount of heat leading to form BUE. Consequently, the cutting resistant force is increased as well. A great energy has dissipated for compensating the remarkable increase in friction force deteriorating the surface quality and producing a high scatter in the measured surface roughness. Because of

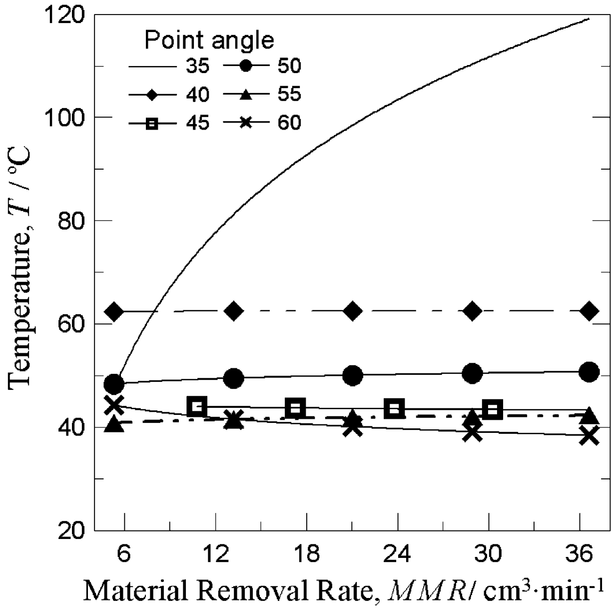


Fig. 5 The peak temperature on workpiece under different point angles of drill bits (35°–60°) and MMRs.

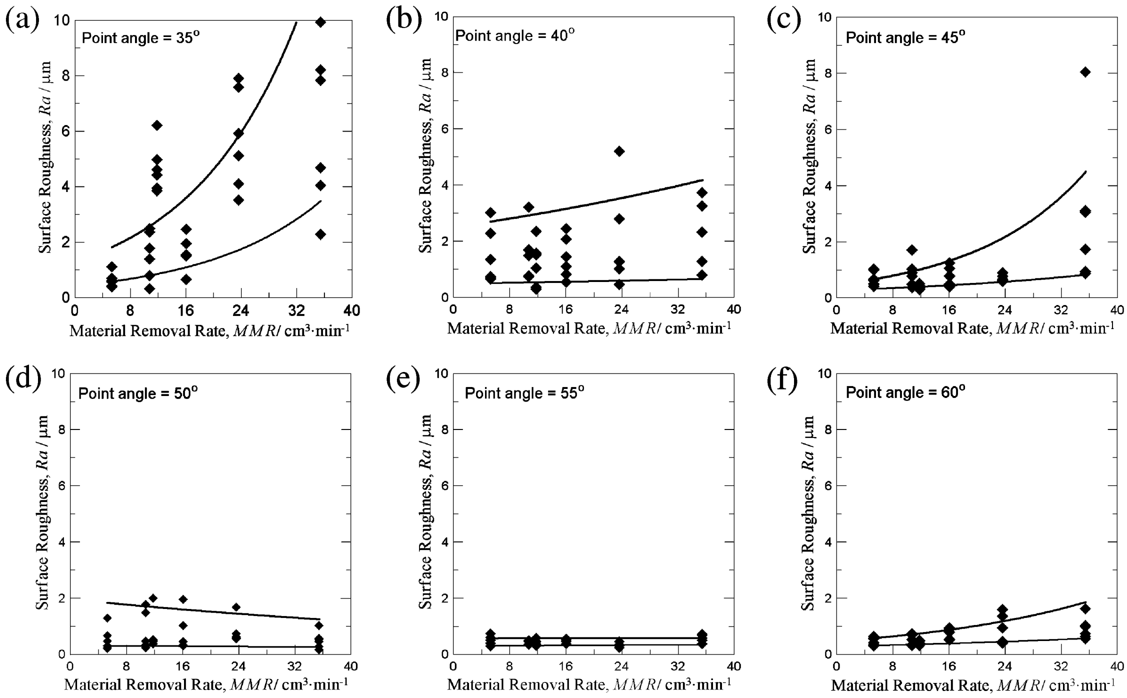


Fig. 4 Relation of measured surface roughness versus MMRs for drill bits with different point angles: (a) 35°, (b) 40°, (c) 45°, (d) 50°, (e) 55° and (f) 60° point angle.

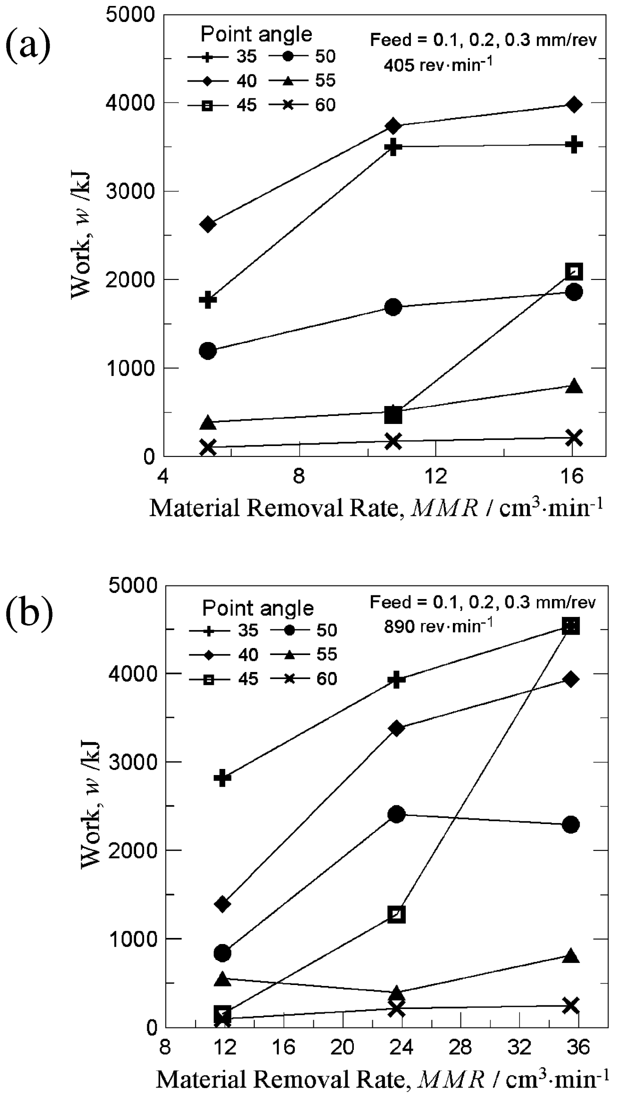


Fig. 6 Energy consumed during drilling respecting to MMRs under different point angles of drill bits, (a) rotational speed of 405 rev·min^{-1} and (b) rotational speed of 890 rev·min^{-1}.

low cutting efficiency due to formation of BUE, most energy was transferred into heat and accumulated at the interface of chips and drill bit. This greatly rises the probability of ignition locally and may cause firing hazard. If a drill point angle is set at 55°, the dilled hole shows a superior surface roughness when the MMR varies from 5.3 to 35.4 cm^3/min (Fig. 4(e)). When a point angle deviates from 55°, the drilled hole lifts up its deviation in surface roughness regardless of the MMR studied.

3.3 Effect of drilling parameters on microstructure of AZ61A alloy

Magnesium alloy has a HCP structure and the ratio of c/a of 1.6235, which is less than ideal value of 1.633. Referring to Ref. 10), an angle, 43.15°, exists between basal plane and K_2 plane $(\bar{1}012)$ in magnesium and its alloys. Once magnesium alloy is subjecting to a compressive shear stress, it forms twinning to compensate the shortened crystal length in the direction parallel to the basal plane resulting from veering the undistorted K_2 plane. Since K_2 plane $(\bar{1}012)_{\text{in twinning}}$ is necessary to be rotated to maintain the symmetry condition, the displacement, S, occurs, shown in Fig. 7.[10] Therefore, the twinning is favored by compressive shear stress and formation of twinning can maintain the angle symmetrically across twin planes.

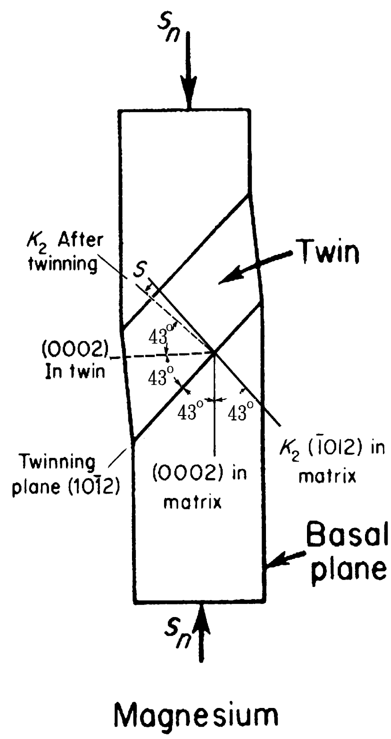


Fig. 7 Schematic illustration of forming twinning for magnesium under compressive shear stress.[10]

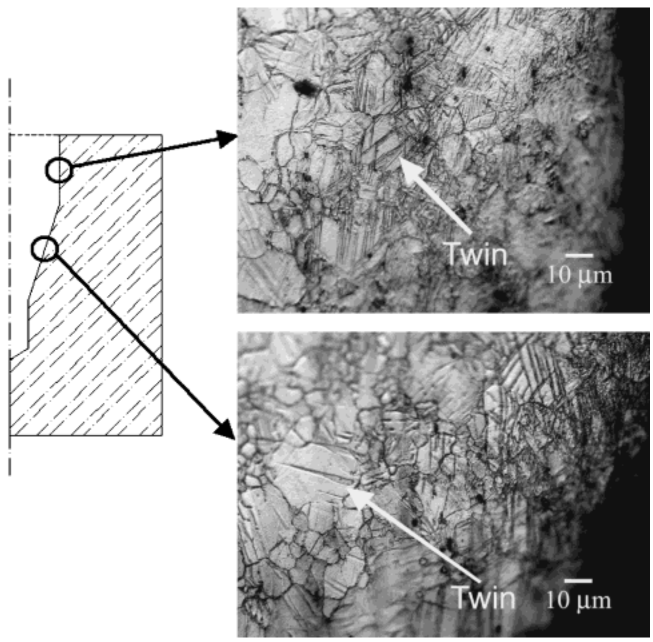


Fig. 8 Typical twinning microstructure of magnesium alloy after drilling.

Shih *et al.* studied the high-cycle fatigue life of AZ61A.[11] They point out that the specimen of AZ61A develops a deteriorated fatigue life (cycles to failure) for a given stress amplitude when its surface exerted a twinning structure. Regarding to the quality of drilled parts, two factors should therefore be concerned: surface roughness and the degree or extent of twinning resided within the matrix of drilled parts.

During drilling, the downward pressure compresses directly on the matrix of the workpiece and provides a compressive shear force on the plastic deformation zone (or shear zone). This pressure increases following the increasing point angle of the drill bit. The matrix of drilled hole is readily to generate some extent of twinning. The matrix near surface of drilled wall demonstrates a mixture of slip and twinning structure, Fig. 8.

Figures 9(a)–(f) demonstrate the microstructures of a matrix near the surface of the drilled hole taking a feed of 0.3 mm/rev and a rotational speed of 890 rev·min^{-1} but with different point angles. Figures 9(a), (c) and (e) show the matrix from the wall (or free surface) of drilled hole and Figs. 9(b), (d) and (f) illustrate the matrix locating near the chisel edge of drill bit. Numbers listed in the figures are the measured extents of twinning structure optically. Use of point angle 55° develops a minimum extent of twinning, as shown in Figs. 9(c) and (d). Besides, the extent of twinning structure decreases, when a MMR decreases from 35.4 cm^3/min

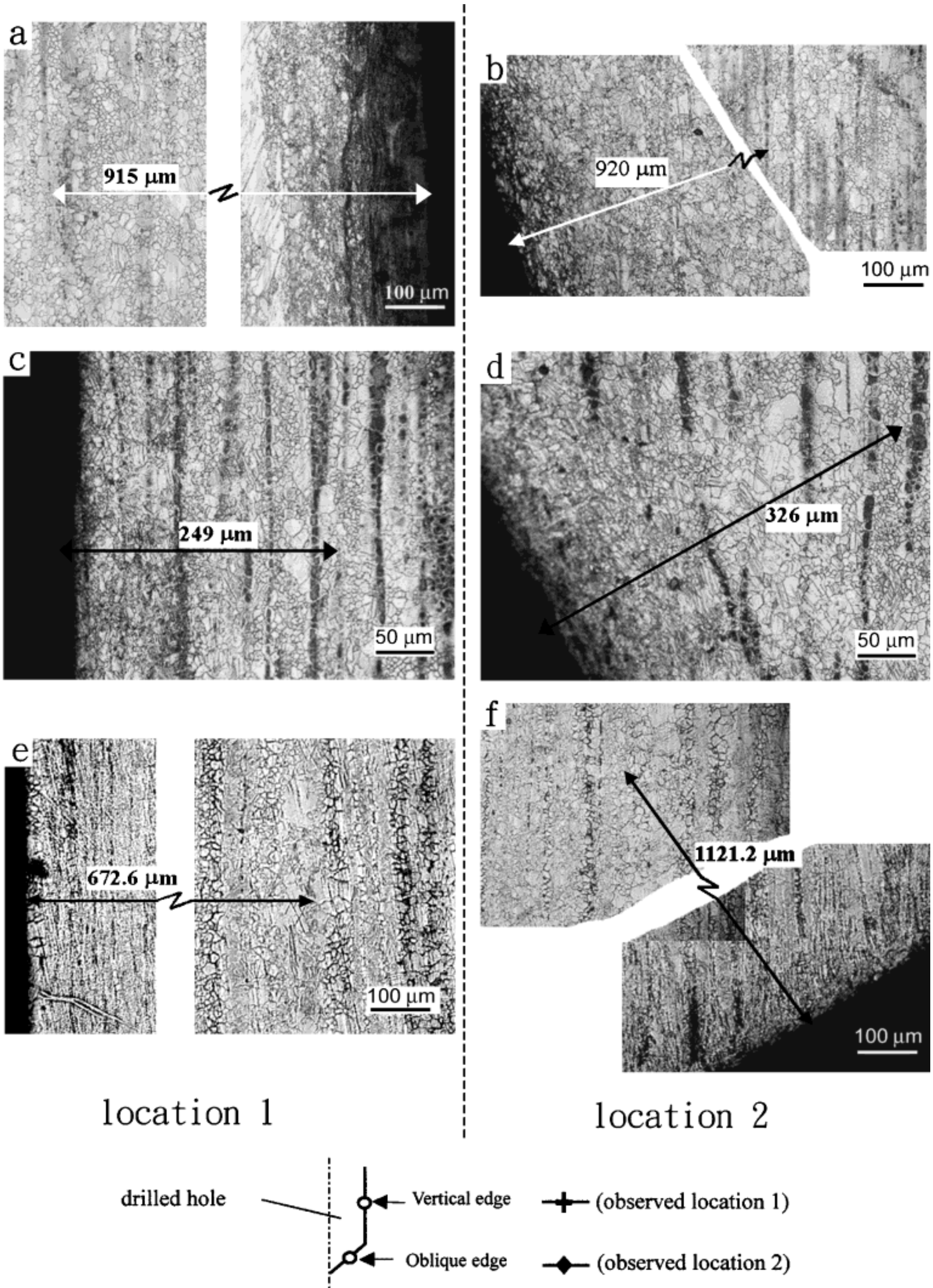


Fig. 9 Microstructure of the section of a drilled hole indicating distance away from the wall of which twin existed under a given MMR (35.4 cm^3/min); (a) and (b) 35° point angle, (c) and (d) 55° point angle, (e) and (f) 80° point angle; location 1- (a), (c) and (e): vertical edge, location 2- (b), (d) and (f): oblique edge of the drilled hole.

(890 rev·min^{-1}, 0.3 mm/rev) to 16 cm^3/min (405 rev·min^{-1}, 0.3 mm/rev), comparing Figs. 9(a)–(f) with Figs. 10(a)–(f). Figures 11(a) and (b) indicate the measured extents of twinning layer for point angles of drill bit varying from 35° to 118°.

These measured data come to an important conclusion that the matrix of drilled hole resides a minimum extent of twinning, when 55° point angle was adopted. Some band structures are still visible on the matrix underneath the drilled hole due to less amount of heat was produced during drilling. This result agrees to the previous discussion that using a 55° point angle generates the lowest cutting resistant force and a minimum amount of heat accumulated at the matrix than other point angle used.

As discussed previously, decreasing a point angle increases the length of cutting edge and raises the amount of heat accumulated at the tool-chip interface. This heat provides a driving force for recrystallization in the deformation (shear) zone in the as-extruded AZ61A and leads to grain growth underneath the drilled wall, showing columnar-type coarse grains,

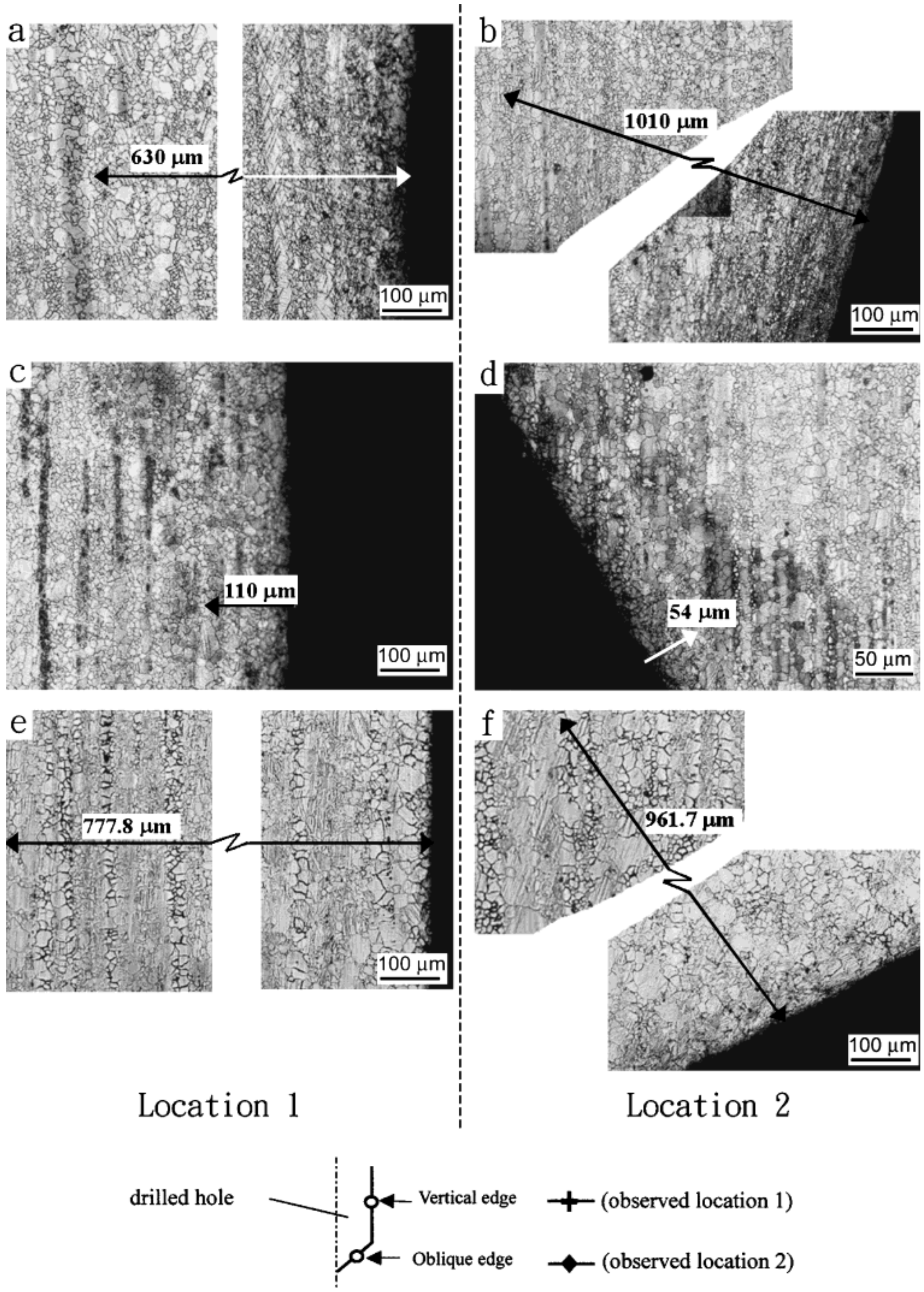


Fig. 10 Microstructure of the section of a drilled hole indicating distance away from the wall of which twin existed under a given MMR (16 cm^3/min); (a) and (b) 35° point angle, (c) and (d) 55° point angle, (e) and (f) 80° point angle; location 1- (a), (c) and (e): vertical edge, location 2- (b), (d) and (f): oblique edge of the drilled hole.

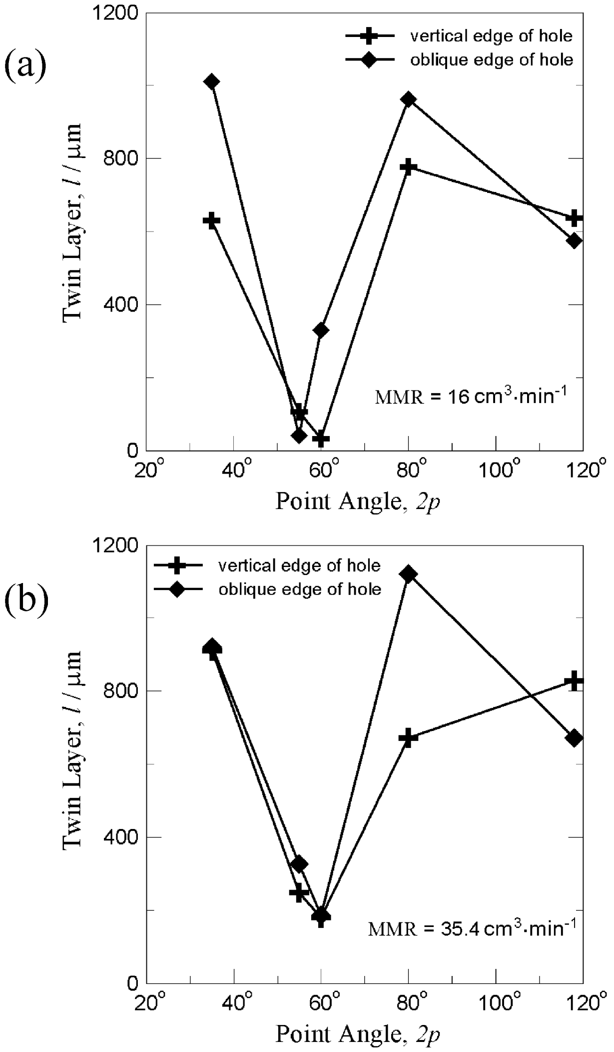
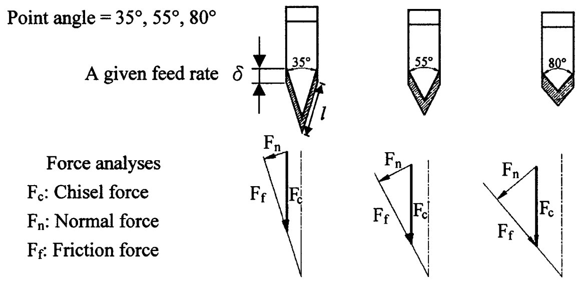


Fig. 11 Existed extent of twinning versus point angles of drill bits under specific MMR, (a) 16 cm^3/min and (b) 35.4 cm^3/min.



Cutting length l	Long	Medium	Short
Peak temperature near cutting edge	Very high	Low	Low
Normal force due to acting force, Fn	Lowest	Middle	Highest
Cutting energy	High	Medium	Medium/low
Cutting condition	BUE	Smooth	Smooth
Existed extent of twinning layer	Great	Medium	Great

Fig. 12 The Schematic illustration of the force analyses in drilling associated with explanations.

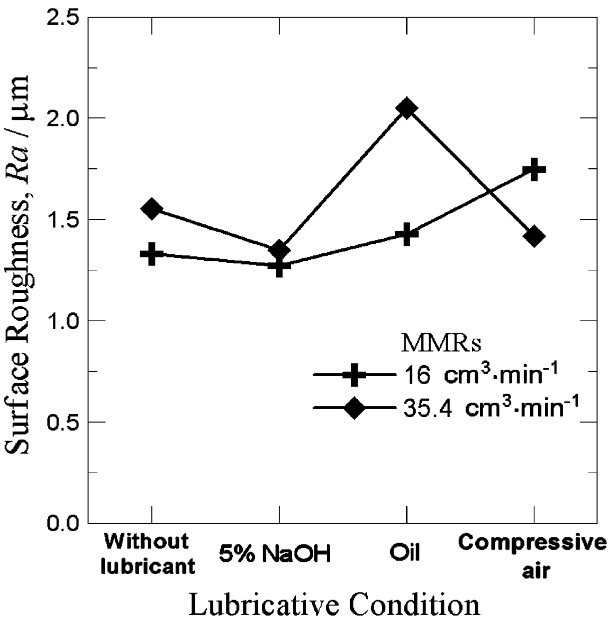


Fig. 13 Measured surface roughness of drilled holes with or without using lubricants under two MMRs (drill bit with 55° point angle).

Fig. 9(a) and Fig. 10(a). Severe deformations slips exist at the vicinity of free surface indicating that burnishing likely occurred during drilling. The acting force normal to the cutting edge is increased with the increasing point angle lifting up cutting pressure on the cutting edge and produces the slips. Besides, the heat conducting from drill bit into the matrix of machined workpiece drives grain growth of matrix as well. It is readily to see a columnar type of coarse grain in Fig. 9(e) and Fig. 10(e), where a point angle 80° was used. Few deformation slips show on the vicinity of drilled surface indicating that drilling operation is smooth without forming BUE.

Summary speaking, drill bit with a 55°–60° point angle produces the minimum extent of twinning and optimum surface roughness associated with low overall resistant force during drilling. The correlation of point angle, force analyses and the resultant effects is summarily described in Fig. 12, when the AZ61A is drilled without using lubricant. Using a 55°–60° point angle can not only maintain a good surface roughness but also reduce the extent of twinning (Figs. 11(a) and (b)), which is beneficial for improving the fatigue life of AZ61A.

3.4 Effect of lubricants on surface roughness, cutting resistant force and twinning

Effects of different lubricants on the quality of drilled holes were evaluated in this study. After drilling, the surface roughness of the drilled hole was measured and workpiece was then cut and prepared for observing the microstructure by optical microscope. The extent of twinning was measured and compared to assess the effect of lubricants.

3.4.1 Surface roughness

Figure 13 shows the measured surface roughness of drilled holes after drilling with different lubricants (5%NaOH solution, oil, compressed air) for a given point angle 55° and at two MMRs (16 cm^3/min and 35.4 cm^3/min). These measured data indicate that only using lubricant, 5%NaOH solution can minify the roughness of drilled holes. Using oil and com-

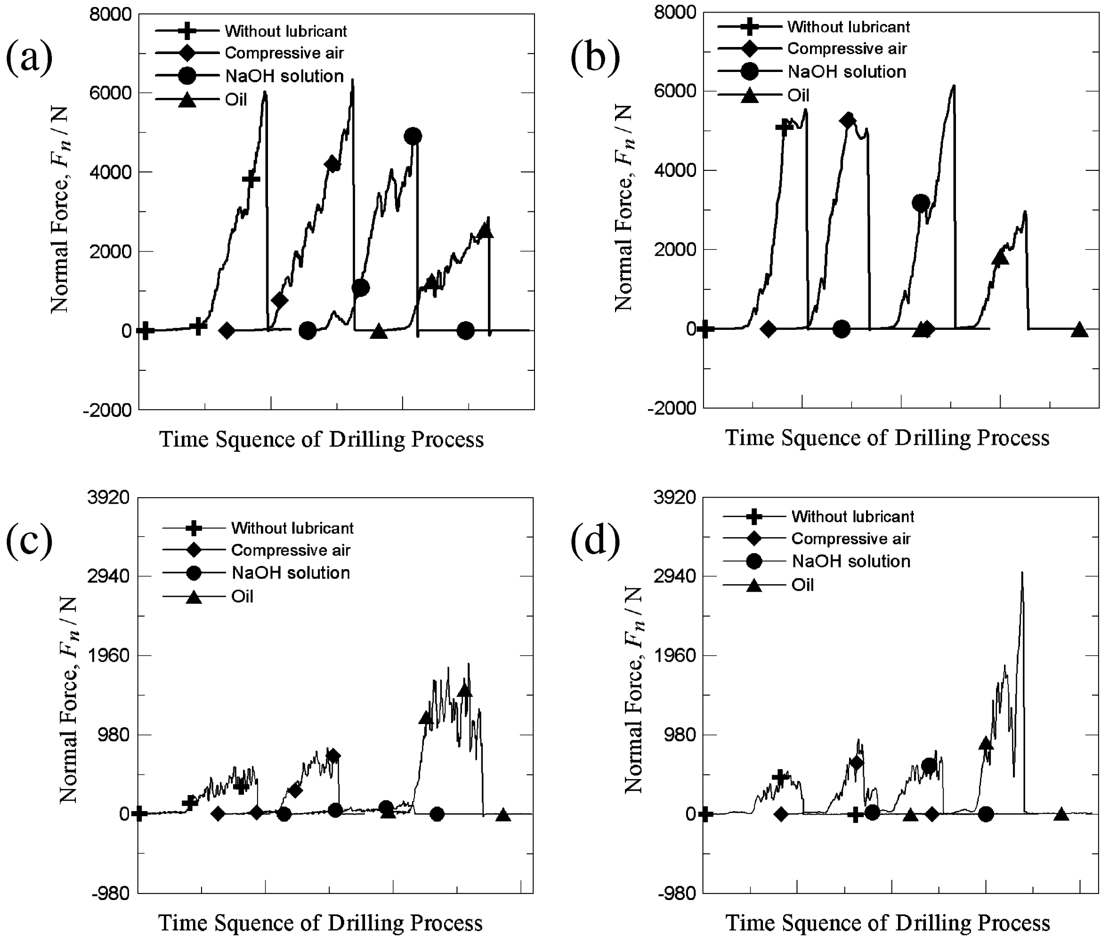


Fig. 14 Effect of lubricants on cutting resistant forces measured from drilling process, (a) 35° point angle, MMR 16 cm^3/min, (b) 35° point angle, MMR 35.4 cm^3/min, (c) 55° point angle, MMR 16 cm^3/min and (d) 55° point angle, MMR 35.4 cm^3/min.

pressive air are not effective to remove chips and to conduct heat away from the chip-tool interface. Temperature raised at the interface increases the friction resistance from removing chips. This drags the movement of chip and decreases the cutting efficiency deteriorating the quality of drilled surface.

3.4.2 Cutting resistant force and twinning

Figures 14(a)–(d) demonstrate the measured cutting resistant force in the z-axis during drilling with and without using lubricants. Two point angles (35° and 55°) coupling with two MMRs (16 cm^3/min and 35.4 cm^3/min) were adopted to compare the effects of above variables on the measured nominal force in the z-axis. Use of lubricant can greatly reduce the coefficient of friction between chips and tool and eliminates the amount of heat accumulated at the chip-tool interface. Chance for forming BUE and the resistant force measured in the z-axis are both reduced, Figs. 14(a) and (b).

Using a point angle 55° generates a lower resistant force than using a point angle 35°. The friction force developed at the chip-tool interface has substantially decreased due to the decreasing normal force. For a given spindle speed 405 rev·min^{-1} (MMR = 16 cm^3/min, feed = 0.3 mm/rev), using an aqueous solution exerts a very low resistant force in the z-axis, Fig. 14(c). The resistant force is increased with increasing rotation speed (405 to 890 rev·min^{-1}), when aqueous solution was used, due to effect of viscosity and specific heat of solutions. For a low rotating speed (or MMR), the aqueous solution tends to readily penetrate into interface of chips and tool and reduces significantly the friction force when chips were removing from cutting edge. The volume of chips removed from the cutting edge is increased with increasing rotational speed for a given time. The aqueous solution at the interface between chips and tool may partly decompose or vaporize due to a high local temperature generated at the cutting edge. The capability for heat releasing from the cutting edge is greatly reduced and therewith the friction force is increased when chips are removing from the tool surface, Fig. 14(d). Using a point angle 55° and a spindle speed 405 rev·min^{-1}, MMR 16 cm^3/min, coupling with 5%NaOH solution as the metalworking fluid can produce a minimum resistant force in the z-axis and a superior surface roughness of the drilled hole.

Figures 15(a) and (b) show the measured extents of twinning layer for drilling with or without using lubricants at two MMRs. In both conditions, using the aqueous solution exerts a minimum extent of twinning layer. Using forced air can also improve the capability for removing debris from the helix slots of drill bit in which drilling produces a very low compressive stress acting on the wall of drilled hole. This reduces a chance for forming twinning underneath the drilled surface so that compressive air can be used effectively under a high material removal rate, 35.4 cm^3/min.

Heat generated at the cutting edge is increased inevitably with increasing the material removal rate. Using oil can't be

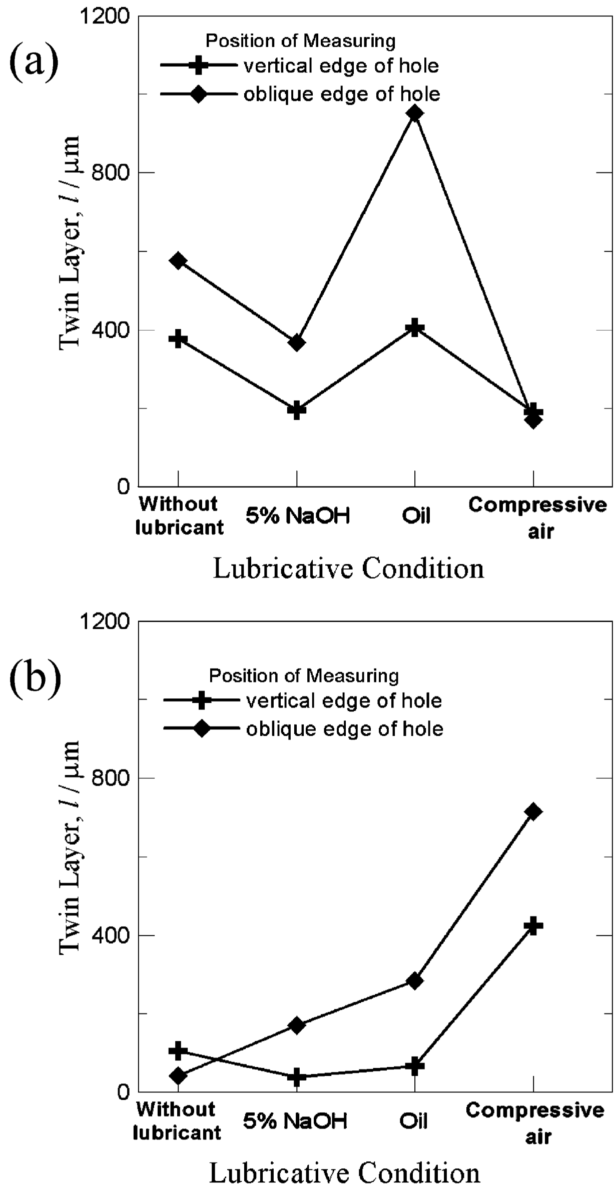


Fig. 15 Existed extent of twinning layer observed at two locations of drill holes; drilling parameters of (a) 55° point angle, 16 cm^3/min and (b) 55° point angle, 35.4 cm^3/min; with or without using lubricants.

effective to remove debris away from the helix slots and from the gap between drill and wall of hole due to the drag of viscosity. Heat tends to accumulate at the chip-tool interface. Therefore, the resistant force is increased (Fig. 14(d)) and the quality of surface is deteriorated, especially at a high MMR and a great rotational speed 890 rev·min^{-1}.

4. Conclusion

(1) The drilled surface produced twinning structure during drilling. The existence of twinning layer on the vicinity of machined AZ61A is mainly induced by the compressive shear stress from the thrust force and from the chisel action of cutting.

(2) Using a point angle 55° not only maintains the surface roughness of drilled hole as recommended by handbooks but also generates an ideal microstructure (the smallest extent of deformation twinning layer).

(3) Using a 5%NaOH solution as lubricant, improved further the surface quality of drilled holes and also reduced the extent of deformation twin layer underneath the drilled wall.

(4) Using both the aqueous solution (5%NaOH) and a point angle 55° produced a superior surface roughness and a minimum extent of twinning layer in drilling of AZ61A.

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