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Direct Observation of Fluid Action at the Chip-Tool Interface in Machining

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The present study seeks to realize an improved understanding of the action of cutting fluid through direct observation of the chip-tool interface. That is, using transparent tools made of sapphire in conjunction with a high-speed, CCD-based imaging system, the chip-tool contact condition and its evolution in the presence of cutting fluid are directly observed during 2-D orthogonal machining of pure lead and Al6061-T6. Then, spatial and temporal analysis of the images of the chip-tool interface is made for measuring the contact length and velocity profile along the tool rake face, and the contact conditions are correlated with the cutting forces measured. The results are compared with those made when cutting dry to clarify the effects of cutting fluid action, and a picture of the action of cutting fluid at the chip-tool interface is presented finally.

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1. Introduction

Cutting fluid plays an important role in metal cutting. That is, cutting fluid can reduce cutting force and power, decrease temperature of the tool and the workpiece, and improve surface finish and accuracy of the finished part when it is used properly. However, cutting fluid has ill effects such as environmental contamination or rising cost for its disposal as well, which restricts indiscreet use of cutting fluid. Therefore, it is necessary to exactly understand the mechanism by which a cutting fluid works and assists in the cutting process.

For this reason, many efforts have been made to investigate the action of cutting fluid while cutting is performed. However, an exact understanding of its action at the chip-tool interface has been hindered by the complexities and unusual features encountered in the cutting process: the unique tribological condition at the chip-tool interface characterized by high pressure and temperature, the interaction between the chip formation in the primary deformation zone and the frictional condition at the interface, and the small time and length scales. This led to different views drawn regarding the action of cutting fluid at the chip-tool interface.

Among these, the most commonly referred view is that cutting fluid gains partial or complete access onto the chip-tool contact region and forms a soft film,[1-4] reducing friction or preventing seizure at the interface. Another view is that cutting fluid mainly reduces the chip-tool contact length, rather than simply decreases the frictional resistance between the chip and the tool.[5-8] Some researchers also have claimed that the presence of cutting fluid at the chip surface and/or within the chip lowers the flow stress of the work material, facilitating chip formation in the primary deformation zone - the so-called ‘Rehbinder effect’.[9-12] The first view tends to be more favored than the others when explaining the action of cutting fluid at the chip-tool interface. However, it should be noted that any conclusive evidence to support this view has been provided due to the complexities and unusual features encountered in the cutting process as mentioned earlier.

In this regard, the present study seeks to enhance our understanding of the action of cutting fluid by directly observing the chip-tool interface while cutting is performed in the presence of cutting fluid. This is enabled by employing transparent sapphire tools in conjunction with a high-speed, CCD-based imaging system, which allows for a sequence of the chip-tool contact images to be acquired at high spatial and temporal resolution. By analyzing these images, the evolution of contact condition at the chip-tool interface will be characterized and the contact length and velocity profile along the tool rake face will be measured. The results will be related to the cutting forces which are measured while the direct observation is made. Also, the results will be compared with those obtained when cutting is performed in air (dry). Finally, discussions will be made to draw a picture of the mechanism by which the friction at the chip-tool interface is reduced in the

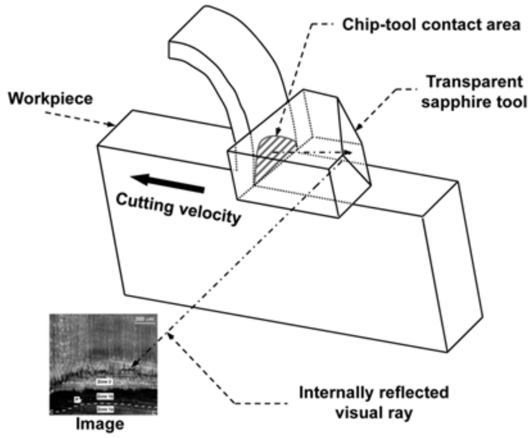


Fig. 1 Schematic of transparent sapphire tool and optical path used for direct observation of the chip-tool interface[17]

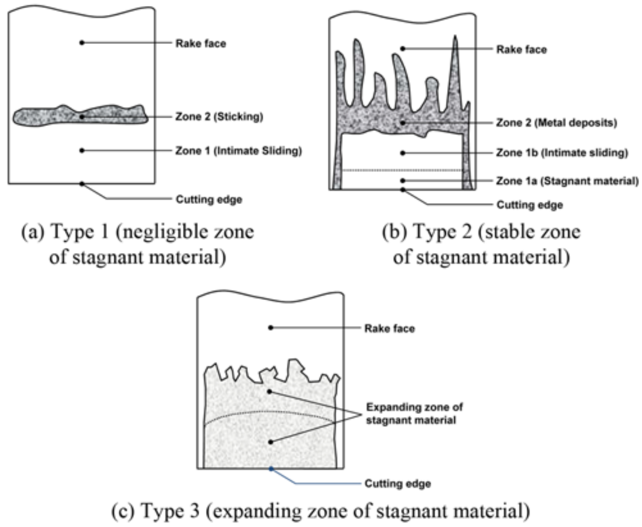


Fig. 2 Classification of chip-tool contact conditions based on the nature of stagnant material present ahead of the cutting edge[17]

presence of cutting fluid.

2. Direct Observation of the Chip-Tool Interface

Direct observations of the chip-tool interface were enabled by employing transparent cutting tools that were made of glass or sapphire, with all of their faces highly polished. Their shape is a parallelepiped with an additional, inclined facet, which allows the chip-tool interface to be directly observed through a side of the tool as illustrated in Fig. 1. In the figure, the visual ray leaving the chip-tool contact region is internally reflected by the facet and then reaches the viewer parallel to the cutting edge and perpendicular to the side of the tool. For example, a chip-tool contact image taken through the sapphire tool is given along the optical path of the tool within the figure. The view in this image is as if one were sitting inside the transparent tool and looking at the chip underside through the tool rake face, the bottom of this image representing the cutting edge.

Tabor and his co-workers[13-14] were those who actively used such transparent cutting tools to directly observe the chip-tool interface while cutting pure metals such as lead, aluminum, copper and indium in dry condition. Chandrasekar and his co-workers[15-17] improved this method by employing a high-speed, CCD based camera which allowed for recording of the chip-tool contact images and their quantitative analysis at high temporal and spatial resolutions. Most recently, Hwang and Chandrasekar[18] directly observed the chip-tool interface when cutting various workpiece materials in dry condition and classified the contact conditions at the interface into three types, based on the nature of stagnant material present ahead of the cutting edge as shown in Fig. 2: negligible zone of stagnant material (Type 1), zone of stagnant material that is stable and confined to the vicinity of the cutting edge (Type 2), and zone of stagnant material that expands upward from the cutting edge as cutting progresses (Type 3). It was found that the chip slides over the tool rake face in the region adjoining the zone of stagnant material and the chip material transfers to the tool rake face at the boundary of this region where the chip underside begins to lose its intimate contact with the tool rake face.

It was Horne et al.[18] who first applied the direct observational approach to investigate the action of cutting fluid at the chip-tool interface. While cutting lead and pure aluminum with application of cutting fluid using transparent tools, some interesting features were observed at the chip-tool interface. When lead was machined under flood lubrication condition using a light mineral oil, it was directly observed that the oil seeped in from the sides of the chip to the diverging gap which was developed at the perimeter of the intimate contact in the initial stage of the cut. The two oil films joined up approximately in the middle of the chip, the oil then apparently providing lubrication for the rest of the cut. The metal transfer of the chip material at the edge of the intimate contact zone which occurs when cutting in air, was eliminated when cutting lead with the mineral oil or distilled water and when cutting pure aluminum with the mineral oil or CCl_4.

The work by Horne et al.[18] showed high potential of the direct observational method for studying the action of cutting fluid at the chip-tool interface in machining. However, the images were not clear enough to allow for clarification of penetration of the cutting fluid into the chip-tool contact region, analysis of contact evolution in the presence of cutting fluid, systematic comparison of contact conditions when cutting in air and with application of cutting fluid, and investigation into the dependence of the effectiveness of cutting fluid on cutting speed. In this regard, the present study seeks to give an improved understanding of the action of cutting fluid at the chip-tool interface with an emphasis on these aspects. This is enabled by using the direct observational method in conjunction with a high-speed, CCD based digital imaging system that allows images of the chip-tool interface to be recorded at high resolution for analysis as in Hwang and Chandrasekar's work.[17]

3. Experimental Details

3.1 High-speed digital imaging system

A CCD-based, high-speed camera (Kodak Motion Corder Analyzer Sr-Ultra) in combination with an optical microscope (Nikon Optiphot) was used for the direct observation of the chip-tool interface. The high-speed camera equipped with a black and white CCD chip allows the chip-tool contact images to be digitally recorded at the framing rates upto 10,000 frame per second (fps). The optical microscope allows the images to be zoomed up by 200 X. The optical microscope was mounted onto a precision microstage that was supported by a tripod. Such an arrangement facilitated the focusing of the optical microscope onto the small chip-tool contact area. The chip-tool contact images taken on the 'record' mode of the high-speed camera were temporarily saved in its internal memory and then downloaded to a PC, allowing for later analysis of the images at high temporal and spatial resolution.

3.2 Orthogonal machining configuration

To realize a true 2-D orthogonal machining configuration, the cutting tool was held stationary and the workpiece was moved perpendicular to the cutting edge by a ball-screw driven linear slider (Parker ERB80-B02LAJX-GXS677-A96). The maximum speed attainable by this slider was 750 mm/sec. The cutting tool was glued to a tool holder which was fixed onto a micro-positioning stage (Newport Model 433). The micro-positioning stage was coupled with a digital micrometer (Newport Model DMH-1) that had a resolution of 1 μm over a range of 15 mm. The depth of cut could be accurately set based on the readings from this digital micrometer. The assembly of the micro-positioning stage and the digital micrometer was again mounted onto a tool dynamometer (Kistler CompacDyn) for the force measurements during cutting. The orthogonal machining arrangement is illustrated in Fig. 3.

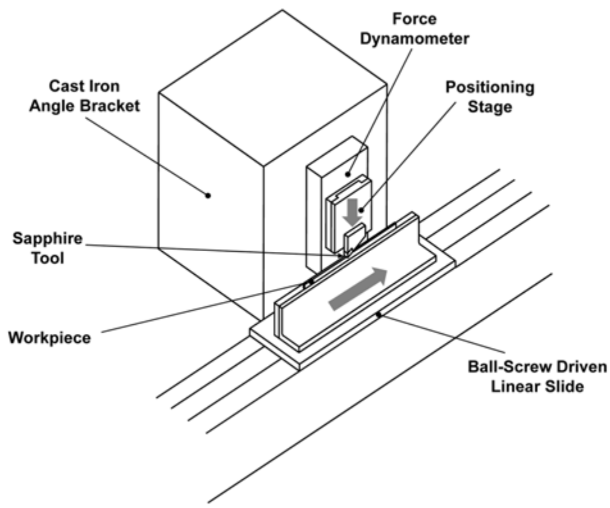


Fig. 3 Orthogonal machining arrangement[17]

3.3 Cutting conditions

For work materials, pure lead and Al 6061-T6 were chosen because of their differing chip-tool contact conditions that can be represented by Type 2 and Type 3 in Fig. 2, respectively. The workpiece was in the form of plate (thickness of 1.65 mm for pure lead and 2 mm for Al 6061-T6). The use of thin plates for the workpiece ensured plane strain, or two dimensional (2-D) deformation for each of the cuts.

The transparent sapphire tool as shown in Fig. 1 was used for cutting. The rake and clearance angle of the tool was +10° and 5°, respectively. The cutting edge radius of the tools was less than 3 μm when measured by a surface profilometer (Taylor Hobson Form Talysurf-50). The rake face of the tools was carefully inspected prior to each of the cuts, making sure that it was absent from deep scratches that would, otherwise, blur the chip-tool contact images.

The depth of cut was fixed at 200 μm for pure lead and 100 μm for Al 6061-T6. Cutting was performed in the speed range of 0.5~500 mm/sec. Organic oil (Coolube 2210) was used as the cutting fluid. The cutting fluid was applied onto the tool surface in fluid prior to and during cutting, ensuring that the cutting fluid remained throughout a cut without being entirely washed away from the tool surface.

4. Results

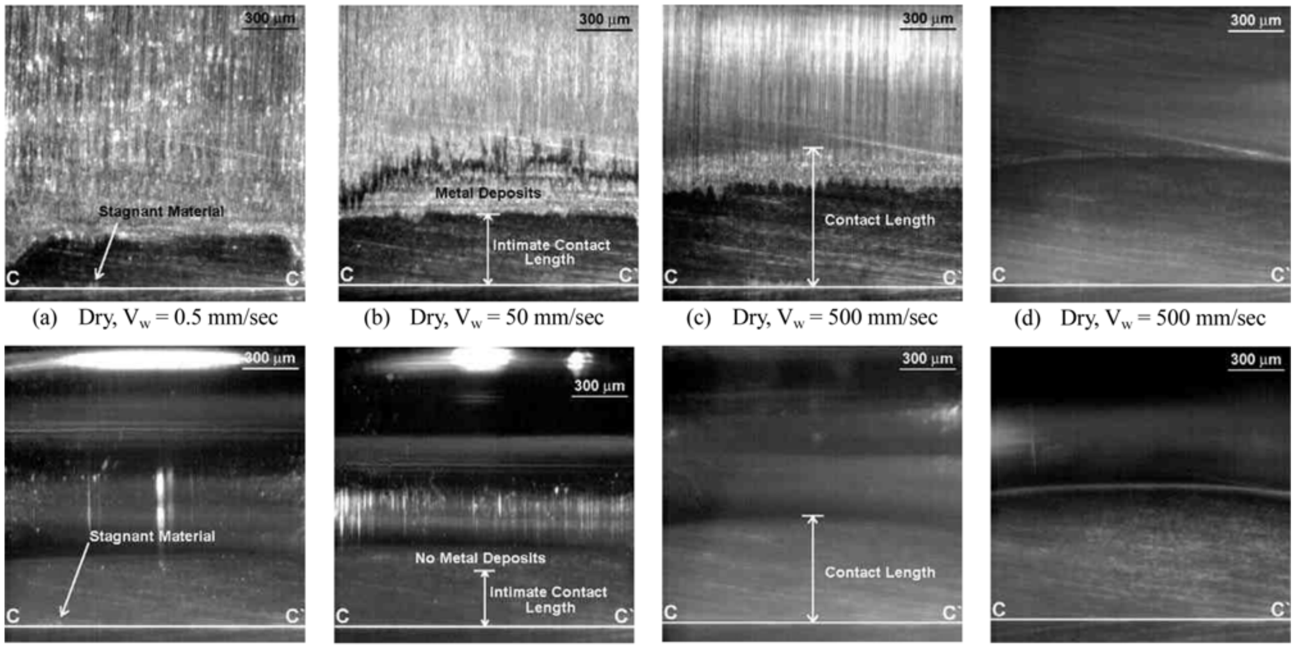
4.1 Pure lead

Fig. 4 shows photographic images of the chip-tool interface taken while cutting commercially pure lead in air (Fig. 4(a)~(d)) and with application of fluid (Fig. 4(e)~(h)), respectively. Cutting was performed at four different speeds: 0.5 mm/sec, 5 mm/sec, 50 mm/sec and 500 mm/sec. The view in these images is as if one were sitting inside the transparent tool and looking at the chip underside through the tool rake face. The bottom of these images marked by C-C' represents the cutting edge. A droplet of the cutting fluid appears distinctively bright in the area surrounding the chip-tool contact region in these images. It should be noted that, in the figures presented here, 'Wet' represents cutting with application of cutting fluid while 'Dry' represents cutting in air.

In Fig. 4, the most distinct feature of the chip-tool contact condition when cutting with application of fluid (Fig. 4(e)~(h)) is complete absence of the zone of metal deposits. The zone of metal deposits is found farther away from the cutting edge when cutting in air (Fig. 4(a)~(d)). In the region near the cutting edge, the zone of stagnant material is present when cutting both with application of fluid and in air. In Fig. 4, the presence of the zone of stagnant material is evidenced by the complete absence of asperity motions and a faint thin layer of metal found in this region as pointed by arrows in Fig. 4(a) and 4(e).

In the chip-tool contact region, retardation of the chip underside occurs when cutting with application of fluid in the same manner as when cutting in air. This is evidenced by the velocity profiles shown in Fig. 5. The velocity profiles were obtained by tracking asperities moving up the tool rake face in a sequence of the chip-tool contact images. In the velocity profiles, the chip underside undergoes retardation in the contact region; its velocity increases linearly with distance from the cutting edge till it reaches that of bulk of the chip material. The velocity of the chip underside in the presence of cutting fluid is greater than that of the chip underside in air over the entire contact region. In the region near the cutting edge, the velocity profiles are not shown because the asperity motions could not be resolved due to the stagnant material present in this region. A linear fit of the velocity profile in this region indicates that the velocity of the chip underside approaches zero at the cutting edge.

The chip-tool contact length is reduced in the presence of cutting fluid as compared to that when cutting in air. In Fig. 4(e)~(h), the chip-tool contact region in the presence of cutting fluid extends to a line which is believed to be the limit for possible penetration of the cutting



(a) Dry, V_w = 0.5 mm/sec (b) Dry, V_w = 50 mm/sec (c) Dry, V_w = 500 mm/sec (d) Dry, V_w = 500 mm/sec

(e) Wet, V_w = 0.5 mm/sec (f) Wet, V_w = 50 mm/sec (g) Wet, V_w = 500 mm/sec (h) Wet, V_w = 500 mm/sec

Fig. 4 Photographic images of the chip-tool interface when cutting pure lead (a)~(d) in air (dry) and (e)~(h) with application of cutting fluid (wet)

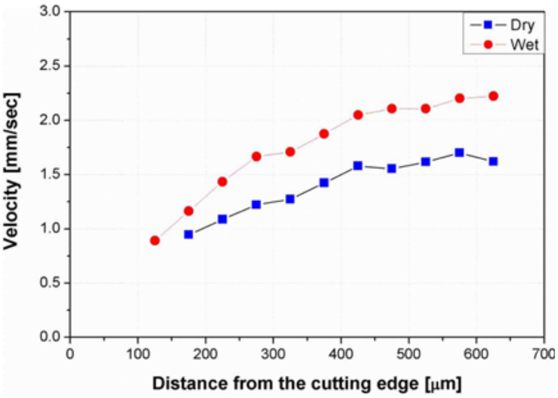
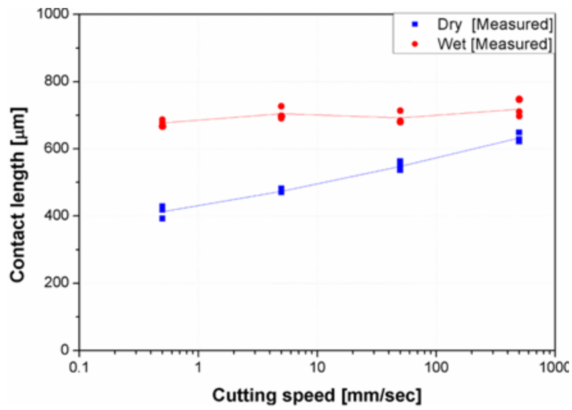


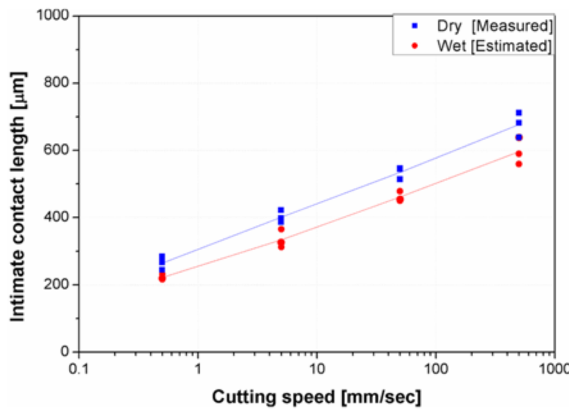
Fig. 5 Velocity profile of the chip underside along the tool rake face when cutting pure lead

fluid in the form of droplet. Below this line, the cutting fluid may penetrate into the chip-tool contact in the form of molecules through a network of micro-capillaries. In contrast to this, the chip-tool contact region when cutting in air extends to the upper edge of the zone of metal deposits seen in Fig. 4(a)~(d). Fig. 6(a) shows variation of the chip-tool contact length measured with cutting speed in this manner from Fig. 4. This figure confirms that the chip-tool contact length is reduced in the presence of cutting fluid. Also, it is found that the chip-tool contact length increases with cutting speed when cutting with application of fluid, while it is relatively constant when cutting in air in Fig. 6(a). The reduction of chip-tool contact length becomes almost negligible at the cutting speed of 500 mm/sec.

The upper edge of the intimate contact region corresponds to the lowest limit for the possible penetration of contaminants such as air or cutting fluid. In Fig. 4(a)~(d), the zone of metal deposits is found farther away from the cutting edge. This zone is believed to be a product of



(a) Contact length



(b) Intimate contact length

Fig. 6 Contact length (a) and intimate contact length (b) when cutting pure lead (3 replications and their average shown)

the reaction between the freshly generated chip and air.[2,13,14] Therefore, by measuring the distance from the cutting edge to the beginning of this zone of metal deposits in Fig. 4(a)-(d), the intimate contact length when cutting in air could be obtained. The results showed that the intimate contact length increases with the increase of cutting speed when cutting in air (Fig. 6(b)).

It was also found that the normal force measured simultaneously during the direct observation of the chip-tool contact increases with cutting speed when cutting in air as shown in Fig. 7(a). The measured normal force should be close to the normal force acting in the intimate contact region because the normal stress in the intimate contact region is substantially higher than in the rest of contact region.[19-22] Therefore, Fig. 6(b) and Fig. 7(a) jointly indicate that the intimate contact length increases with the increase of the normal force acting in the intimate contact region. This relation is in agreement with classical friction theory[23] which states that the real contact area should be increased with the increase of normal force.

The intimate contact length in the presence of cutting fluid was estimated using the relation between the intimate contact length and the normal force measured when cutting in air because the intimate contact region in the presence of cutting fluid is not discernible in Fig. 4(e)~(h). The estimation is based on the assumption that the normal force is the main determinant of the intimate contact length. The estimated intimate contact length is shown in Fig. 6(b). In the figure, when cutting with application of fluid, the reduction of intimate contact length is relatively small as compared to that of the total contact length. Also, when cutting with application of fluid, the intimate contact length increases with cutting speed in the same manner as when cutting in air.

On the other hand, the cutting forces in the presence of cutting fluid are smaller as compared to those when cutting in air as shown in Fig. 7(a). This is more significant for the frictional force than the normal force. The friction coefficient in the presence of cutting fluid is smaller than that in air as shown in Fig. 7(b). In Fig. 7(b), the friction coefficient in the presence of cutting fluid appears to increase asymptotically with cutting speed while it doesn't vary significantly when cutting in air. The smaller friction coefficient at the lower cutting speed in the presence of cutting fluid indicates that the cutting fluid is more effective at the lower cutting speed.

4.2 Al 6061-T6

Fig. 8 shows photographic images of the chip-tool interface when cutting Al 6061-T6 at four different speeds - 0.5 mm/sec, 5 mm/sec, 50 mm/sec and 500 mm/sec, in the presence of cutting fluid. When the cutting speed is low (0.5 mm/sec and 5 mm/sec), the contact condition in the presence of cutting fluid is characterized by the stability of the zone of stagnant material which is confined to the region near the cutting edge. That is, in the presence of cutting fluid, the zone of stagnant material which has initiated at the cutting edge, stops expanding when it reaches the upper edge of intimate contact as seen in Fig. 8(a) and (b). Then, with continued cutting, the upper part of the zone of stagnant material is eliminated until it takes the final shape as seen in Fig. 8(e) and (f). Once it is stabilized, the zone of stagnant material doesn't change much in its shape and size during the rest of a cut. The area of the zone of stagnant material at this stage is smaller at the speed of 0.5 mm/sec than at 5 mm/sec. This is to be contrasted with the expanding zone of stagnant material found when cutting Al 6061-T6 in air at the entire range of cutting speed or in the presence of cutting fluid at the

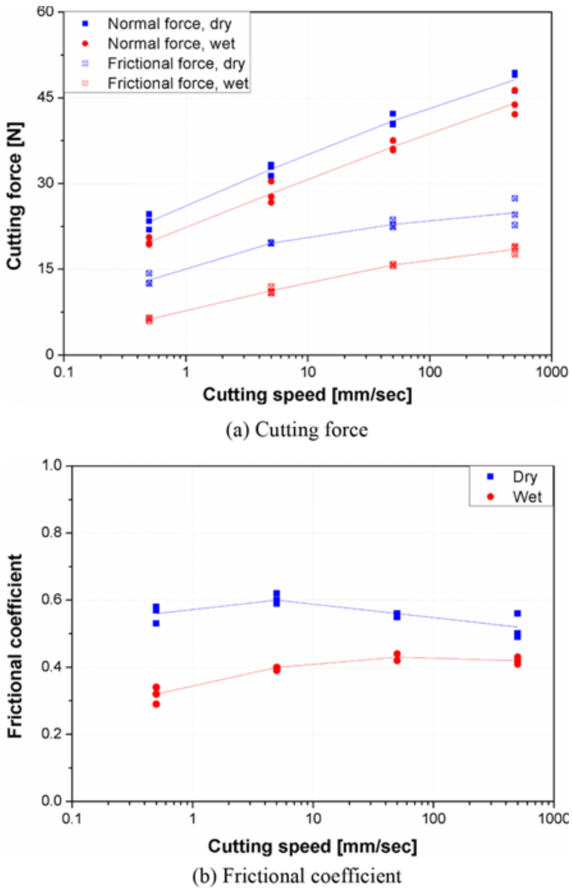
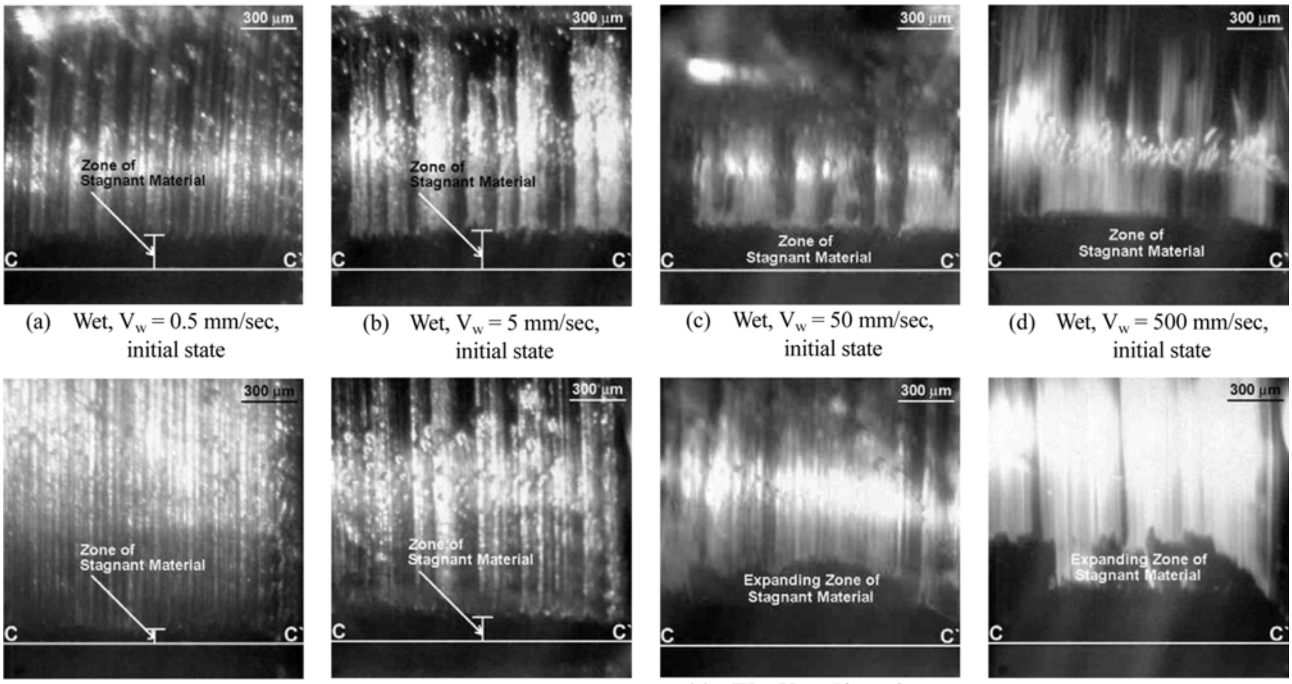


Fig. 7 Cutting force (a) and frictional coefficient (b) when cutting pure lead (3 replications and their average shown)

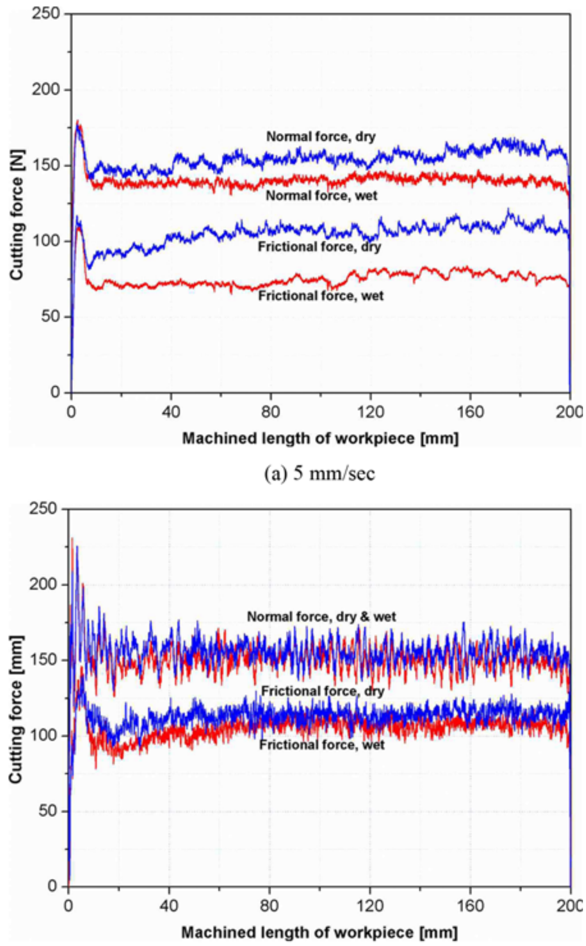
higher cutting speed (see Fig. 8(g) and (h)), which keeps growing over the chip-tool contact as cutting progresses. At the higher cutting speed (50 mm/sec and 500 mm/sec), the contact condition in the presence of cutting fluid is not significantly different from that when cutting in air. That is, the zone of stagnant material is not confined to the region near the cutting edge but keeps expanding even after it has reached the upper edge of intimate contact. Fig. 8(c) and (d) show that the zone of stagnant material has reached the edge of intimate contact, and Fig. 8(g) and (h) show that the zones of stagnant material are expanding beyond the intimate contact region with continued cutting likewise when cutting in air.

Fig. 9 shows cutting force profiles measured simultaneously during the direct observation of the chip-tool interface. In the force profiles, spikes are observed in the initial stage of cutting both with application of fluid and in air. This phenomenon can be related to the change of intimate contact length. In the initial stage of cutting, the intimate contact length increases as cutting progresses. With the increase of intimate contact length, cutting forces also increase until the intimate contact is fully developed and the zone of stagnant material expands to the upper edge of intimate contact. Then, an abrupt reduction of the intimate contact length occurs, followed by the reduction of the zone of stagnant material. Up to this point, the force profiles in the presence of cutting fluid and in air are almost identical, indicating that the cutting fluid does not have any significant influence on the chip-tool contact condition in the initial stage of cutting. However, once the reduction of



(a) Wet, V_w = 0.5 mm/sec, initial state
(b) Wet, V_w = 5 mm/sec, initial state
(c) Wet, V_w = 50 mm/sec, initial state
(d) Wet, V_w = 500 mm/sec, initial state
(e) Wet, V_w = 0.5 mm/sec, steady state
(f) Wet, V_w = 5 mm/sec, steady state
(g) Wet, V_w = 50 mm/sec, later state
(h) Wet, V_w = 500 mm/sec, later state

Fig. 8 Photographic images of the chip-tool interface when cutting Al 6061-T6



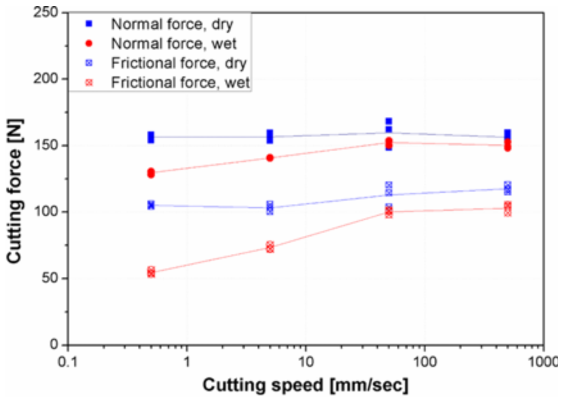
(a) 5 mm/sec

(b) 500 mm/sec

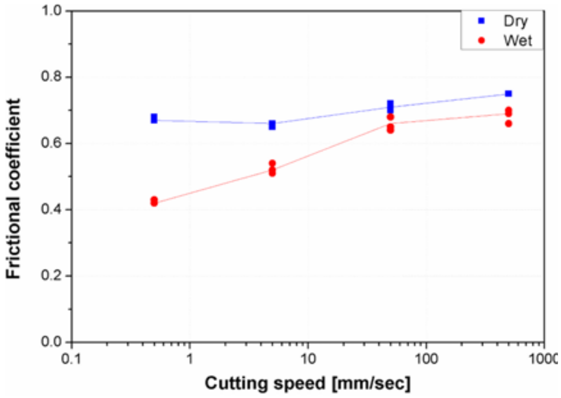
Fig. 9 Cutting force profiles during cutting of Al 6061-T6

intimate contact length has occurred, the force profiles in the presence of cutting fluid and in air begin to deviate from each other - the cutting forces in the presence of cutting fluid drop more than those in air. Considering that the higher the normal force is, the greater is the intimate contact length, this indicates that the reduction of the intimate contact length is more substantial in the presence of cutting fluid than in air. This also indicates that the cutting fluid has started to play a role in the contact region. The deviation between the cutting force profiles in the presence of cutting fluid and in air is more apparent at the low cutting speed (5 mm/sec) than that at the high cutting speed (500 mm/sec). This is in accordance with the direct observation that at the high cutting speed, the chip-tool contact condition in the presence of cutting fluid is not significantly different from that in air.

Fig. 10 shows variation of the cutting forces and friction coefficient with cutting speed when cutting Al 6061-T6. In Fig. 10(a), the cutting forces were measured after the initial spikes as shown in Fig. 9 have occurred and the cutting forces have leveled off. In Fig. 10(a), the cutting forces for Al 6061-T6 in air are independent of cutting speed. This is related to the direct observation that the chip-tool contact condition changes little with cutting speed when cutting Al 6061-T6 in air. However, with application of cutting fluid, the cutting forces are substantially affected. That is, in Fig. 10(a), the cutting forces drop with application of cutting fluid at the low cutting speed (0.5 mm/sec and 5 mm/sec) as compared to those when cutting in air. At these cutting speeds, the influence of cutting fluid on the frictional force is more substantial than on the normal force. At the higher cutting speeds of 50 mm/sec and 500 mm/sec, the cutting forces in the presence of cutting fluid are not substantially different from those when cutting in air. Also, at these speeds, the cutting forces are almost constant and independent of cutting speed. This can be related to the direct observation that, at



(a) Cutting forces



(b) Frictional coefficient

Fig. 10 Cutting forces and frictional coefficient when cutting Al 6061-T6 (3 replications and their average shown)

these cutting speeds, the chip-tool contact conditions in the presence of cutting fluid and in air are almost identical, and change little with cutting speed. In Fig. 10(b), the friction coefficient in the presence of cutting fluid increases with cutting speed up to 50 mm/sec, while the friction coefficient in air doesn't change much with cutting speed. Above 50 mm/sec, the friction coefficient in the presence of cutting fluid is almost constant and independent of cutting speed; it is close to that in air as expected from Fig. 10(a).

5. Discussion

Regarding the action of cutting fluid at the chip-tool interface, the followings were noted in the present study. First, with application of cutting fluid, the zone of metal deposits found farther away from the cutting edge when cutting pure lead in air is completely eliminated. This is because the cutting fluid penetrates into the intermittent contact region and wets the freshly generated chip underside before it is exposed to air.

Second, with application of cutting fluid, the expansion of the zone of stagnant material is prevented as illustrated in Fig. 11. In the initial stage of cutting of Al 6061-T6 in Fig. 8, the intimate contact region increases as cutting progresses. At the same time, the zone of stagnant material which has initiated at the cutting edge expands in the intimate contact region. When the zone of stagnant material has reached the

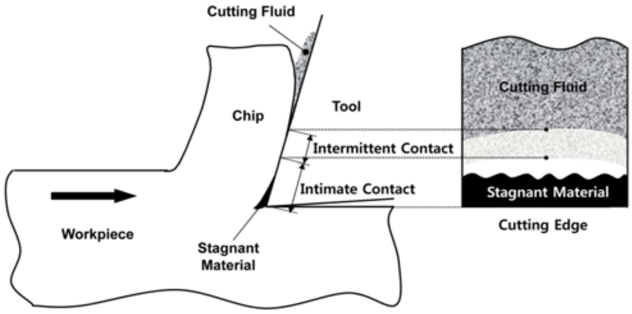


Fig. 11 Contact condition at the chip-tool interface in the presence of cutting fluid

upper edge of the fully developed intimate contact region, the frictional condition changes possibly due to the exposure of the chip-tool contact to the contaminants (air or cutting fluid). This probably causes the abrupt reduction of the intimate contact length and the force drop as seen in Fig. 9. When Al 6061-T6 is cut in air, this condition still facilitates the expansion of the zone of stagnant material. However, when Al 6061-T6 is cut with application of cutting fluid, the cutting fluid which has been applied onto the tool rake face prior to cutting and then squeezed out of the intimate contact region as cutting proceeds, acts against further expansion of the zone of stagnant material. When cutting is performed at the low speed, the upper part of the zone of stagnant material is eliminated with the reduction of the intimate contact length. The cutting fluid then penetrates into the region which was initially part of the intimate contact region. The elimination of the zone of stagnant material in this region indicates that the bonding between the zone of stagnant material and the tool rake face becomes weak as the normal pressure is decreased in this region with the reduction of the intimate contact region. At the high cutting speed, however, the supply of cutting fluid into this region is not sufficient enough to meet the demand of the chip flowing with the cutting fluid. As a result, the zone of stagnant material begins to expand immediately as the cutting fluid at the edge of intimate contact region is washed away with the chip.

Third, with application of cutting fluid, the chip-tool contact region is reduced. In Fig. 4(a)~(d), the upper edge of the zone of metal deposits corresponds to that of the chip-tool contact region. Beyond this point, the chip loses contact with the tool rake face completely. When cutting with application of fluid, the upper edge of the contact region corresponds to the limit for possible penetration of the cutting fluid in the form of droplet and distinguished by a line as seen in Fig. 4(e)~(h). The chip-tool contact length measured in this manner has shown that the contact region is significantly reduced in the presence of cutting fluid as compared to that in air (Fig. 6). When cutting Al 6061-T6, the contact length can be estimated by measuring the farthest distance from the cutting edge to the upper edge of the zone of stagnant material ever found throughout a cut along the width of chip. This is approximately equal to the limit for possible penetration of the cutting fluid in the form of droplet. When cutting Al 6061-T6 in air, the zone of stagnant material expands as cutting proceeds. However, the expansion of the zone of stagnant material is prevented in the presence of cutting fluid. Therefore, it is apparent that the chip-tool contact region is reduced

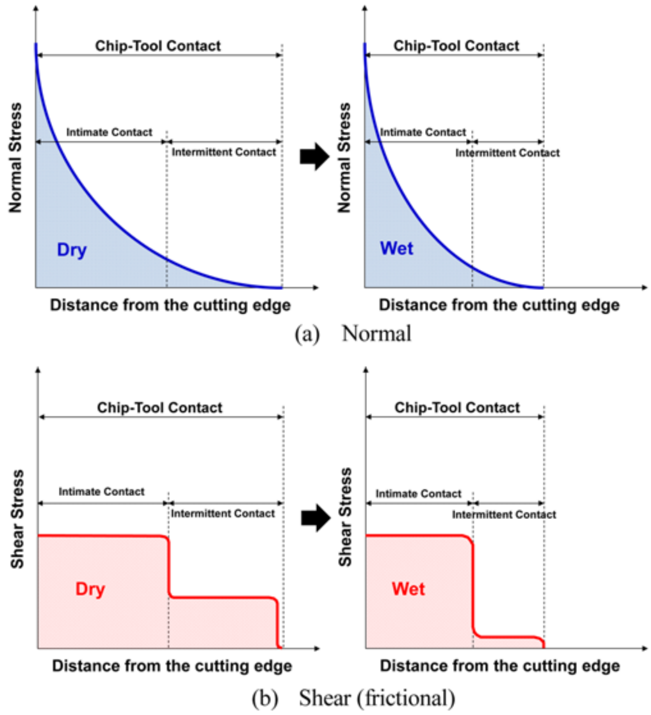


Fig. 12 Comparison of stress distribution along the tool rake face when cutting is performed in dry and wet conditions

when cutting Al 6061-T6 as well.

The changes of the contact condition caused by the application of cutting fluid as described above result in a reduction of friction between the chip and the tool. First, the reduction of the chip-tool contact region which consists of the intimate and intermittent contact regions would lead to a decrease of the frictional force at the chip-tool interface. When cutting pure lead with application of fluid, the reduction of the intimate contact region is not substantial. This indicates that the reduction of the contact region as seen in Fig. 6 is mainly due to the reduction of the intermittent contact region. The reduction of intermittent contact region by itself leads to a decrease in the frictional force as seen in Fig. 12. When cutting Al 6061-T6 with application of cutting fluid, the zone of stagnant material is confined in the contact region initially developed. When cutting in air, however, it expands over the tool rake face, resulting in the increase of contact region. The smaller zone of contact region in the presence of cutting fluid would lead to a significant decrease of frictional force.

Second, the low friction in the intermittent contact region in the presence of cutting fluid would play a role in decreasing the frictional force. When cutting pure lead in air, the chip material is transferred onto the tool rake face in the intermittent contact region. However, in the presence of cutting fluid, the transfer of chip material does not occur. The friction under this condition (sliding) should be lower than that when the chip material is transferred onto the tool rake face (sticking) as highlighted in Fig. 12. When cutting Al 6061-T6 with application of cutting fluid, the expansion of the zone of stagnant material is prohibited in the intermittent contact region. However, when cutting Al 6061-T6 in air, the frictional condition in the intermittent contact region facilitates the expansion of the zone of stagnant material. Therefore, the friction in the intermittent contact region in the presence of cutting fluid (sliding) should be lower than that when cutting in air (sticking) likewise.

6. Summary

In the present study, the chip-tool contact condition and its evolution in the presence of cutting fluid were directly observed during 2-D orthogonal machining of pure lead and Al6061-T6. The findings made through the direct observation regarding the action of cutting fluid in machining can be summarized as followings.

In the initial stage of cutting when the chip-tool contact is in development, the normal pressure in the contact region is enormously high, with most of contact being intimate. Therefore, the cutting fluid which has been applied onto the tool rake face prior to a cut is squeezed out of the contact region and does not play a significant role until the chip-tool contact is fully developed. Therefore, the force profiles in this stage are almost identical and independent of application of the cutting fluid.

When the chip-tool contact is fully developed, the contact region consists of two sub-regions - intimate and intermittent contact regions. When cutting is performed with application of cutting fluid, either the intimate contact length or the intermittent contact length is reduced, leading to the reduction of total contact length. This, in turn, would cause the frictional force at the chip-tool interface to be decreased. Also, the chip flows faster over the tool rake face when cutting pure lead in the presence of cutting fluid than in air. Besides, the transfer of the chip material onto the tool rake face in the intermittent contact region which occurs when cutting pure lead in air is prohibited with application of cutting fluid. Also, the expansion of the zone of stagnant material in the intermittent contact region which is observed when cutting Al6061-T6 in air is prohibited when cutting is performed in low speed with application of cutting fluid. This change of frictional condition from sticking into sliding in the intermittent contact region, in itself, would decrease the frictional force as well as the reduction of the intermittent contact length.

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