Fundamental Research on Hobbing with Minimal Quantity Lubrication of Cutting Oil

Comparison of Cutting Performance with Dry Cutting

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***Abstract*-This paper compares the cutting performance of minimal quantity lubrication (MQL) system with dry cutting in terms of flank wear, crater wear and finished surface roughness when using various kinds of cutting tools. Experiments were conducted by simulating hobbing by fly tool cutting on a milling machine. The results obtained are summarized as follows. (1) When using an uncoated tool, TiN- and (Al, Ti) N-coated tools without coating on the rake face, and fully TiN- and (Al, Ti) N-coated tools, MQL decreases the flank wear, crater wear and finished surface roughness compared with the wear and the roughness by dry cutting, particularly at the high cutting speed of 159 m/min. The reason suggested is the lubricating properties improved even with an extremely small quantity of cutting oil, which reduces the occurrence of deposited metal on the cutting edge. (2) With both the fully TiN- and (Al, Ti) N-coated tools, the MQL system showed better cutting performance in terms of reduced tool wear and reduced finished surface roughness compared with that by dry cutting; in particular, the fully (Al, Ti) N-coated tool is suitable for an MQL system in hobbing.**

Keywords- Gear; Hobbing; MQL; Dry Cutting; Fly Tool; Flank Wear; Crater Wear; Finished Surface Roughness

I. INTRODUCTION

In hobbing, a large amount of cutting oil is flooded on a hob made of high-speed steel (HSS). This process is used extensively. Chlorine components had been used as extreme pressure (EP) additives for hobbing to improve the cutting performance by reducing tool wear and finished surface roughness [1]. Chlorine components, however, change into deleterious materials, for example, dioxins and hydrochloric acid, when waste cutting oil is burnt, which creates environmental problems. Hence, the use of cutting oil containing chlorine components has been eliminated. Although the use of water-soluble cutting fluid as a substitute for cutting oil for hobbing has been investigated [2], it is generally not yet used, because water-soluble cutting fluid is inferior to cutting oil in tool wear and finished surface roughness.

Recently, dry hobbing without the need for cutting oil has become possible due to the development of new coating films with improved thermal resistance and wear resistance. As expected, these advances are the best solution to environmental problems. However, further study is required to ascertain whether dry hobbing can be applied to all kinds of gear materials, hobbing methods and conditions. So far, dry hobbing has presented many unsolved problems: scratch marks on the surface of the gear teeth, dimensional accuracy, scattering and disposal of cutting chips, and thermal expansion of gears caused by hot cutting chips.

Semi-dry machining systems, which are comparable to dry cutting and more environmental friendly than traditional oils, have been developed for turning, milling and drilling [3]. In particular, minimal quantity lubrication (MQL) machining system shows good cutting performance in drilling and reaming operations, in which a negligible amount of cutting oil penetrates into the cutting zone. In addition, MQL is advantageous in terms of cost. However, there has been little investigation on hobbing using the MQL system, except for reports on fundamental MQL research on hobbing by the authors [4～9], a report on hob wear and finished surface roughness by Suda et al. [10] and another report on the improvement of scratch marks on the surface of gear teeth by Nakae [11]. Thus, it is necessary to investigate whether MQL can be applied to dry cutting.

In this study, the cutting performances of MQL and dry cutting were investigated and compared in terms of flank wear, crater wear and finished surface roughness. The results set the foundation of the MQL system for hobbing.

II. EXPERIMENTAL METHOD AND CONDITIONS

As the experimental method, tests were conducted by simulating hobbing by fly tool cutting on a milling machine (see Fig. 1). In other words, testing the durability of a hob by actual hobbing is so complicated, because it is influenced by many factors, that after analyzing the size of cutting chips produced by the tooth of the hob carrying the greatest load, a fly tool of the same shape as a single hob tooth was made to perform cutting identical to this tooth on the milling machine. The shape of fly tool is given in Fig. 2. For the correspondency between hobbing and fly tool cutting, one of the authors recognized that the results, e.g., flank wear and surface roughness, obtained by using a fly tool with flooded cutting oil [12] and under dry cutting conditions [13], generally agree with those obtained by hobbing. Therefore, the experimental results of fly tool cutting using the MQL system seem applicable to hobbing on a hobbing machine.

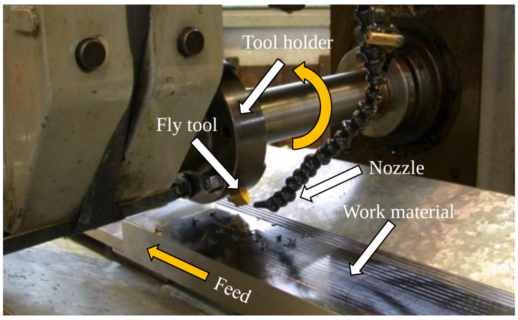

Fig. 1 Setting condition of the fly tool, work material and fluid

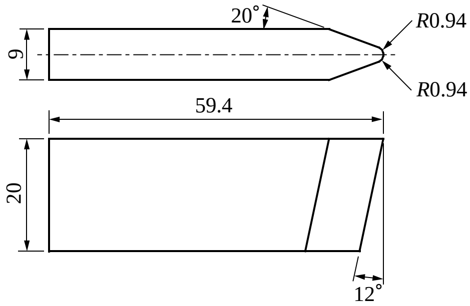

Fig. 2 Profile of the fly tool

The gear, which became the object in the experiments, is a spur gear. The module is 3, the number of teeth is 42, and the hob has a 3-thread right-hand form. The experimental conditions for the milling machine are listed in Table 1. Fly tool cutting was performed by upward milling. The fly tool used in these tests is formed from the HSS equivalent to JIS SKH55. Most fly tools are coated with TiN or (Al, Ti) N films by arc ion plating. In this study, cutting tests were conducted using tools without a coating on the rake face, because the hobs are usually used without coating on the rake face by regrinding in many cases in the workshops, (referred to as TiN-coated and (Al, Ti) N-coated tools), and with full coating of the fly tools (referred to as fully TiN-coated and fully (Al, Ti) N-coated tools). The thickness of both coating films is about 5 μm. The work material used in the tests is SCM415 (HB143) chromium molybdenum steel, which is 500 mm in length, 100 mm in width and 100 mm in thickness. In the present experiments, grooves with a length from 0.5 m to 60 m were cut by fly tool cutting on the milling machine, which corresponds to hobbing with 1.6 gears to 193.5 gears on the hobbing machine. The cutting speeds used in the experiments were 86, 117 and 159 m/min, because hobbing is ordinarily performed in the cutting speed range of 80～150 m/min.

TABLE 1 THE SAME CONDITIONS AS IN THE CASE OF HOBBING BY FRY TOOL CUTTING ON MILLING MACHINE

Hobbing		**Fly tool cutting on milling machine**	
3-thread hob		Feed of table	0.99 mm/rev
Feed of hob	3.0 mm/rev	Depth of cut	3.25 mm
Length of maximum chip	23.57 mm	For cutting corresponding to the gear	
		Total number of revolutions (Sum of approach distance and face width)	315
Thickness of maximum chip	0.27 mm	Length of groove to be cut	0.31 m

Note: The turning radius of the tip of fly tool is 85 mm.

Fig. 3 shows the types of wear at the tip of the tool. The widths of the center wear, top corner part wear on the top cutting edge, and the corner wear occurring at the boundary region between the rounded portion on the top cutting edge and the side cutting edge, were measured with a microscope. As shown in Fig. 4, the depth was measured at 25 points at intervals of 0.1 mm to obtain the crater profile. The finished surface roughness Rz on the bottom of the cutting groove in the cutting direction was measured using a surface-measuring instrument. Moreover, photographs of flank wear, crater wear and examples of finished surfaces were taken. The milling machine used in the tests is the 2MF model (universal type) manufactured by Hitachi Seiki Co., Ltd. The MQL supply system is the FK-type external applicator produced by Fuji BC Engineering Co., Ltd. The cutting oil for the MQL tests is polyol ester, which was selected for its low viscosity [5]. Polyol ester has an excellent biodegradability and it is environmentally friendly oil. Table 2 shows the oil properties. The quantity of oil supplied, 15 ml/h, and the compressed air pressure, 0.5 MPa, were selected on the basis of the results of a previous report [4]. The oil was supplied from the rake face side.

TABLE 2 PROPERTIES OF THE OIL TESTED

Item \ Oil	Polyol ester
Specific gravity (15 °C, g/cm³)	0.95
Kinematic viscosity (40 °C, mm²/s)	19
Viscosity index	137
Flash point (COC, °C)	250
Pour point (°C)	<-45
Acid number (mgKOH/g)	0.02
Biodegradability (OECD, %)	72

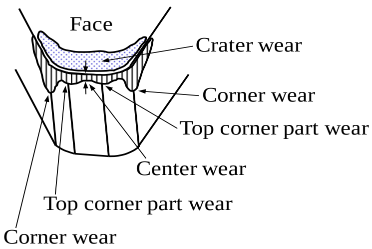

Fig. 3 Wear at cutting edge

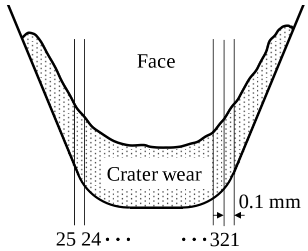

Fig. 4 Measurement position of crater wear

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Uncoated Tool

To confirm the reproducibility of flank wear in this study, tests were conducted under several conditions, and two tests were conducted for each condition. Fig. 5 illustrates the reproducibility of flank wear obtained using the MQL system with the uncoated tool after a groove of length 0.5 m was cut at 117 m/min. In these tests, the width of the flank wear is considered to be almost the same.

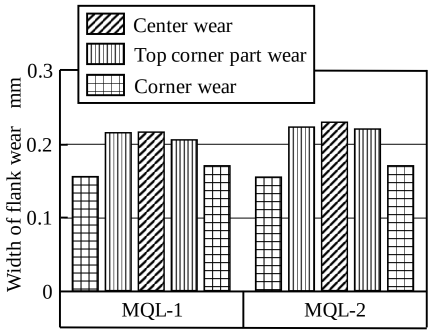

Fig. 5 Reproducibility of flank wears with MQL system
(uncoated tool, cutting speed of 117 m/min, cutting length of groove of 0.5 m)

Fig. 6 compares the width of flank wear obtained by dry cutting and that with the MQL system when cutting a groove length of 0.5 m. The cutting speeds are 86, 117 and 159 m/min. The widths of flank wear, center wear and top corner part wear obtained with the MQL system are smaller than those obtained by dry cutting. The wear reduction effect of MQL is the smallest overall at the cutting speed of 86 m/min. At 117 m/min, although the width of corner wear with MQL shows almost the same value as with dry cutting, the widths of the center wear and top corner part wear decrease to approximately one-half the widths with dry cutting. At the high speed of 159 m/min, not only the width of corner wear decreases, but also the width of wear at the top cutting edge decreases to less than one-fourth. Thus, the effect of MQL increases with an increase in cutting speed; especially, when using the uncoated tool, the MQL system is effective for reducing the wear at the top cutting edge. The assumed reason for this behavior is the influence of the thermal loads, because the cutting chip around the center of the top cutting edge is thickest at the cutting edge [14], which heavily loads the cutting edge. So, the large wear obtained by dry cutting is due to the higher cutting temperature, which is more detrimental without lubrication. Thus, it is assumed that MQL shows an excellent lubrication property in comparison with that of dry cutting in a region of the severe condition with higher cutting temperatures.

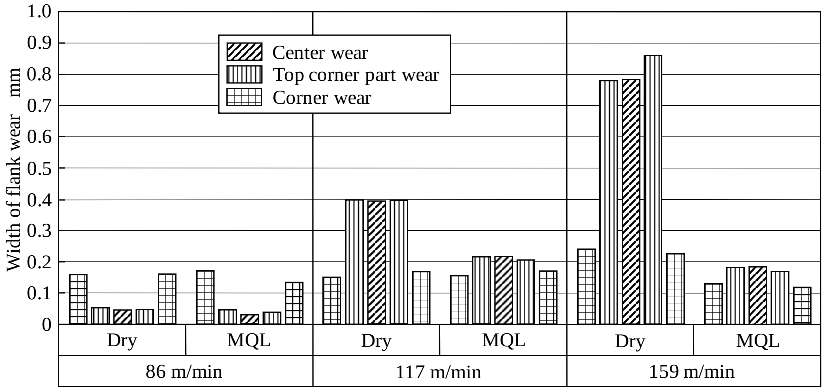

Fig. 6 Comparison of flank wears between dry cutting and MQL system (uncoated tool, cutting length of groove of 0.5 m)

The flank wear of the top cutting edge at cutting speeds of 117 m/min and 159 m/min are shown in Fig. 7. The length of the groove is 0.5 m. In the case of dry cutting at 117 m/min, the adhesion of deposited metal is observed over the entire region of flank wear. Thus, it is considered that the flank wear is dominated by the welding wear [15] caused by the lack of lubricating component, or a transfer-type wear [16], caused by seizure of the substrate due to tearing of the deposited metal from the cutting edge. However, although it is thought that the flank wear obtained with MQL shows the same wear pattern as that obtained by dry cutting, reduced wear is observed with MQL, because even an extremely small quantity of oil provides excellent lubrication, resulting in a lower cutting temperature and also inhibition of the growth of deposited metal. This explained that in MQL cutting, the reactivity of the lubricant ester is intensified by atmospheric oxygen, leading to the formation of a robust and tribologically effective lubricating film [17]. The mechanism of action in MQL is currently under investigation. Furthermore, no chipping is observed at the cutting edge. In dry cutting at the high cutting speed of 159 m/min, welding wear is promoted because the amount of adhesion of deposited metal increases and shows abnormal wear. It is adhesive wear that is a complex flank wear pattern because the coating and the_tool steel are abraded by the particles of the work-hardened deposited metal [18]. The use of MQL is further validated since it has a higher wear reduction effect at 159 m/min than that at 117 m/min, although adhesion of the deposited metal is observed at the cutting edge.

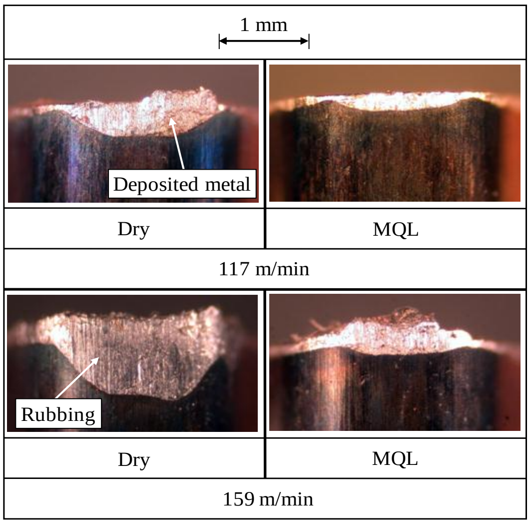

Fig. 7 Conditions of flank wear (uncoated tool, cutting a groove of 0.5 m)

When using the uncoated tool under these cutting conditions, the depth of crater wear could not be measured due to deposited metal adhered on the crater. Therefore, the heights of the deposited metal on the rake face are compared. Fig. 8 compares the height of the deposited metal on the rake face at 117 m/min and 159 m/min. The largest height of the deposited metal (the largest among 25 measurement points for the rake face, see Fig. 4) and the mean height of the deposited metal (the average of the 25 points) are given. In the comparison of MQL with dry cutting at 117 m/min, the quantity of deposited metal decreases with MQL. The heights of deposited metal obtained with both MQL and dry cutting at 159 m/min are higher than those obtained at 117 m/min. At 159 m/min, the largest heights of the deposited metal obtained for both MQL and dry cutting show almost the same value, but the mean height of the deposited metal obtained with MQL is lower than that obtained by dry cutting. Fig. 9 shows the conditions of the rake face after dry cutting and MQL at 117 m/min. The quantity of deposited metal is decreases in the case of MQL, although adhesion of the deposited metal on the entire zone of the contact surface between the rake face and the cutting chips is observed in both cases.

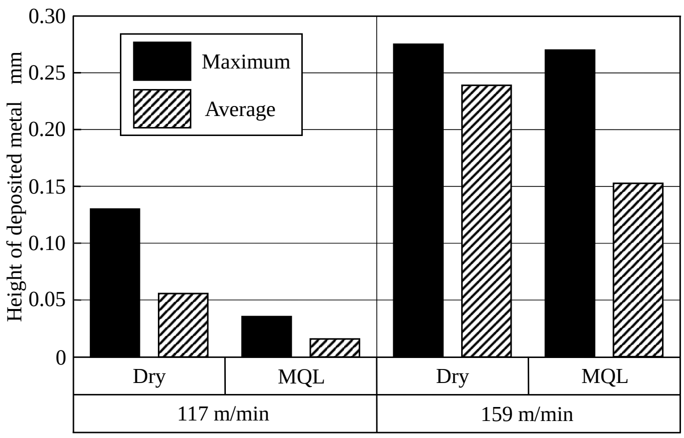

Fig. 8 Comparison of height of deposited metal on rake face between dry cutting and MQL system (uncoated tool, cutting a groove of 0.5 m)

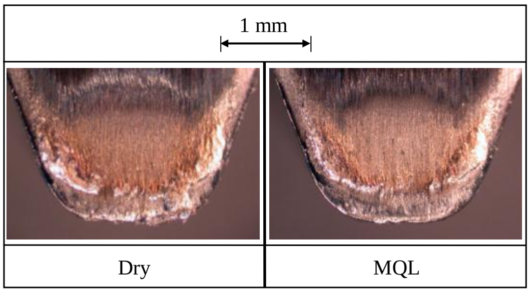

Fig. 9 Conditions of rake face (uncoated tool, cutting speed of 117 m/min, cutting a groove of 0.5 m)

Fig. 10 shows the comparison of surface roughness Rz obtained by dry cutting and the MQL system at various cutting speeds. The surface roughness is excellent at 86 m/min; the roughness obtained by both dry cutting and MQL is approximately 2 µm, although the roughness obtained with the MQL is smaller. The assumption of the small surface roughness at this cutting speed is that there is little adhesion of deposited metal on the cutting edge. Both at 117 m/min and 159 m/min, the roughness becomes large because deposited metal adheres on the cutting edge. The roughness obtained with MQL is also smaller than that obtained with dry cutting at these two higher cutting speeds. In summary, the MQL system shows surface roughness reduction.

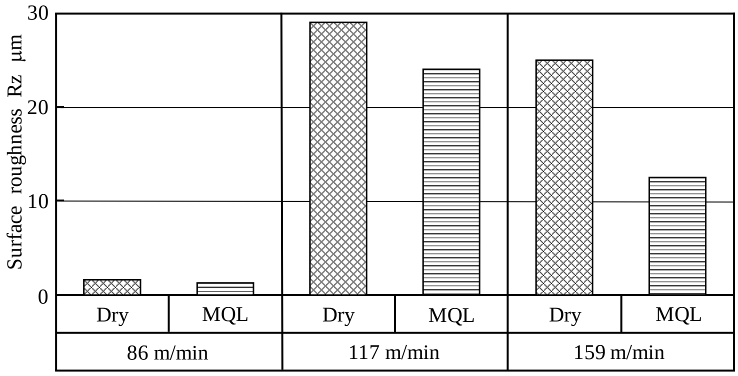

Fig. 10 Comparison of surface roughness between dry cutting and MQL system (uncoated tool, cutting a groove of 0.5 m)

B. TiN-coated Tool

Fig. 11 compares the flank wear obtained by dry cutting and MQL when using TiN-coated tool at 117 m/min and 159 m/min. A groove with a length of 40 m was cut at 117 m/min. The widths of the center, top corner part wear and corner wear observed for the MQL system are smaller than those observed for dry cutting. In dry cutting at the high speed of 159 m/min, cutting was impossible because the maximum flank wear, which is defined as the highest amount of center wear, top corner part wear and corner wear, reached more than 0.4 mm after cutting a groove of length 1.5 m. In the case of MQL, however, the maximum flank wear obtained using the MQL system is half of that obtained using dry cutting, in spite of the groove cut of 40 m. Therefore, it is possible to cut with the MQL system even at the high cutting speed of 159 m/min.

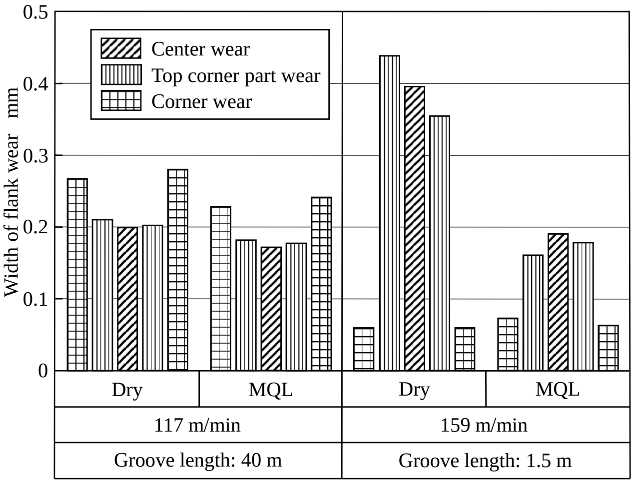

Fig. 11 Comparison of flank wears between dry cutting and MQL system (TiN-coated tool, cutting a groove of 40 m)

Fig. 12 shows the conditions of flank wear at 117 m/min and 159 m/min. In dry cutting after cutting a groove of length 40 m at 117 m/min, some small chippings appear on the side cutting edge, and abnormal wear, which is considered to be caused by the delamination and/or seizure of the coating film, also appears. This abnormal wear is larger than the flank wear obtained by MQL. In MQL, although small chippings are observed on the cutting edge, flank wear is dominated by the abrasive wear pattern. In the cases of dry cutting and MQL after cutting a groove of length 1.5 m at 159 m/min, the adhesion of deposited metal on the cutting edge can be seen, and it is thought that this flank wear is the transfer-type wear, which occurs due to seizure of the substrate.

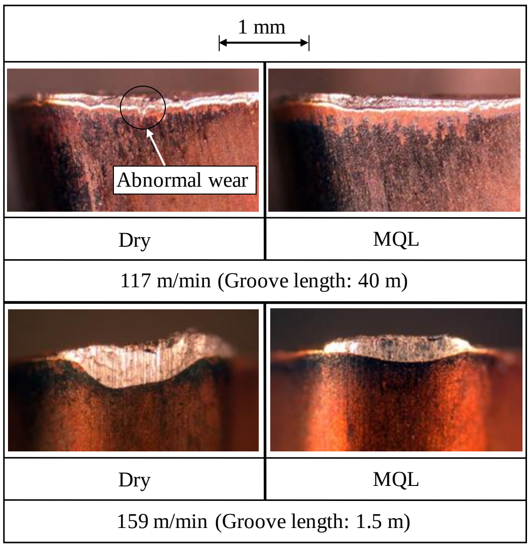

Fig. 12 Conditions of flank wear (TiN-coated tool)

The depth of crater wear at 117 m/min and the height of deposited metal at 159 m/min are shown in Fig. 13. The maximum value of crater wear (the deepest among 25 measurement points for the depth of crater wear, see Fig. 3) and the mean value of crater wear (the average of those 25 points) at 117 m/min, and the largest height of the deposited metal and the mean height of the deposited metal at 159 m/min are given. Both the maximum value and the mean value of crater wear obtained with MQL are smaller than those obtained with dry cutting at 117 m/min. In the comparison of MQL with dry cutting at 159 m/min, the quantity of deposited metal decreases, this means that MQL is effective for TiN-coated tools.

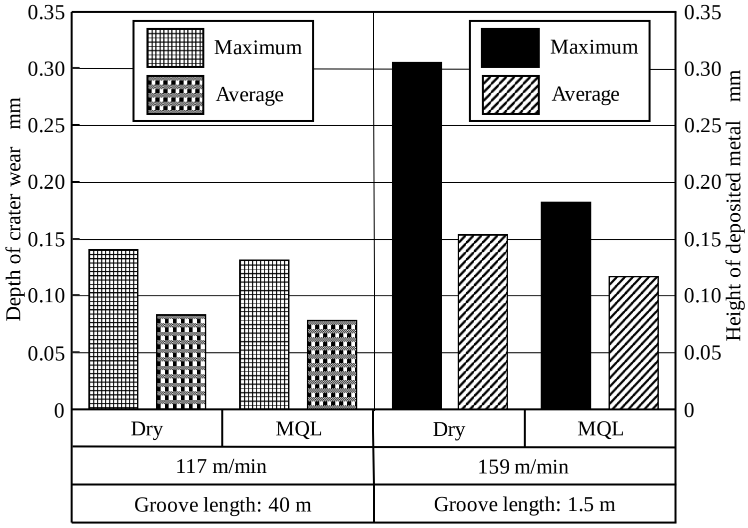

Fig. 13 Comparison of depth of crater wear and height of deposited metal between dry cutting and MQL system (TiN-coated tool)

Fig. 14 shows the conditions of the rake face at 117 m/min and 159 m/min. In dry cutting after cutting a groove of length 40 m at 117 m/min, a mark caused by rubbing of the cutting chips (referred to as a “rubbing mark”) on the rake face in the vicinity of the cutting edge is clearly observed, and, in particular, at the center of the rake face, a deep mark cut by the cutting chips can be seen. A mark caused by seizure of the substrate (referred to as a “seizure mark”) far from the cutting edge is observed. Although the crater wear pattern in the case of MQL is similar to that in the case of dry cutting, the crater surface obtained with MQL is smooth compared to that obtained by dry cutting. After cutting a groove of 1.5 m at 159 m/min, the adhesion of deposited metal, over the entire region of the contact surface is observed in both dry cutting and MQL, but the quantity of deposited metal obtained with MQL seems to be smaller.

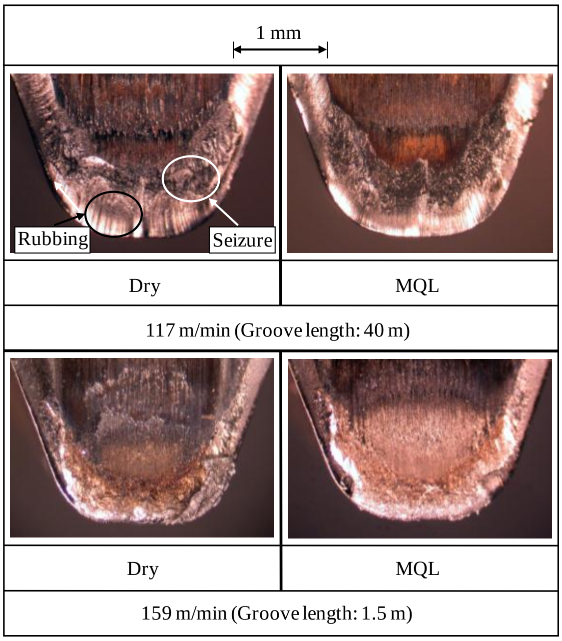

Fig. 14 Conditions of rake face (TiN-coated tool)

Fig. 15 compares the surface roughness, Rz, obtained by dry cutting and MQL at 117 m/min and 159 m/min. The roughness is given for the beginning and end of cutting. In dry cutting and the MQL system at 117 m/min, the surface roughness values range from 20 μm to 30 μm at the beginning of the cut (after cutting a groove length of 0.5 m), but the roughness obtained with the MQL is small. At the end of cutting (after cutting a groove length of 40 m), the roughness is the same at 2～3 μm for both dry cutting and MQL. The reason why the surface roughness is large at the beginning of the cut seems to be significantly related to the occurrence of deposited metal, which we observed to adhere on the cutting edge. An interesting phenomenon also occurs: namely, the surface roughness decreases suddenly. In dry cutting [19], the sudden decrease of surface roughness is assumed to be related to crater wear; that is, when the crater wear width increases to some degree, the working rake angle becomes large, which smoothes the flow of the cutting chips, resulting in a decrease in the quantity of deposited metal. At 159 m/min, the roughness obtained by dry cutting and MQL is 20～30 μm at the beginning (after cutting a groove length of 0.5 m) and at the end (after cutting a groove length of 1.5 m), but the roughness obtained with MQL at the end of the cut is small.

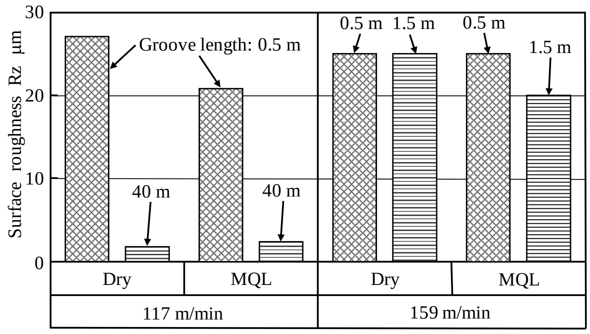

Fig. 15 Comparison of surface roughness between dry cutting and MQL system (TiN-coated tool)

C. (Al, Ti) N-coated Tool

Fig. 16 shows the comparison of flank wear obtained by dry cutting and MQL when using the (Al, Ti) N-coated tool at the cutting speeds of 117 m/min and 159 m/min. The length of the groove is 40 m. The width of the flank wear obtained with MQL is smaller than that obtained with dry cutting at 117 m/min. In dry cutting at the high speed of 159 m/min, the test was stopped because the maximum flank wear increased to almost 0.4 mm after cutting a groove with a length of 4 m. In MQL, however, the maximum flank wear is 0.27 mm, even after cutting a groove cutting of length 40 m, which is larger than that obtained at 117 m/min. Therefore, it is found that the MQL system is more effective than dry cutting for the (Al, Ti) N-coated tool at high cutting speed.

The conditions of flank wear at 117 m/min and 159 m/min are shown in Fig. 17. In dry cutting at 117 m/min, abnormal wear, which is considered to be caused by delamination of the coating film on the side cutting edge, can be confirmed, and this abnormal wear determines the tool life. In the MQL system, small chippings on the top cutting edge are observed, but the abrasive wear pattern dominates. After cutting a groove with a length of 4 m in dry cutting at 159 m/min, abnormal wear is observed. This abnormal wear is thought to be caused by delamination of the coating film and/or seizure of the substrate when the deposited metal tears off from the cutting edge. In contrast, the wear pattern with the MQL system is considered to be abrasive wear, although chippings are observed on the cutting edge in spite of the groove length of 40 m.

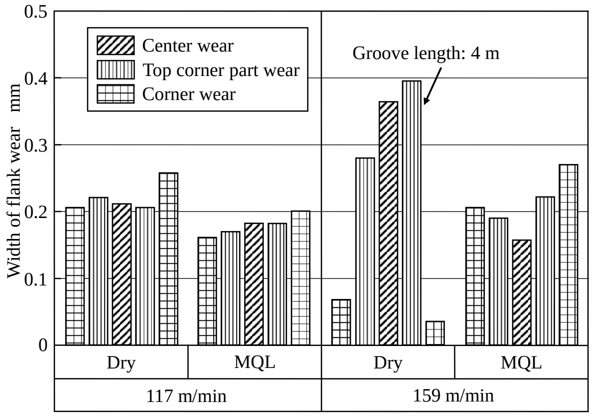

Fig. 16 Comparison of flank wear between dry cutting and MQL system [(Al, Ti) N-coated tool, cutting a groove of 40 m]

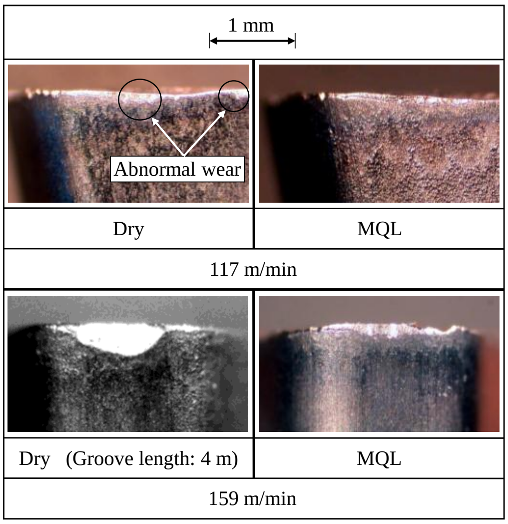

Fig. 17 Conditions of flank wear [(Al, Ti) N-coated tool, cutting a groove of 40 m]

Fig. 18 compares the depth of crater wear obtained by dry cutting and MQL at 117 m/min and 159 m/min. The depth of crater wear for 1 m, which is obtained by dividing the crater depth by cutting groove length, is evaluated, because the groove length is cut according to the different cutting conditions. At 117 m/min, the crater wear obtained by MQL is smaller than that obtained by dry cutting. In dry cutting at 159 m/min, the crater wear increases compared with that at 117 m/min, but in the MQL system, the crater wear shows almost the same value as that obtained at 117 m/min, which decreases markedly to approximately one-fourth in comparison with that obtained by dry cutting.

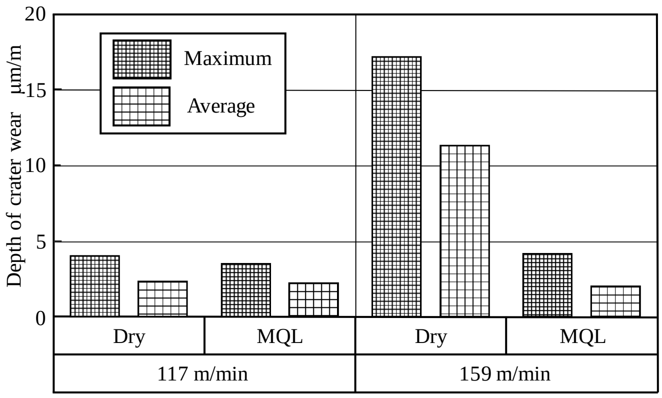

Fig. 18 Comparison of depth of crater wear between dry cutting and MQL system [(Al, Ti) N-coated tool, cutting a groove of 1 m]

Fig. 19 shows the comparison of the surface roughness at the beginning and end of cutting at 117 m/min and 159 m/min. At the beginning, after cutting a groove of 0.5 m at 117 m/min, the surface roughness obtained using MQL is smaller than that obtained by dry cutting. At the end, after cutting a groove length of 40 m, the surface roughness obtained by both dry cutting and MQL becomes approximately 3 μm. At the beginning of the cut at the high cutting speed of 159 m/min, the roughness obtained by dry cutting is the same as that obtained with MQL, which is approximately 25 μm. With the MQL system, however, the roughness shows a very acceptable value of 2 μm after reaching a cutting groove length of 40 m.

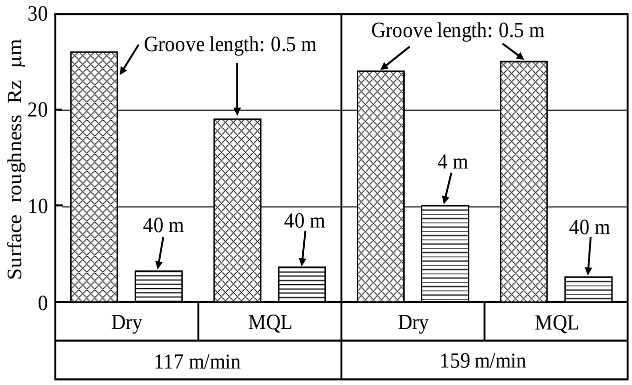

Fig. 19 Comparison of surface roughness between dry cutting and MQL system [(Al, Ti) N-coated tool]

D. *Fully-coated Tool*

Fig. 20 compares the width of the flank wear obtained by dry cutting and MQL when using the fully TiN- and (Al, Ti) N-coated tools. The cutting groove length is 25 m for the fully TiN-coated tool and the groove length is 60 m for the fully (Al, Ti) N-coated tool. The cutting speed is 159 m/min. With both the fully TiN- and (Al, Ti)N-coated tools, the flank wear obtained with the MQL system is small, and, in particular, the MQL system decreases the top flank wear.

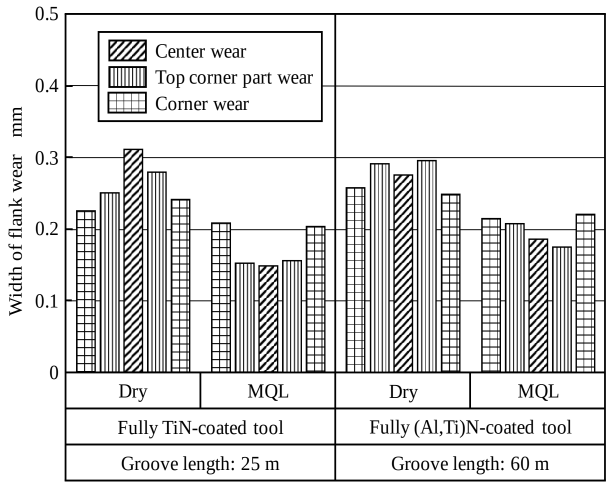

Fig. 20 Comparison of flank wear between dry cutting and MQL system with fully coated tools

The conditions of flank wear when using the fully coated tools are shown in Fig. 21. With both fully coated tools, neither adhesion of deposited metal nor chippings are observed on the cutting edge. Although there is a difference in the width of flank wear between dry cutting and the MQL system, the flank wear is thought to be caused by abrasive wear.

The acceleration in the feed direction was estimated to compare the cutting force with dry cutting and the MQL system. Fig. 22 shows the profiles of acceleration obtained when cutting one chip. The acceleration with the MQL system is smaller than that with dry cutting. In the case of dry cutting, a large acceleration occurs at the commencement of cutting (round mark). This acceleration is considered to be affected by rubbing due to the lack of lubrication in dry cutting, because the thickness of the chip is very thin at the commencement of cutting. Moreover, it can be seen that the fluctuation of acceleration with dry cutting is large. In contrast, the acceleration at the commencement of cutting obtained with the MQL system decreases compared with that obtained with dry cutting. Thus, it is assumed that the lubrication from the extremely small quantity of cutting oil in MQL is effective for decreasing the acceleration.

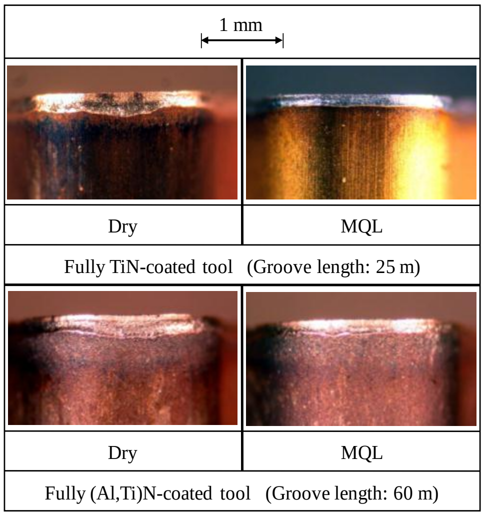

Fig. 21 Conditions of flank wear of fully coated tools

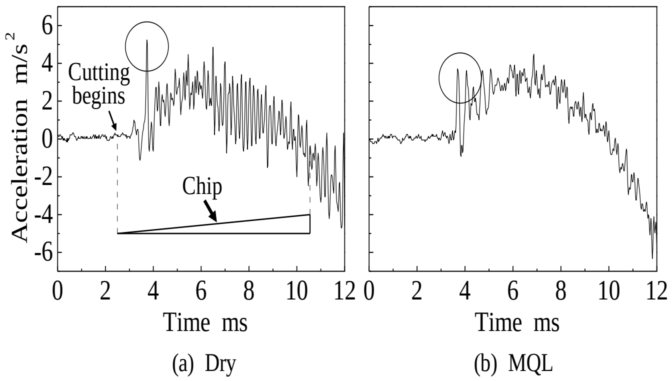

Fig. 22 Profiles of acceleration when cutting one chip (new fly tool)

Fig. 23 shows the comparison of the depth of crater wear obtained by dry cutting and MQL using the fully coated tools. When using the fully TiN- and (Al, Ti) N-coated tools, the MQL system decreases the crater wear and is also effective when using the fully coated tools. The conditions of crater wear of the fully coated tools obtained by dry cutting and MQL are shown in Fig. 24. The cutting groove length is 25 m. When using the fully TiN-coated tool, although crater wear occurs in almost the entire zone of the contact surface with the cutting chips in dry cutting, the area of crater wear is small with the MQL system. In dry cutting with the fully (Al, Ti) N-coated tool, crater wear occurs in approximately one-third of the contact area. In contrast, in the MQL system, crater wear is observed at only both sides of the contact surface, that is, near the boundary between the rounded portion and the side cutting edge. The reason for this phenomenon was stated in the previous paper [20]. A hob tooth has three different cutting edges, the top cutting edge, the nose rounded potion and the side cutting edge. Since the cutting chips, which are cut by these cutting edges, have different outflow directions on the rake face, the chips collide into each another, and interference between these cutting chips [21, 22] occurs. Therefore, high temperature and high pressure in this region are generated and cause the crater wear. From the above results, it was found that the MQL system retards the occurrence of crater wear.

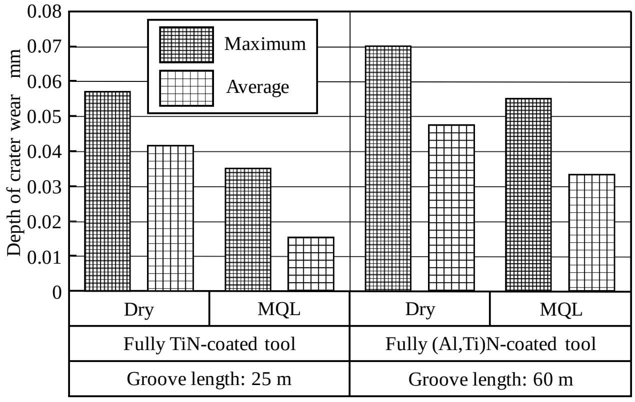

Fig. 23 Comparison of depth of crater wear between dry cutting and MQL system with fully coated tools

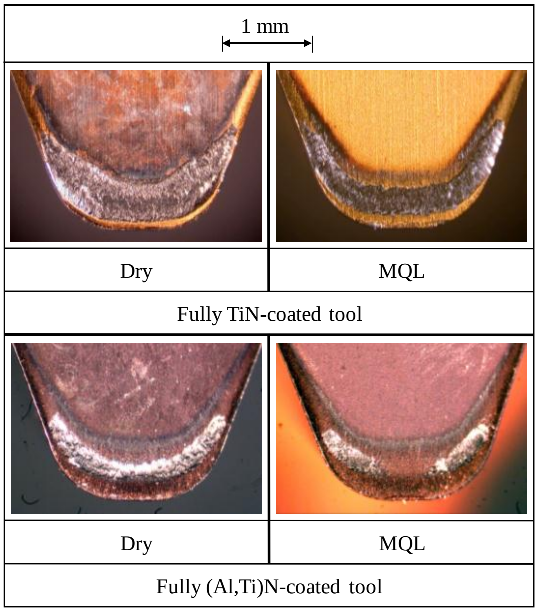

Fig. 24 Conditions of rake face (cutting a groove of 25 m)

Fig. 25 shows the progress curves of the finished surface roughness obtained in the cases of dry cutting and the MQL system when using fully coated tools. When using the fully TiN-coated tool, the surface roughness obtained with the MQL system is smaller than that obtained with dry cutting at each cutting groove length. In dry cutting, when using the (Al, Ti) N-coated tool, the roughness increases until a cutting groove length of 20 m is reached, and then, it tends to repeatedly increase and decrease. In contrast, with the MQL system, the roughness shows a tendency to increase, but the increase is small compared with that obtained by dry cutting and it is about 2.5 μm at the end of cutting a groove length of 60 m. Thus, MQL shows good surface roughness.

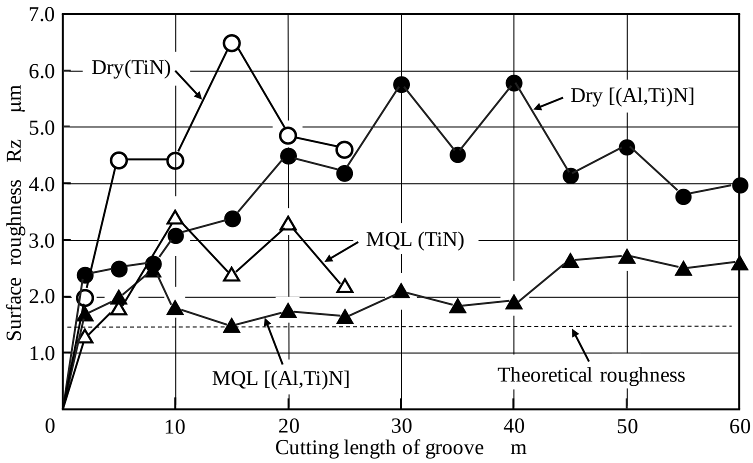

Fig. 25 Progress curves of surface roughness obtained with fully coated tools

From the results described above, the fully coated tools are more effective for decreasing tool wear and finished surface roughness than the coated tools without coating on the rake face. In particular, with the MQL system, the fully (Al, Ti) N-coated tool shows better cutting performance in terms of tool wear and surface roughness at a high cutting speed.

IV. CONCLUSIONS

From fly tool cutting tests, which simulate hobbing, the difference in cutting performance with dry cutting and the MQL system was investigated in terms of flank wear, crater wear and finished surface roughness. The following points were clarified.

(1) For the uncoated tool, the TiN- and (Al, Ti) N-coated tools without coating on the rake face and the fully TiN- and (Al, Ti) N-coated tools, the MQL system markedly decreases the flank wear, crater wear and surface roughness compared with the results by dry cutting, particularly at the high cutting speed of 159 m/min. The reason for the improved cutting performance by the MQL system was suggested as follows: the lubricating properties improve even with an extremely small quantity of cutting oil, resulting in a decrease of the occurrence of deposited metal on the cutting edge.

(2) When using the fully (Al, Ti) N-coated tool among the cutting tools tested, the MQL system is effective for decreasing tool wear and surface roughness, and it is possible to cut at a high cutting speed using the MQL system.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to Mitsubishi Materials Corporation for the supply of cutting tools and to JX Nippon Oil & Energy for providing us with cutting oils.

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