Fundamental Research on Hobbing with Minimal Quantity Lubrication of Cutting Oil

Influence of Hardness of Work Materials Under Several Cutting Conditions

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***Abstract*-This paper deals with the influence of hardness of work materials on flank wear, crater wear and finished surface roughness when using two types of high-speed steel (HSS) hob tool materials coated with (Al,Ti)N film. Specifically, hobbing with a minimal quantity lubrication (MQL) system is compared with dry hobbing. Experiments were conducted by simulating hobbing by fly tool cutting on a milling machine. The results are summarized as follows. (1) With SCM415 work material changed to hardness HB131, HB144 and HB161 by heat treatment, flank wear and crater wear of the tool are small when cutting comparatively hard HB161 work material, irrespective of the change in hob materials and cutting speeds. (2) With SCM435 work material changed to hardness HB172, HB195 and HB214, flank wear and crater wear tend to be small when cutting annealed HB172 work material. (3) When cutting SCM415 of hardness HB161 and SCM435 of hardness HB172, the finished surface roughness is small and the surface roughness of SCM415 is smaller than that of SCM435. (4) SCM415 of hardness HB161 is suitable for an MQL system in hobbing in terms of flank wear, crater wear and finished surface roughness.**

Keywords- Gear; Cutting; Gear; Hobbing; MQL; Work Material; Hardness; Fly Tool; Flank Wear; Crater Wear; Finished Surface Roughness

I. INTRODUCTION

Recently, the technologies of dry hobbing without cutting oil and with semi-dry machining systems with an oil mist supply have been developed from the viewpoint of improvement of working environment and prevention of global environmental pollution [1-3]. In other machining processes, a 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. Additionally, MQL is advantageous in terms of cost. To date, few investigations have been conducted on hobbing with an MQL system. However, in fundamental MQL and hobbing research, the authors of this paper have reported the following: effect of quantity of oil supply [4], influence of viscosity grade of base oil [5, 6], effect of cutting speed [7], influence of concentration of sulfurous and phosphorous EP additives in cutting oil [8], influence of kinds of cemented carbide hob materials [9, 10], and comparison of cutting performance with dry cutting [11]. In other related research, Suda et al. [12] reported on hob wear and finished surface roughness, and Nakae [13] reported on the improvement of scratch marks on the surface of gear teeth. Thus, more research is needed to investigate whether MQL can be applied to dry cutting.

Generally, work materials such as chromium molybdenum steel and chromium steel have been used as gear materials for automobiles. These particular kinds of gear materials considerably affect hob wear [14]. One of the authors found that crater wear in dry hobbing is small when cutting SCM415 among three kinds of gear materials having almost the same hardness (HB155) [15]. Moreover, one of the authors clarified that crater wear in dry hobbing decreases with increasing hardness of work materials when changing the hardness of SCM415 work materials by heat treatment [16].

In this study, the influence of the hardness of gear materials (work materials) in hobbing with the MQL system was investigated and compared with dry cutting in terms of flank wear, crater wear of two types of tool materials and the finished surface roughness of two types of work materials.

II. EXPERIMENTAL METHOD AND CONDITIONS

Experiments were conducted by simulating hobbing with fly tool cutting on a milling machine, as shown in Fig. 1. Testing the durability of a hob by actual hobbing is complicated because it is influenced by many factors. After analyzing the size of chips produced by the tooth of a hob carrying the greatest load, a fly tool of the same shape as the single hob tooth was made for simulated hob cutting on the milling machine. For the correspondence 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 [17] and under dry cutting conditions [18], 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.

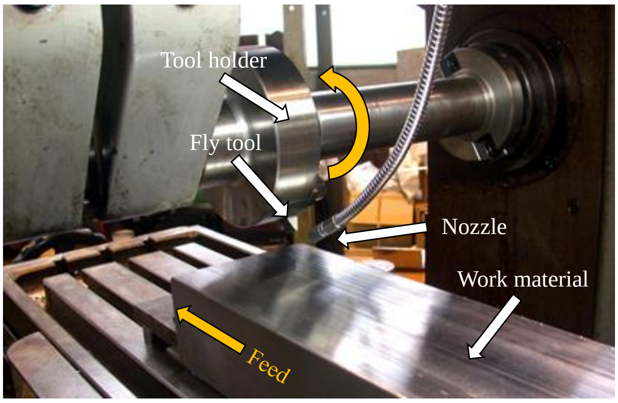

Fig. 1 Setting condition of the fly tool and work material to simulate hobbing

The dimensions of the gear and the hob used in the experiments are listed in Table 1. The experimental conditions for the milling machine are listed in Table 2. Fly tool cutting was performed by upward milling. The fly tools used in these tests are formed from two high-speed steel (HSS) materials, AISI M34 and T15. The fly tools are coated with (Al, Ti) N film by arc ion plating (referred to as an (Al, Ti)N-coated tool). In this study, cutting tests were conducted by using tools without a coating on the rake face, because many workshops regrind the rake face of the hob. The thickness of the coating film of flank face was approximately 5 μm. The work materials used in the tests were chromium molybdenum steels SCM415 and SCM435, which have been extensively used as gear materials. Their chemical compositions are given in Table 3. The hardness of the work materials, which came from the same lot, was either as-rolled or changed by annealing and normalizing heat treatments. The heat treatment condition and hardness of the work materials are listed in Table 4 and their metallographic structures are shown in Fig. 2. The dimensions of the work materials were 500 mm in length, 100 mm in width, and 100 mm in thickness. In the present experiments, a groove of length 40 m was cut for SCM415 by fly tool cutting on the milling machine; this generally corresponds to hobbing 129 gears on the hobbing machine. The cutting speed for SCM415 was 117 m/min. Since all hardness values of SCM435 were higher than those of SCM415, the cutting speed was decreased to 86 m/min. A groove of length 8 m was cut for SCM435 by fly tool cutting on the milling machine; this generally corresponds to hobbing 26 gears on the hobbing machine.

TABLE 1 DIMENSIONS OF THE GEAR AND HOB

Gear		**Hob**	
Module	3	Module	3
Pressure angle	20°	Pressure angle	20°
Number of teeth	42	Lead angle	4° 35′ 18″
Helix angle	0°	Form	3-thread, Right hand
Pitch diameter	126 mm	Size	ϕ118 × 125 × ϕ40
Face width	40 mm	Rake angle	0°
Cutting depth	6.75 mm	Relief angle	12°
Tooth profile	Full depth tooth	Number of gashes	12
		Gash	Straight

TABLE 2 CORRESPONDING CONDITIONS FOR HOBBING AND FLY TOOL CUTTING ON A MILLING MACHINE

<table>
<tr><th colspan="2">Hobbing</th><th colspan="2">Fly tool cutting on milling machine</th></tr>
<tr><td colspan="2">3-thread hob</td><td>Feed of table</td><td>0.99 mm/rev</td></tr>
<tr><td>Feed of hob</td><td>3.0 mm/rev</td><td>Depth of cut</td><td>3.25 mm</td></tr>
<tr><td rowspan="2">Length of maximum chip</td><td rowspan="2">23.57 mm</td><td colspan="2">For cutting corresponding to the gear</td></tr>
<tr><td rowspan="2">Total number of revolutions (Sum of approach distance and face width)</td><td rowspan="2">315</td></tr>
<tr><td rowspan="2">Thickness of maximum chip</td><td rowspan="2">0.27 mm</td></tr>
<tr><td>Length of groove to be cut</td><td>0.31 m</td></tr>
</table>

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

TABLE 3 CHEMICAL COMPOSITION OF WORK MATERIALS

	Chemical composition %								
	C	Si	Mn	P	S	Cu	Ni	Cr	Mo
SCM 415	0.14	0.18	0.71	0.013	0.023	0.01	0.02	1.04	0.19
SCM 435	0.35	0.20	0.75	0.021	0.022	0.01	0.02	1.00	0.18

TABLE 4 HEAT TREATMENT AND HARDNESS OF WORK MATERIALS

	Heat treatment condition			Brinell hardness HB
		Temperature ˚C	Time h	
SCM 415	Annealing	850	2	131
	Normalizing	950	2	144
	As-rolled	—	—	161
SCM 435	Annealing	850	2	172
	Normalizing	860	2	195
	As-rolled	—	—	214

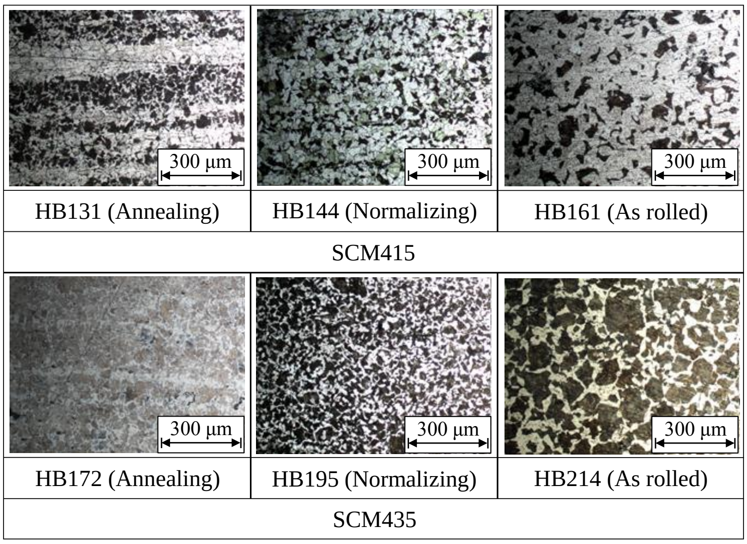

Fig. 2 Metallographic structures of SCM415 and SCM435

Fig. 3 shows the types of wear at the tip of the tool. The widths of center wear, top corner part wear on the top cutting edge, and 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 with a surface-measuring instrument. In addition, photographs of flank wear, crater wear and examples of finished surfaces were taken. The milling machine used in the tests is the 2 MF 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.

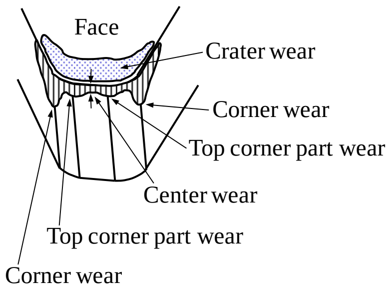

Fig. 3 Wear at cutting edge

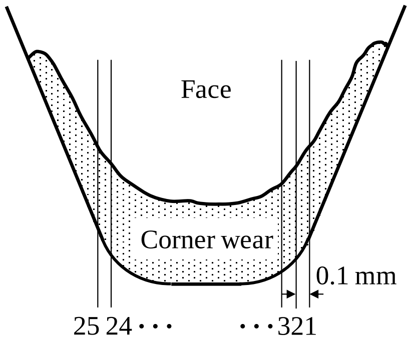

Fig. 4 Measurement position of crater wear

TABLE 5 PROPERTIES OF POLYOL ESTER OIL USED IN THE TEST

Item \ Oil	Polyol ester
Specific gravity (15 °C, g/cm^3)	0.95
Kinematic viscosity (40 °C, mm^2/s)	19
Viscosity index	137
Flash point (COC, °C)	250
Pour point (°C)	<-45
Acid number (mgKOH/g)	0.02
Biodegradability (OECD, %)	72

The cutting oil for the MQL tests is polyol ester, which was selected for its low viscosity [5]. Table 5 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 results of a previous report [4]. The oil was supplied from the rake face side. The effect of MQL was compared to that caused by dry cutting.

III. EXPERIMENTAL RESULTS AND DISCUSSION

To confirm the reproducibility of flank wear and crater wear in this study, tests were conducted under several conditions, and two tests were conducted for each condition. Fig. 5 illustrates the reproducibility of the width of flank wear and the depth of crater wear obtained by the MQL system with the M34 tool after a groove of length 8 m of SCM435 (HB195) was cut at 86 m/min. In these tests, the width of flank wear and the depth of crater wear were considered to be almost the same.

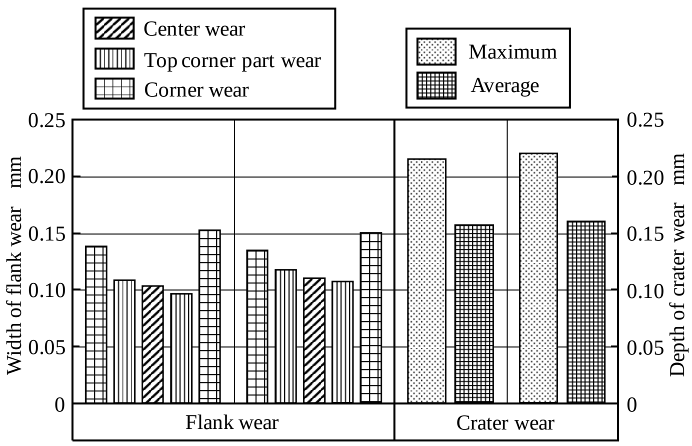

Fig. 5 Reproducibility of the width of flank wear and the depth of crater wear
(SCM435, HB195, M34, MQL, cutting speed: 86 m/min, cutting length of groove: 8 m)

A. Flank Wear

Fig. 6 shows the influence of the hardness of work material on the width of flank wear obtained with the MQL system and that caused by dry cutting when cutting SCM415 with the M34 cutting tool. In the case of MQL, the width of flank wear is small when cutting the work material of the hardest HB161, and the wear becomes large in the order of HB131 and HB144.

Although flank wear under both dry and MQL machining tends to similarly change with the hardness of work materials, the flank wear with the MQL system is smaller than that by dry cutting. Thus, the wear reduction effect of the MQL system is observed. This result is explained as follows: the reactivity of the ester lubricant is assumed to be intensified by atmospheric oxygen and this leads to the formation of a robust and tribologically effective lubrication film [19]. In general, it seems that tool wear increases with increasing hardness of the work material. In investigations on the influence of hardness of work materials with flooded oil in hobbing, one of the authors reported that tool wear becomes large when cutting harder work material [20]. In this experiment, however, the width of flank wear became small when cutting the hardest work material. The influence of the deposited metal may be a reason for this behavior.

Fig. 7 shows the appearances of the deposited metal at the beginning of cutting. The deposited metal adheres at the cutting edge when cutting HB144 work material, but no adhesion of deposited metal is observed when cutting HB131 and HB161 work materials. The reason may be that the cutting temperature is related to the occurrence of deposited metal.

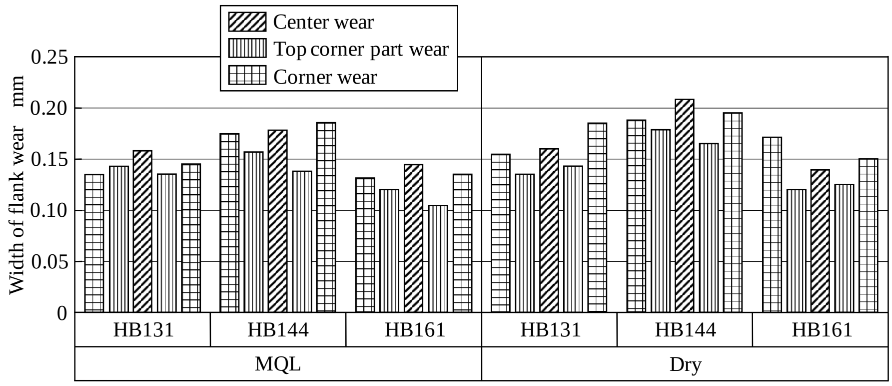

Fig. 6 Influence of hardness of work material on the flank wear (SCM415, M34, cutting speed: 117 m/min, cutting a groove: 40 m)

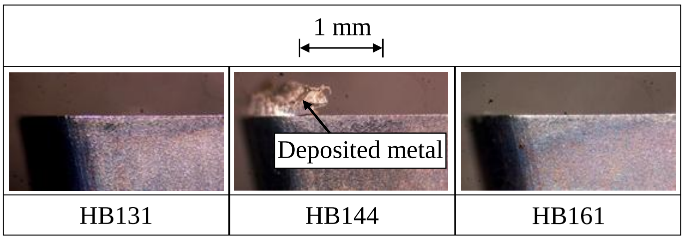

Fig. 7 Appearances of deposited metal (SCM415 M34, MQL, cutting speed: 117 m/min, cutting length of groove: 0.5 m)

Therefore, in these experiments, even though cutting temperatures were not measured, the temperature difference between the chip and the rake face was assumed due to the color difference of the chip formed. Fig. 8 shows the colors of the chips after reaching a groove cutting length of 0.5 m when cutting the SCM415 work material. The color at a portion of the beginning of the cut of a chip is dark blue-purple and the color at a portion of the end of the cut is brown in all chips obtained by changing the hardness. When cutting the HB144 work material, the area of the brown portion of the chip is the widest and it becomes narrow in the order of HB131 and HB161. Judging from the chip colors, as proposed by Fujimura [21], it is supposed that the cutting temperature is the highest when cutting the HB161 work material and is the lowest when cutting the HB144 work material. It is assumed that the tool wear increases because of tearing of the coating film and/or the tool substrate when the deposited metal falls from the cutting edge.

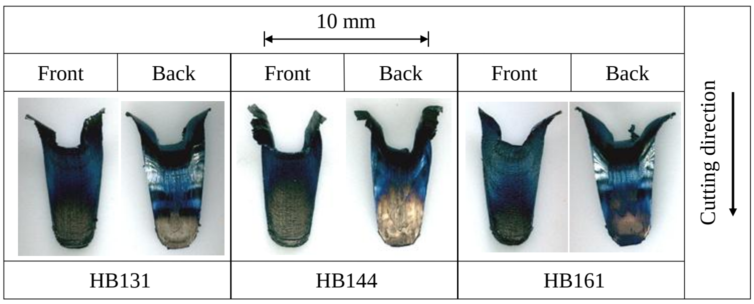

Fig. 8 Colors of the chips (SCM415, M34, MQL, cutting speed: 117 m/min, cutting length of groove: 0.5 m)

In the case of changing the hardness of SCM415, the width of flank wear decreased when cutting the hard HB161 work material under the as-rolled condition. The HB131 work material was made by annealing, which removed the internal stress and the refined crystal grain softened the material. On the other hand, the HB144 work material, which was made by normalizing, had a coarse grain structure that caused smaller directional properties, smaller segregation, finer-grained and more homogeneous structures. These heat treatments were applied to standardize the metal, but it was found that flank wear is small when cutting as-rolled work material.

Fig. 9 compares the conditions of the top cutting edge and the side cutting edge when using the M34 cutting tool with the MQL system (experimental results shown in Fig. 6). It is thought that the flank wear at the top cutting edge and at the side cutting edge obtained by changing the hardness of the work materials shows almost the same wear pattern, which is abrasive wear. The flank wear obtained by dry cutting also shows the same wear pattern as that obtained with MQL. In the case of changing the hardness of the work materials, a difference is found in the displacement of the cutting edge (mechanical abrasion) obtained with MQL and by dry cutting, as shown in Fig. 10. Displacements of both the top cutting edge (Displacement A) and the side cutting edge (Displacement B) are small when cutting the HB161 work material, and their displacements become large in the order of HB131 and HB144; this is the same tendency shown in the case of flank wear. Furthermore, the tendency that the displacement with MQL is smaller than that by dry cutting is also the same as that in the case of flank wear. The displacement of the cutting edge decreases due to the lubrication effect of a small quantity of cutting oil in MQL.

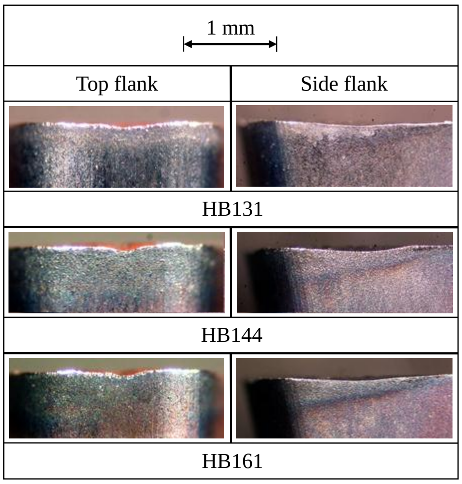

Fig. 9 Conditions of flank wear (SCM415, M34, MQL, cutting speed: 117 m/min, cutting length of groove: 40 m)

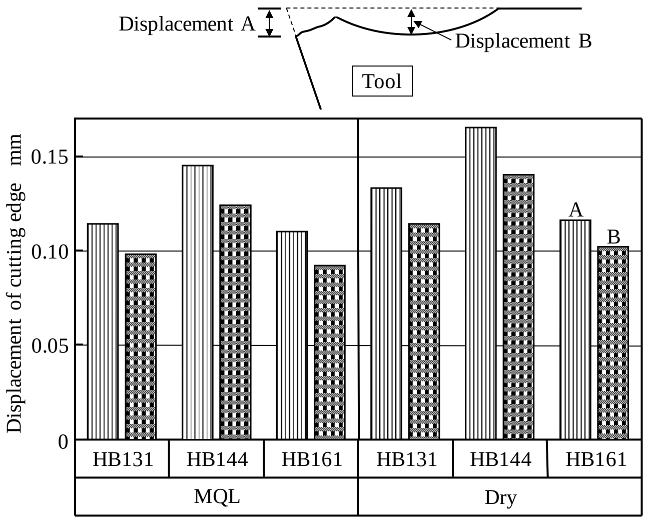

Fig. 10 Comparison of displacement of cutting edge (SCM415, M34, cutting speed: 117 m/min, cutting length of groove: 40 m)

Fig. 11 shows the influence of the hardness of the work material on the width of flank wear obtained with the MQL system and that by dry cutting when using the T15 cutting tool. In both cases of MQL and dry cutting, the width of flank wear when cutting the HB161 work material is small, and the wear becomes large in the order of HB131 and HB144; this is the same tendency as that for the M34 cutting tool (shown in Fig. 6). Moreover, the width of flank wear obtained with MQL is smaller than that by dry cutting. In comparing the two cutting tools, the T15 cutting tool shows a smaller flank wear width than the M34 cutting tool does in both cases of MQL and dry cutting. The reason for the smaller flank wear for the T15 cutting tool is its rich vanadium content (shown in Table 6). One of the authors clarified the decreasing tool wear with increasing vanadium content [22].

As described above, the powdered metal HSS (PM-HSS) of T15 is suitable for SCM415 work material, which is comparatively hard (HB161) as-rolled with the MQL system.

Fig. 12 shows the influence of the hardness of the work materials on flank wear width when cutting SCM435 with the M34 cutting tool. With MQL, the flank wear width is small when cutting soft HB172 work material, but becomes large in the order of HB214 and HB195. Although the same tendency was also obtained by dry cutting, the flank wear width obtained with MQL is smaller at all hardness values. Fig. 13 shows the conditions of maximum flank wear in the cases of MQL and dry cutting when cutting the HB195 work material. This figure shows the large flank wear width plotted in the experimental results shown in Fig. 12. In the case of MQL, some small chippings appearing on the side cutting edge are considered to be due to the delamination and/or seizure of the coating film. In dry cutting, however, the flank wear is considered to be dominated by the welding wear caused by the lack of a lubricating component, or a transfer-type wear [23] caused by seizure of the substrate due to tearing of the deposited metal off the cutting edge. The different wear patterns between MQL and dry cutting were recognized, as mentioned above, when changing the hardness of work materials. Thus, it is suggested that the wear patterns in MQL and dry cutting are clearly different.

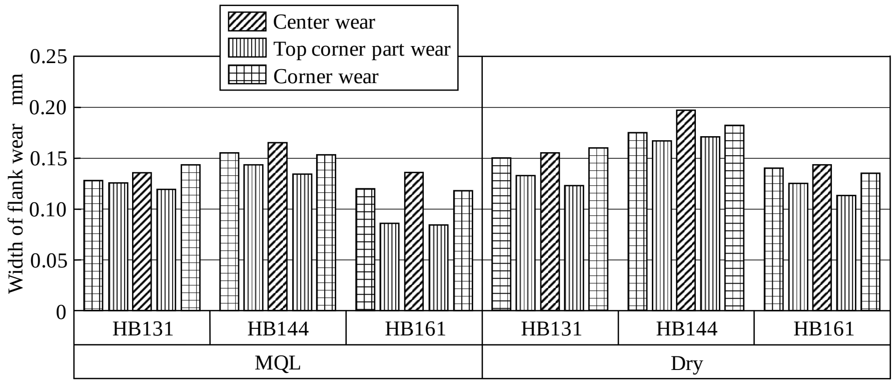

Fig. 11 Influence of hardness of work material on flank wear (SCM415, T15, cutting speed: 117 m/min, cutting length of groove: 40 m)

TABLE 6 CHEMICAL COMPOSITION AND HARDNESS OF HIGH-SPEED STEEL TOOLS

	AISI	Composition %						Rockwell hardness HRC
		C	W	Mo	Cr	V	Co	
HSS	M34	0.9	2.0	8.0	4.0	2.0	8.0	65
PM-HSS	T15	1.5	12.0	0.75	4.0	5.0	5.0	65.5

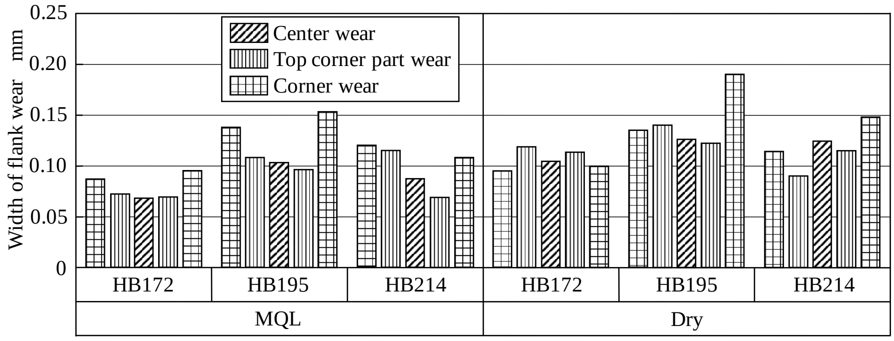

Fig. 12 Influence of hardness of work material on flank wear (SCM435, M34, cutting speed: 86 m/min, cutting length of groove: 8 m)

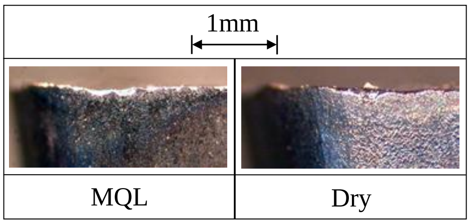

Fig. 13 Conditions of maximum flank wear (SCM435, M34, cutting speed: 86 m/min, cutting length of groove: 8 m)

Fig. 14 shows the influence of the hardness of the work materials on displacement of the cutting edge when cutting the SCM435 work material with the M34 cutting tool. In both cases of MQL and dry cutting, displacements of both the top cutting edge (Displacement A) and the side cutting edge (Displacement B) are small when cutting the HB172 work material, and they become large in the order of HB214 and HB195; this result shows the same tendency as that of flank wear. Furthermore, the smaller displacement of the cutting edge obtained with the MQL system shows the wear reduction effect of MQL.

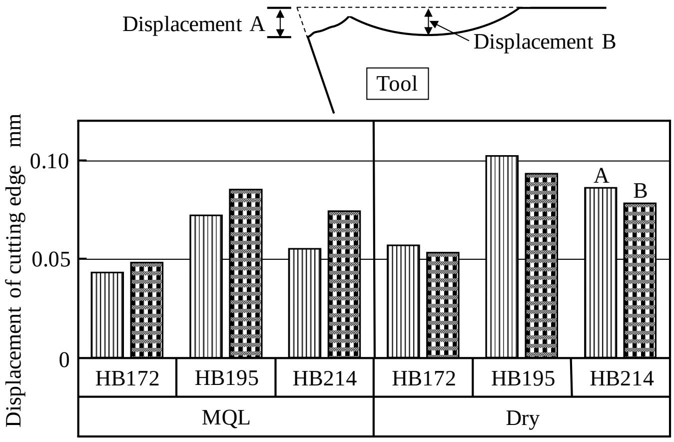

Fig. 14 Comparison of displacement of cutting edge (SCM435, M34, cutting speed: 86 m/min, cutting length of groove: 8 m)

Fig. 15 shows the influence of the hardness of the work materials on the width of flank wear when using the T15 cutting tool. In both MQL and dry cutting, the width of flank wear is small when cutting the HB214 work material and becomes large in the order of HB172 and HB195. In the SCM435 work material, the flank wear obtained with T15 is larger than that obtained with M34 (shown in Fig. 12), and therefore the tendency is different from that in the SCM415 work material. It is assumed that the tool material containing much cobalt increases the hardness at high temperature for hard work materials (see Table 6). When using the T15 tool material, the wear reduction effect of MQL is markedly recognized.

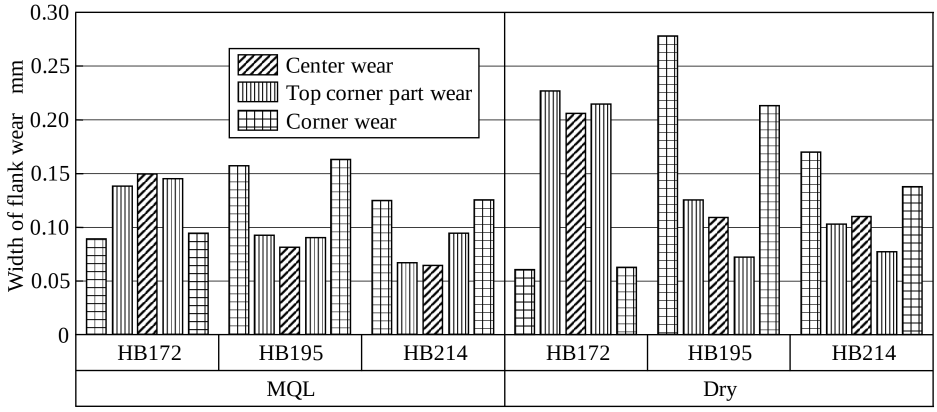

Fig. 15 Influence of hardness of work material on flank wear (SCM435, T15, cutting speed: 86 m/min, cutting length of groove: 8 m)

Fig. 16 shows the conditions of maximum flank wear in the experiment shown in Fig. 15. When cutting the HB172 work material, the flank wear around the center of the top cutting edge is maximum in both cases of MQL and dry cutting. It is considered that the flank wear is dominated by the abrasive wear pattern. On the other hand, when cutting the HB195 and HB214 work materials with MQL, the displacement of the side cutting edge is large and the maximum flank wear occurs in this region and some small chippings appear; this result is considered to be caused by the delamination and/or seizure of the coating film. In dry cutting, although the displacement of the side cutting edge is small, abnormal wear, which is considered to be caused by chipping on the rounded portion due to the lack of lubrication, is confirmed. When cutting the SCM435 work material, it is conceivable that the cutting temperature is high due to cutting the hard work material, and no deposited metal on the cutting edge is recognized, in contrast with cutting the SCM415 work material (shown in Fig. 9).

As mentioned above, M34 is suitable for cutting the SCM435 work material in the MQL system, and the flank wear is much smaller when cutting the annealed HB172 work material, which is comparatively soft.

Because of the different groove lengths when cutting SCM415 and SCM435, Fig. 17 compares the maximum flank wear width for cutting a groove of 1 m. The width of maximum flank wears when cutting SCM435 is several times larger than that when cutting SCM415, in spite of the lower cutting speed for SCM435. Moreover, it seems that the difference in maximum wear width when cutting SCM415 and SCM435 may become large if SCM435 is cut at the same cutting speed of 117 m/min used for SCM415. From the above, although it is thought that the difference in the kinds of work material affects flank wear, it is found that the width of maximum flank wear increases dramatically from HB161 to HB172 when considering the hardness only. On the other hand, the influence of the heat treatment on the tool wear might also be considered, and the width of maximum flank wear is small when cutting as-rolled work material.

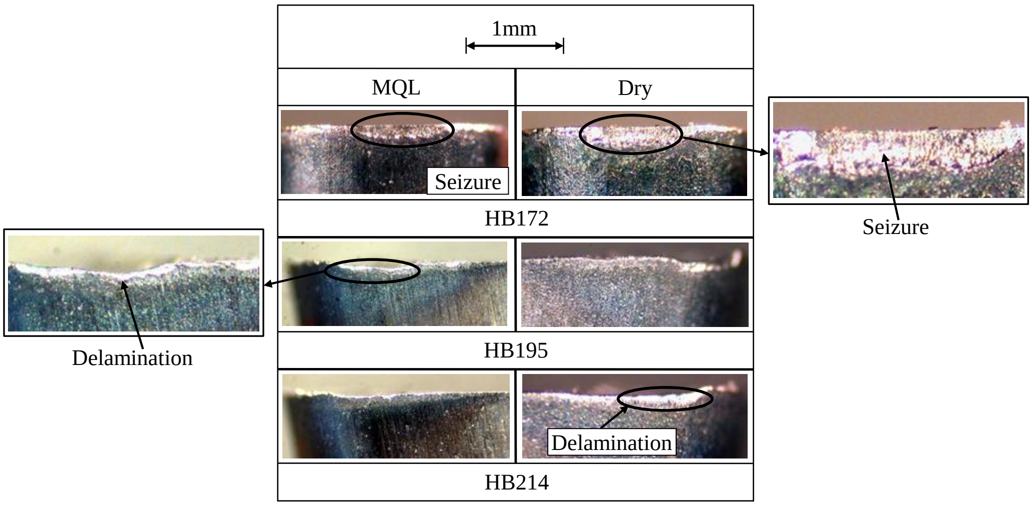

Fig. 16 Conditions of maximum flank wear (SCM435, T15, cutting speed: 86 m/min, cutting length of groove: 8 m)

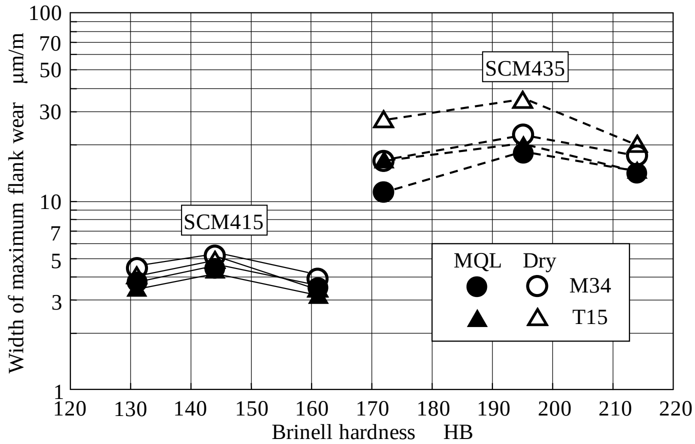

Fig. 17 Comparison of maximum flank wear between SCM415 and SCM435 (cutting speed: 117 m/min for SCM415, cutting speed: 86 m/min for SCM435, cutting length of groove: 1 m)

B. Crater Wear

Fig. 18 shows the influence of work material hardness on the depth of crater wear when cutting SCM415. 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) are given. In the case of MQL using the M34 and the T15 cutting tools, the crater wear obtained with HB131 work material is the smallest, and it becomes large in the order of HB161 and HB144. The crater wear obtained with the T15 tool is smaller than that obtained with the M34 tool. In contrast, in the case of dry cutting when using both cutting tools, the crater wear decreases with increasing hardness of the work material; the crater wear is smallest when cutting the HB161 work material. As compared with MQL and dry cutting, the crater wear obtained with MQL is smaller than that by dry cutting when cutting the HB131 work material. However, the crater wear obtained by dry cutting is smaller than that obtained with MQL when cutting the HB144 and HB161 work materials.

The reason why the crater wear obtained with MQL is smaller than that by dry cutting when cutting the HB131 work material seems to be related to the occurrence of deposited metal. The amount of deposited metal on the rake obtained with MQL is smaller than that obtained by dry cutting at the beginning of cutting, as shown in Fig. 19. It is considered that crater wear is dominated by the welding wear caused by seizure of the substrate due to tearing of the deposited metal off the cutting edge if much deposited metal is present on the cutting edge, although the deposited metal is supposed to increase the crater wear. On the other hand, when cutting HB144 and HB161 work materials, the crater wear obtained by dry cutting is smaller than that obtained with MQL. The probable reason why the crater wear is small in dry cutting is that the deposited metal prevents the progress of crater wear. Namely, the deposited metal has two different effects.

From the above results, the crater wear is small when cutting HB131 work material, which is comparatively soft, and the T15 cutting tool is suitable for cutting SCM415.

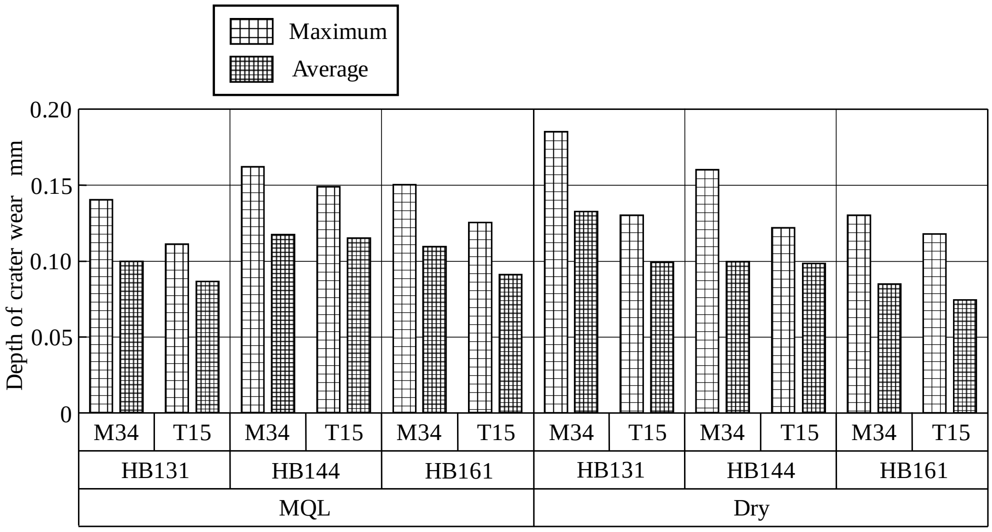

Fig. 18 Influence of hardness of work material on the crater wear (SCM415, cutting speed of 117 m/min, cutting a groove of 40 m)

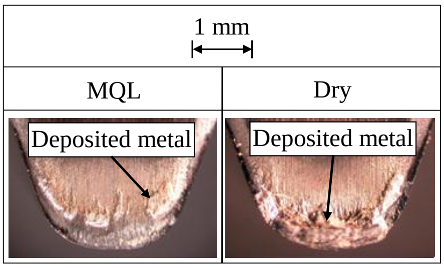

Fig. 19 Comparison of the deposited metal between MQL and dry cutting (SCM415, HB131, M34, cutting speed: 117 m/min cutting length of groove: 0.5 m)

Fig. 20 shows the influence of the hardness of the work material on the depth of crater wear when cutting SCM435. In the comparison of SCM435 and SCM415, the influence of work material hardness on the depth of crater wear is clearly recognized. When using the M34 cutting tool, the crater wear is small when cutting the HB172 work material, and it becomes large in the order of HB214 and HB195 in both MQL and dry cutting. In this case, the crater wear obtained with MQL is smaller than that obtained by dry cutting, even though the hardness of the work material was changed. In contrast, in the case of the T15 cutting tool, the crater wear is small when cutting the HB172 work material, and it becomes large in the order of HB214 and HB195 in both MQL and dry cutting, in the same way as with the M34 cutting tool. In this case, however, the crater wear obtained by dry cutting is smaller than that with MQL; this is a different tendency from that of the M34 tool. The reason is also considered to be the protective effect of the deposited metal.

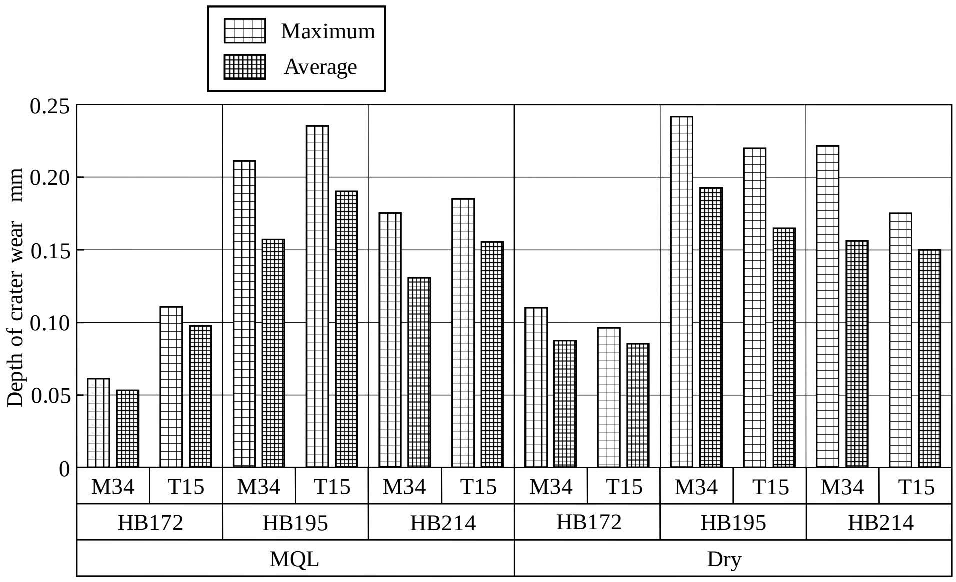

Fig. 20 Influence of hardness of work material on the crater wear (SCM435, cutting speed: 86 m/min, cutting length of groove: 8 m)

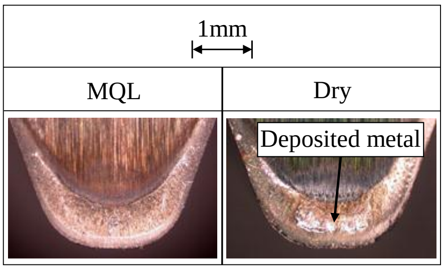

Fig. 21 Comparison of the deposited metal between MQL and dry cutting (SCM435, HB195, T15, cutting speed: 86 m/min cutting length of groove: 0.5 m)

Fig. 21 compares the amount of deposited metal on the rake obtained with MQL and dry cutting at the beginning of cutting. In the case of MQL, the adhesion of the deposited metal can be hardly recognized. In contrast, in the case of dry cutting, the deposited metal is recognized. The deposited metal has two different effects as mentioned above. In this case, it is thought that the protective effect appeared.

From the above, the M34 cutting tool is suitable for SCM435, since the crater wear obtained with MQL is small when changing the hardness of the work material, especially when cutting the relatively soft HB172 material.

Fig. 22 compares the maximum depth of crater wear for a groove of 1 m when cutting SCM415 and SCM435. The crater wear is smaller when cutting SCM415, and the depth of crater wear drastically increases from HB161 to HB172 hardness; this shows the same tendency as the width of flank wear does.

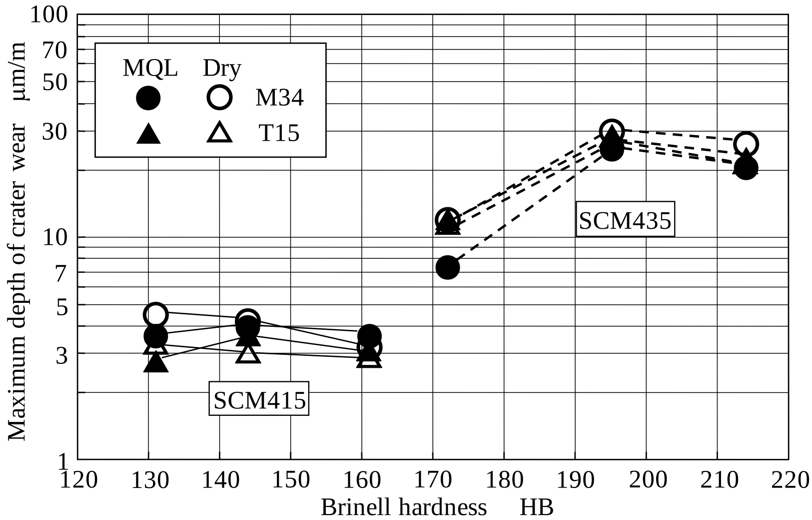

Fig. 22 Comparison of maximum crater wear when cutting SCM415 and SCM435 (cutting length of groove: 1 m)

C. Finished Surface Roughness

Fig. 23 shows the comparison of the finished surface roughness, Rz, at the end of the cut when cutting SCM415 and SCM435. In the case of SCM415, the finished surface roughness is small when cutting HB161 work material, and it becomes large in the order of HB131 and HB144 with MQL when using both the M34 and T15 cutting tools. Furthermore, the finished surface roughness with the M34 tool is smaller than that with the T15 tool. The finished surface roughness obtained by dry cutting shows a similar tendency to that obtained with MQL, but the finished surface roughness obtained with MQL is small for all hardness values.

When cutting SCM435, the finished surface roughness is small when cutting HB214 work material, and it has a tendency to become large in the order of HB172 and HB195. Moreover, the finished surface roughness obtained with the M34 tool is smaller than that with the T15 tool. The finished surface roughness is smaller for MQL than for dry cutting, although both show the same tendency. In the comparison of SCM415 and SCM435, the finished surface roughness is small when cutting SCM415, especially when cutting HB161 work material.

Fig. 24 shows the profiles of the finished surface roughness observed with MQL and dry cutting when using the M34 tool for cutting SCM415 HB161 work material and SCM435 HB214 work material, and when the finished surface roughness is small in each experimental condition, as shown in Fig. 22. When cutting SCM415 with MQL, the revolution mark can be seen at almost the same interval as the feed rate of 0.99 mm/rev, even after cutting a groove of length 40 m; good finished surface roughness is recognized. In the case of dry cutting, though the revolution mark can be observed, the finished surface roughness indicates a rough profile and minor scratch marks are recognized. When cutting SCM435 with MQL, the profile of finished surface roughness is disordered and scratch marks are observed. In the case of dry cutting, the finished surface roughness shows a rough profile without revolution marks, and big scratch marks are recognized. It is supposed that these scratch marks are caused by deposited metal. Especially in the case of dry cutting, much deposited metal on the cutting edge was observed.

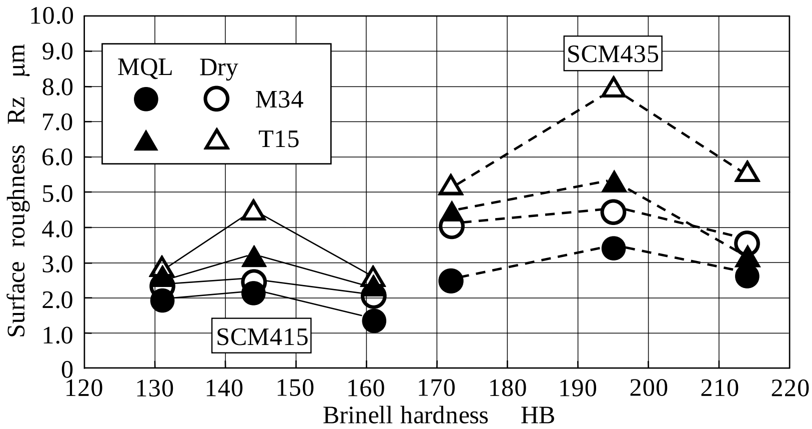

Fig. 23 Comparison of surface roughness when cutting SCM415 and SCM435 (cutting length of groove: 40 m for SCM415, cutting length of groove: 8 m for SCM435)

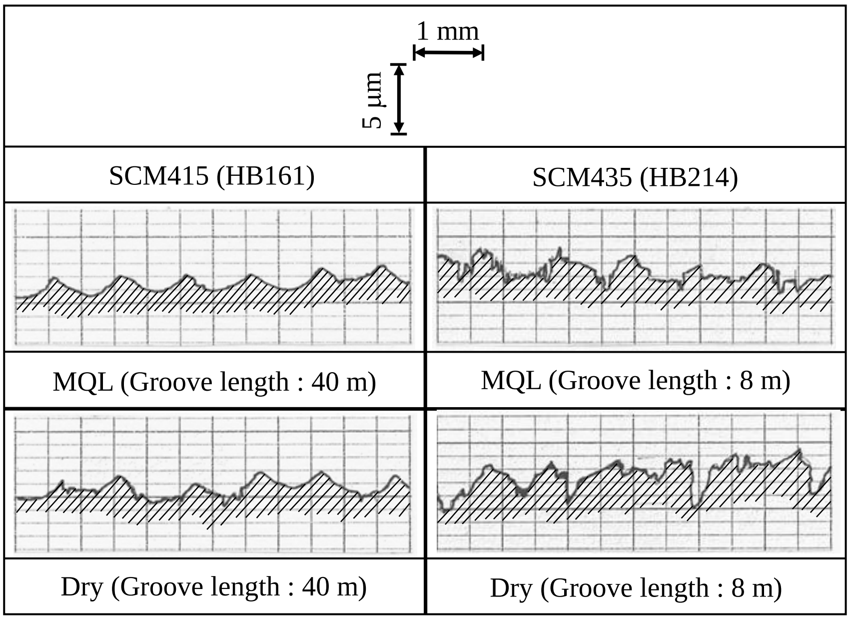

Fig. 24 Profiles of the finished surface (SCM415 cutting speed: 117m/min, SCM435 cutting speed: 86 m/min)

IV. CONCLUSIONS

In this study, experiments using fly tool cutting tests to simulate hobbing were conducted. Changing the hardness and the kinds of work materials and cutting tools was carried out to compare the MQL system and dry cutting. Flank wear, crater wear and finished surface roughness were evaluated. The following points were clarified.

(1) When cutting SCM415 work material with HB131, HB144 and HB161 values of hardness, in the case of MQL, the flank wear is small when cutting the comparatively hard HB161 as-rolled work material, even if the kinds of cutting tools are changed. The T15 cutting tool decreases flank wear more than the M34 tool does. Although the flank wear observed by dry cutting shows the same tendency as that observed with MQL, the flank wear obtained with the MQL system is smaller than that obtained by dry cutting.

(2) The crater wear is small when using both the M34 and T15 cutting tools to cut HB131 work material, and the crater wear obtained with the T15 tool is smaller than that obtained with the M34 tool. Moreover, in the comparison of the MQL system and dry cutting, the MQL system decreases the crater wear more. When changing the work material hardness, the finished surface roughness observed with the MQL system is also smaller than that observed with dry cutting, and especially the finished surface roughness is small when cutting HB161 work material.

(3) In the case of changing the SCM435 work material SCM435 to HB172, HB195 and HB214 hardness values, the flank wear, the crater wear, and the finished surface roughness are small when cutting annealed HB172 work material, which is comparatively soft, even if the kinds of cutting tools are changed. The M34 cutting tool is suitable for cutting SCM435, which is different from cutting SCM415. The wear reduction effect and the finished surface roughness improvement with MQL as compared with dry cutting are recognized.

(4) Although there was a difference in the kinds of work materials, the flank wear and the crater wear show an exponential increase between cutting SCM415 HB161 work material and cutting SCM435 HB172 work material. Cutting SCM415 is easier than cutting SCM435.

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