Wear Reduction Effects of Ca Sulfonate on Coated Tools in Hobbing*

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This paper presents the influence of Ca sulfonate on tool life (flank wear), crater wear and finished surface roughness in hobbing. Experiments were carried out using two kinds of fully coated fly tools with TiN and (Al, Ti)N films respectively. As the results, when using the TiN fully coated tool, Ca sulfonate prolongs the tool life, and decreases the crater wear compared with the machine oil 23 as a base oil. With the (Al, Ti)N fully coated tool, an interesting result was obtained that the base oil containing no additives gives a longer tool life and a smaller crater wear than those obtained with Ca sulfonates added. It was suggested that the increase in the flank wear and the crater wear is caused by the chemical and/or the corrosive actions of Ca sulfonate, when Ca sulfonate was used for the (Al, Ti)N coated tool. Ca sulfonates improve the finished surface roughness for both coated tools.

Key Words: Cutting, Gear, Cutting Fluid, Tool Life, Hobbing, Fly Tool, Fully Coated Tool, Crater Wear, EP Additive, Ca Sulfonate, Finished Surface Roughness

1. Introduction

In cutting oils for hobbing, chlorine components as extreme pressure (EP) additives are usually used to improve tool wear⁽¹⁾. Chlorine compounds, however, change into deleterious materials such as dioxin and hydrochloric acid when waste cutting oils containing them are destroyed by fire. Worldwide attention is especially focused on the dioxin because of its environmental pollution for human beings. Since chlorine components were, moreover, excluded in JIS K 2241 concerning the cutting fluids, it is said that the use of chlorine-free additives will be henceforth accelerated⁽²⁾. Therefore, the development of new additives in cutting oils, which do not damage to the environment, is strongly demanded.

Overbased sulfonate is considered as one of EP additives which are effective in preventing the envi-

ronmental pollution and improving the safety of operators. It has been reported that overbased sulfonates showed the good EP performance in tapping and pipe threading efficiencies, in terms of reducing tapping torque and improving finished surface roughness^{(3),(4)}. Another report has been given on the reduction of friction coefficient by the synergism of an active polysulfide and a calcium (Ca) sulfonate in turning⁽⁵⁾. Concerning the effect of sulfonate on the tool wear, however, there has been virtually no work.

The authors tried to apply some Ca sulfonates to cutting oils for hobbing using two kinds of coated tools⁽⁶⁾, and found that: (1) Ca sulfonate improved the tool life of (Al, Ti)N coated tool rather than that of TiN coated tool at the concentration of Ca sulfonate from 10 to 15%. (2) The crater wear tends to increase with increase in the concentration of Ca sulfonate. (3) The finished surface roughness has a tendency to decrease with increase in the concentration of Ca sulfonate. The surface roughness becomes small in the high concentration area of Ca sulfonate, when the TiN coated tool was used. With the (Al, Ti)N coated tool, it is small irrespective of the change in the concentration of Ca sulfonate.

Generally, there are many cases in which a hob is

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used in the condition without coating on the face because of regrinding. Recently, however, a hobbing with a fully re-coated hob increases due to the improvement of the re-coating technology, the lowering of coating cost and the shortening in the delivery date. There is a case that the hobbing with the fully coated hob is performed⁽⁷⁾, so it is expected that the hobbing using the fully re-coated hob will be increased in the future. In this study, the evaluation was carried out on the effect of Ca sulfonate, in terms of the tool life (flank wear), the crater wear and the finished surface roughness, when the two kinds of fully coated tools were used in hobbing.

2. Experimental Method and Its Condition

The tests were carried out by replacing the hobbing with fly tool cutting on the milling machine. The authors have recognized that the results obtained with the fundamental tests using a fly tool agree with those obtained with hobbing tests^{(8),(9)}. Table 1 shows the dimensions of the gear and the hob. Experimental conditions are given in Table 2. The cutting tests were conducted with fully coated fly tools, which are made of high speed steel, corresponding to SKH55, coated with TiN and (Al, Ti)N films by the arc ion plating method [TiN fully coated tool and (Al, Ti)N fully coated tool in brief]. Thickness of both coating films is about 5 μm . The work material is chromium molybdenum steel SCM415 (HB143), which has the dimensions of 500 mm length, 100 mm width and 100 mm thickness. The cutting speed is 159 m/min.

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	$\phi 118 \times 125 \times \phi 40$
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 The same conditions as in hobbing in fly 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	
Thickness of maximum chip	0.27 mm	Total number of revolutions (The sum of the approach distance and face width)	315
		Length of groove to be cut	0.31 m

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

Figure 1 shows a failure which took place at the tip of tool. The center wear and top corner part wear of top cutting edge, and the corner wear which occurred at the boundary region between the roundish portion of the top cutting edge and the side cutting edge, as well as the crater wear on the face were measured with a microscope. The tool life was estimated by the cutting groove length, when the maximum wear among the center wear, the top corner part wear and the corner wear reached 0.15 mm. The depth of crater wear was measured at intervals of 0.1 mm in parallel to the axis as shown in Fig. 2. The depth of crater wear per 1 m obtained with dividing the crater depth by the cutting groove length was evaluated. The crater wear and the finished surface roughness on the bottom of the cutting groove, R_y were measured with the surface measuring instrument. The milling machine used in the tests is 2MF Model (Universal type) manufactured by Hitachi Seiki Co., Ltd.

The base oil used in the tests is a paraffinic machine oil ISO VG 23. As additives, two kinds of Ca sulfonates were used, which have different total base numbers as shown in Table 3. The concentration of each additive is 15% (by weight) at which the tool life was longest in authors' previous report⁽⁶⁾. The temperature of the cutting oil was retained at about 30°C.

Fig. 1 Wear at cutting edge

Fig. 2 Measuring position of crater wear

Table 3 Properties of Ca sulfonates

Item \ Ca sulfonate	A	B
Specific gravity (15°C, g/cm ³)	1.13	1.29
Flash point (°C, COC)	193	210
Total base number (mgKOH/g)	305	495
Calcium content (wt%)	11.8	18.7
Sulfonate content (wt%)	29	20

Fig. 3 Influence of Ca sulfonate on tool life of coated tool (tool life criterion: maximum flank wear 0.15 mm)

Though the viscosity of the test oil shows a small change when the additive was added, the viscosity control was not performed. The cutting oil was applied from the face side at a constant flow rate of 2.4 l/min.

3. Experimental Results and Discussions

3.1 Flank wear (tool life)

Figure 3 shows the effects of Ca sulfonates on the tool life. The test results obtained with the fly tools without coatings on the face are also shown for the purpose of comparison. In the case of the TiN coated tool, the tool lives with both Ca sulfonates A and B are longer than that with machine oil 23 (M23, additive-free oil) as a base oil. There is a small difference in performance between Ca sulfonates A and B. The longest tool life was obtained in the case that the cutting oil containing Ca sulfonate was used for the fully coated tools. When Ca sulfonates were added, the tool life became 5 times or 6 times as long as the additive-free oil for the tool without TiN coating on the face, and it was recognized about 2.5 times longer tool life for the TiN fully coated tool.

With the (Al, Ti)N coated tool, on the other hand, there was considerably seen the difference

between the tool without coating on the face and the fully coated tool. When using the former tool, both Ca sulfonates improve the tool life in comparison with the additive-free oil, whose effect is remarkable in Ca sulfonate B. This is assumed to be closely connected with total base number (TBN), thus, Ca sulfonate having high TBN decreases the tool wear, which could be interpreted as evidence supporting of the finding of Cahoon et al.⁽⁴⁾ for the high tapping efficiency obtained with Ca sulfonate having high TBN. It is characteristic, however, that the tool life unexpectedly becomes shorter by adding Ca sulfonate than that obtained with the additive-free oil, and Ca sulfonate B, which was effective for the tool without coating on the face, shows a shorter tool life than Ca sulfonate A, when using the latter tool.

The tool lives with the fully coated tool are much longer than those with the tool without coating on the face, on the whole, therefore, it is thought that the coating film on the face would probably contribute to the prevention of the flank wear.

According to Hong et al.^{(3),(4)}, when an overbased Ca sulfonate is used as an EP additive in metal-working fluid in a tapping test with stainless steel 304 specimens, there is found a morphological structure of a surface layer, by means of XPS and AES analysis, which is composed of CaCO₃ formed in the upper part of the layer. They primarily ascribed the improved tapping efficiencies to the reactivity of the sulfonate to ferrous oxides formed on the surface of the specimen, which suggests the effects of Ca sulfonate; however, as to how the calcium carbonate CaCO₃ takes part in reducing the tool wear, they have given no clear explanation.

Giasson et al.⁽¹⁰⁾ also have reported that sulfonic acid forms a chemical adsorption film on the friction surface, which contributes to the lubrication, at the same time calcium carbonate produces a calcite.

Moreover, the authors have recognized the presence of calcium on the worn surface of both TiN and (Al, Ti)N coated tools^{(6),(11)}. Accordingly, the wear reduction effect of Ca sulfonate with the TiN coated tool and the tool without (Al, Ti)N coating on the face is probably attributable to the calcium carbonate.

The tool life with Ca sulfonates becomes shorter than that with the additive-free oil, when using the (Al, Ti)N fully coated tool alone, as shown in Fig. 3. The reason is seemed to be because the corrosive action (chemical action) is easily promoted by the reaction between Ca sulfonate and (Al, Ti)N coating, and especially, it may occur with Ca sulfonate B having high TBN. Therefore, in these cases, the disadvantage of a corrosive action would have outweighed to the advantage of a wear reduction

Table 4 Characteristics of coated films

Coated films	Vickers hardness HV	Oxidation temperature °C
TiN	1800~2000	600~700
(Al,Ti)N	2700~2900	800~900

Fig. 4 Progress curve of maximum flank wear (TiN fully coated tool)

effect of Ca sulfonate.

The tool lives obtained with the (Al, Ti)N coated tool are longer than those obtained with the TiN coated tool. This reason is thought that (Al, Ti)N coating film has higher hardness and more excellent anti-oxidation compared with TiN coating film as shown in Table 4.

Figure 4 shows the progress curves of the maximum flank wear of TiN fully coated tool. With the additive-free oil, the flank wear increases linearly and rapidly till the cutting groove length of 5 m. The flank wear obtained with Ca sulfonate show almost as same as that obtained with the additive-free oil till the groove length of 2 m, but after that, it is smaller than that obtained with the additive-free oil and shows linearly a gradual increase. The difference in the flank wear between Ca sulfonates A and B is small.

The progress curves of the maximum flank wear of (Al, Ti)N fully coated tool are given in Fig. 5. In the case of additive-free oil, about 50% of the tool life criterion of 0.15 mm occurs until the cutting groove of 2 m in length, and it increases gradually till the length of groove 70 m, but after that, it showed a rapid increase till the end of cutting. When adding Ca sulfonate A, nearly 75% of the wear width of 0.15 mm takes place until the cutting length of 2 m, and the flank wear shows the same value with the additive-free oil till the length of 25 m. After that, however, it becomes bigger than that with the additive-free oil. With Ca sulfonate B, though the flank wear shows the smallest value among the cutting fluids till the cutting

Fig. 5 Progress curve of maximum flank wear [(Al, Ti)N fully coated tool]

groove length of 30 m, but after that, it increased rapidly.

Next, the difference in flank wear patterns between the TiN and the (Al, Ti)N fully coated tools was investigated. Figures 6 and 7 show the photographs of the center and corner wear of TiN and (Al, Ti)N fully coated tools respectively. In Fig. 6, when the additive-free oil was used, although no adhesion of deposited metal was recognized on the cutting edges at the beginning of cutting, much deposited metal are seen on both top cutting edge (Center) and side cutting edge (Corner) after a short cutting groove length of 5 m, resulting the large center wear. Thus, there seems to be the high possibility that the large center wear occurred due to the seizure of coating film and substrate on the top flank caused by the adhesion of deposited metal, and/or due to the cutting off the coating and substrate by the particles of the deposited metal.

When Ca sulfonate A or B was added, both additives produce the similar wear patterns without the adhesion of deposited metal, in which the locally large wear, which are thought to be caused by the chipping, are seen, but they show almost the uniform wear in parallel to the cutting edge.

In the case of (Al, Ti)N fully coated tool shown in Fig. 7, the additive-free oil gives rise to almost the uniform tool wear pattern without the adhesion of deposited metal which was seen with the TiN coated tool, not only on the top flank, but also on the side flank, in spite of a long cutting groove length of 75 m. With Ca sulfonate A, although almost the uniform wear pattern is recognized, in which some small chippings occur on the top flank. With Ca sulfonate B, the width of displacement of the top flank cutting edge shows about 0.1 mm, which decides the tool life. On the side flank, however, the wear is small and almost the uniform wear is seen.

This wear pattern obtained with Ca sulfonate B, in which the width of decreasing of the top flank

Fig. 6 Comparison of flank wear (TiN fully coated tool)

cutting edge is large, appears in the case of Ca sulfonate having high TBN. It may be caused by excess reaction films formed on the friction surface, i.e., more reaction films thereon than those required for lubrication, due to the excessive quantity of basic component.

Moreover, in the previous paper⁽¹²⁾, the authors reported that the same phenomenon on the top flank occurred when the sulfurous EP additive was used, which suggests the possibility of the corrosive wear.

3.2 Crater wear

It is thought that the difference in lubricating effect of Ca sulfonate on the face would greatly appear in comparison with that on the flank, according to the existence of coating film, due to the direct contact between the face and the cutting chips. In addition, it has been reported that the corner wear on the flank is caused by a collapse of the edge of the crater wear⁽¹³⁾, thus, the crater wear is also an important factor.

The crater wear reduction effects of Ca sulfonates are shown in Fig. 8. In the case of TiN fully coated tool, the crater wear decreased by adding Ca sulfonate, and the crater wear with Ca sulfonate A is smaller than that with Ca sulfonate B. Meanwhile, though the absolute value of the crater wear when using the (Al, Ti)N fully coated tool is smaller than that when using the TiN fully coated tool, on the whole, in the case of (Al, Ti)N fully coated tool, the

Fig. 7 Comparison of flank wear [(Al, Ti)N fully coated tool]

Fig. 8 Influence of Ca sulfonate on crater wear of coated tool (depth of crater wear per a cutting groove length of 1 m)

crater wear increases by adding both Ca sulfonates.

Here, we will discuss the difference in crater wear generation mechanism caused by the difference in coating materials and kinds of Ca sulfonates:

Figure 9 shows a change with passage of time in the conditions of the face, when using the TiN coated tool. With the additive-free oil, the contact area with the cutting chips (it becomes the crater wear afterward) after cutting a groove of 0.5 m in length, where slightly discolored due to the heat of friction generat-

Fig. 9 Conditions of the face (TiN fully coated tool)

ed by the contact with the cutting chips, can be observed, and the grinding traces of the substrate are also recognized on the contact area. At a groove of 2 m long, there can be seen the adhesion of deposited metal near the side cutting edge and the roundish portion. It is supposed that the deposited metal would attach not on the coating film but on the substrate which appeared after the delamination and/or the seizure of the coating film occurred, because the deposited metal is difficult to adhere on the coating film, which shows a small coefficient of friction and has a deposition-resisting⁽¹⁴⁾. Moreover, the attached region of deposited metal is expanded at a groove cut of 5 m in length.

When it was tried to examine the surface of crater wear when using the additive-free oil with surface texture measuring instrument, though the maximum height of deposited metal near the cutting edge was about 20 μm after a 2 m length cut, it reached 150 μm in the maximum value after a cutting groove length of 5 m, but at the area where the deposited metal did not attach, the crater wear was conversely 150 μm in the maximum depth. There were remarkable deposited metal in the area of friction, and the smooth surface can be hardly recognized, as shown in Fig. 9. Thus, it is guessed that the crater wear may mainly occur because of the seizure of the substrate.

When using Ca sulfonate A, the contact surface with the cutting chips has appeared clearly after a cutting groove of 0.5 m in length, and there is slightly the delamination and/or the seizure of the coating film at the tip of cutting edge. After a 2 m length cut, the large seizure of coating film occurs on both sides of the contact surface, where the substrate can be seen, that is, the crater wear appears. The adhesion of

deposited metal is hardly recognized on the face. After a groove cut of 5 m in length, the region of the crater wear expands, in which the scratch marks of the substrate caused by the cutting chips can be also recognized. Moreover, the chipping takes place at the cutting edge. At the end of cutting of 10 m groove length, the region of the crater wear, in which the scratch marks by the cutting chips can be clearly also seen, extends more.

In the case of Ca sulfonate B shown in Fig. 9, the delamination and/or the seizure of coating film has already appeared on the right and left sides of the contact surface, in spite of a short cutting groove length of 0.5 m, and also the substrate has partially been seen. Even after a 2 m length cut, the crater wear appears rapidly in comparison with the case of Ca sulfonate A, and furthermore, it occurs in almost the whole area of the contact surface. After cutting groove lengths of 5 m and 10 m, a rapid expansion of the crater wear region can be recognized, and also the scratch marks of the substrate can be also seen.

Figure 10 shows a change with passage of time in the face conditions, when using the additive-free oil with the (Al, Ti)N fully coated tool. A slight discolor of contact surface can be seen after cutting a groove length of 0.5 m. Although the delamination and/or the seizure of coating film on both sides of contact surface began to occur after a groove length of 40 m cut, they could not be recognized only at the cutting edge until the groove length. By comparing the TiN coated tool, it was proven that the occurrence of the delamination and/or the seizure of (Al, Ti)N coating film on the face is considerably late. From the cutting groove length of 60 m to 75 m, moreover, its area on both sides of contact surface expands.

Fig. 10 Conditions of the face [machine oil 23, (Al, Ti)N fully coated tool]

Fig. 12 Conditions of the face [Ca sulfonate B, (Al, Ti)N fully coated tool]

Fig. 11 Conditions of the face [Ca sulfonate A, (Al, Ti)N fully coated tool]

The conditions of (Al, Ti)N fully coated face in the case of Ca sulfonate A are shown in Fig. 11. After cutting a groove length of 0.5 m, the delamination and/or the seizure of the coating film began to occur near the tip of the cutting edge at first, whose tendency is the same as that of TiN coated face. After a cutting groove of 25 m in length, not only the delamination and/or the seizure of the coating film near the cutting edge expands, but also a crater wear takes place at the right side of the contact surface. After cutting groove lengths of 40 m and 50 m, the region of the crater wear becomes large, at which the scratch marks caused by the cutting chips can be clearly recognized at the tip of cutting edge.

(a) Delamination of (Al, Ti)N coating film

(b) Profile of the maximum delamination

Fig. 13 Conditions of the face [Ca sulfonate A, (Al, Ti)N fully coated tool, after cutting length of groove 0.5 m]

The face conditions of (Al, Ti)N fully coated tool obtained with Ca sulfonate B are given in Fig. 12. Although the progress condition of crater wear is similar to the case of Ca sulfonate A, almost the same crater wear pattern appears earlier with Ca sulfonate B than with Ca sulfonate A, for example, after a 35.5 m groove length cut for Ca sulfonate B and after a 50 m groove length cut for Ca sulfonate A.

Figure 13(a) shows an expanded photograph of the (Al, Ti)N coated face with Ca sulfonate A after

cutting a groove length of 0.5 m. The grinding traces of the substrate can be seen and no deposited metal is recognized, as well as the unclear contour of the delamination can be observed from the photograph, which seems to be not caused by the falling off of the deposited metal, but caused by the corrosion. According to the assumption of Kimura and Okabe⁽¹⁵⁾, and Hida⁽¹⁶⁾, the concept of the corrosive wear is as follows; an oxide and/or an sulfide are formed on the friction surface by the reaction of oxygen and/or additives, whose films are brittle compared with the substrate, and after their thickness of films exceed the critical value, the products exfoliate easily. The process of this repetitive phenomenon is called the corrosive wear mechanism.

Figure 13(b) shows the profile of the maximum depth of delamination, which was measured on the face perpendicular to the cutting edge. It is assumed that its maximum depth does not reach to the thickness of (Al, Ti)N coating film, in other words, the delamination occurs within the only surface of the coating and the substrate may not appear. A projection at the tip of cutting edge is a mass of the coating film, which was recognized before cutting, and it has been produced physically along the cutting edge when it was coated.

Generally, the (Al, Ti)N coating film is said to be superior in heat-resisting property, wear-resistance and anti-oxidation^{(17),(18)}. And also, it has been reported that when the cutting was performed, the aluminum in the TiAlN reacts with the oxygen to create a microthin layer (about 1 μm in thickness) of Al_2O_3 on the coating film surface, whose oxidation does not occur inside of the coating film, so that the adhesion of coating with the substrate can be maintained, which may increase the strength of the coating^{(7),(19)}.

It is thought that the contact pressure, in the interface of the rake face and the cutting chips, is so higher that the cutting temperature rises compared with those on the flank. Therefore, it is expected that the action of Ca sulfonate on the rake face is remarkably different from that on the flank.

The decrease in the tool life caused by adding Ca sulfonate, as mentioned above, appears when using the (Al, Ti)N fully coated tool alone, but it does not take place in the case of TiN fully coated tool. In the previous paper⁽²⁰⁾, the authors reported that the delamination of the (Al, Ti)N coating film on the rake face hardly occurs in dry cutting. According to Narutaki et al.⁽²¹⁾, moreover, the tool lives of ceramic (Al_2O_3) tools in turning of Ca-Si deoxidized steel (S55C) are shorter than those of normal carbon steel. As the reason for these results, it has been emphasized out that since non-metallic inclusions in work mate-

rials such as CaO , SiO_2 and so on adhere to the tool surface filmily, they react with ceramic tool, and Ca or Si invades into ceramic tool by diffusion, which softens the tool matrix, resulting poor anti-wear property of tools. And they also clarified that the reaction of Ca is more predominant than Si, and the distance of Ca invasion to the tool is larger than that of Si.

Although the experimental conditions employed in that paper are different from those in this paper, it is considered that this discussion can explain the result obtained in this paper, in the point of clarification of the tool wear mechanism under the presence of Ca and Al.

From the above facts, it may safely be estimated that Ca sulfonate has some adverse effect on the (Al, Ti)N coating film, especially on Al, but we will discuss the details in future studies.

In the crater wear mechanism on the face of two kinds of fully coated tools used for the experiments, the topographies in which the crater wear develops from the delamination and/or the seizure of the coating film are mainly observed, at the right and left sides of the contact surface with the cutting chips. This phenomenon was recognized with almost the cutting oils used in the tests.

Here, the reason for their occurrence of the crater wear at the both sides of the contact surface, in other words, near the boundary between the nose roundish portion and the side cutting edge, may be assumed as follows. A hob tooth has three cutting edges, and the cutting chip, which was separated by these cutting edges, flows in one on the face, on which the interference of the cutting chip^{(22),(23)} is considered to occur. It is, therefore, supposed that the places especially becomes high temperature and high pressure.

3.3 Finished surface roughness R_y

Figure 14 shows the progress curves of the surface roughness, R_y , obtained with the additive-free oil and Ca sulfonates when the TiN fully coated tool was used. With the additive-free oil, although the surface roughness is about 1.8 μm after cutting a groove

Fig. 14 Progress curve of finished surface roughness (TiN fully coated tool)

Fig. 15 Progress curve of finished surface roughness [(Al, Ti)N fully coated tool]

length of 0.5 m, it showed a big value of $18.5\text{ }\mu\text{m}$ after a groove length of 5 m, at which the maximum flank wear reached the tool life criterion of 0.15 mm. This is assumed that the adhesion of deposited metal may influence on the surface roughness, as seen from in Fig. 6. In the case of both Ca sulfonates A and B, on the other hand, the surface roughness obtained with both sulfonates is almost the same as that obtained with the additive-free oil at the beginning of cutting, but after that, it decreases gradually till a cutting groove length of 10 m, and it becomes smaller than the theoretical roughness ($1.44\text{ }\mu\text{m}$) at the 5 m groove length and more.

When using the (Al, Ti)N coated tool given in Fig. 15, the additive-free oil is keeping the surface roughness about $2\text{ }\mu\text{m}$ from the beginning of cutting to the end of cutting of 80 m groove lengths. The surface roughness is thought to be related to the center wear of top cutting edge, because of no occurrence of deposited metal on the cutting edge. However, the surface roughness may be independent of the center wear, since it does not change, in spite of about 0.1 mm center wear width at the groove length of 80 m. In the case of Ca sulfonates A or B added, the surface roughness showed nearly the same value as that with the additive-free oil till the cutting groove length of 25 m, but after that, it was slightly smaller than that with the additive-free oil.

Figure 16 shows the profiles of finished surface when the flank wear reached 0.15 mm. In the case of additive-free oil with the TiN fully coated tool, the machined surface has considerably been disturbed, and the revolution marks cannot be recognized either. When Ca sulfonate was added, the depressed profiles of surface roughness without the revolution marks are seen, though its value consists with about $1\text{ }\mu\text{m}$. There is scarcely a difference in the surface roughness profile between Ca sulfonates A and B.

When using the additive-free oil with the (Al, Ti)N fully coated tool, there are some disorders of the

Fig. 16 Profiles of finished surface (when maximum flank wear reached 0.15 mm)

surface roughness. However, the revolution marks can be almost recognized in the same interval as the feed rate (0.99 mm/rev). With Ca sulfonates added, the clear revolution marks were recognized, therefore, the stabilized beautiful surface was obtained. The reason is that the wear of cutting edge of the (Al, Ti)N fully coated tool was small, so that the revolution marks could be produced enough, in comparison with the TiN fully coated tool.

4. Conclusions

Fly tool cutting tests, to which the hobbing was simulated, were performed by using TiN and (Al, Ti)N fully coated tools at a cutting speed of 159 m/min, in order to determine the influence of Ca sulfonate on the tool life (flank wear), the crater wear and the finished surface roughness. As a consequence, the following points have been clarified:

(1) With the TiN coated tool, the flank wear reduction effects of Ca sulfonates were recognized, and the tool life prolongs compared with the case of the additive-free oil. With the (Al, Ti)N coated tool, it is an interesting result that the tool life obtained with the additive-free oil is longer than that of Ca sulfonates added.

(2) Ca sulfonates make the crater wear smaller than the additive-free oil when using the TiN coated tool. In the case of (Al, Ti)N coated tool, it is

characteristic that the crater wear becomes large by adding Ca sulfonate.

(3) It was suggested that the increase in the flank wear and crater wear of the (Al, Ti)N coated tool, when Ca sulfonates added, is caused by the chemical and/or corrosive actions of Ca sulfonates.

(4) The surface roughness improvement effect of Ca sulfonates could be recognized for both coated tools.

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