Performance of Skiving Hobs in Finishing Induction Hardened and Carburized Gears

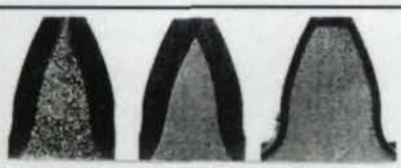
Takeji Sugimoto, Akira Ishibashi, and Masataka Yonekura

In order to increase the load carrying capacity of hardened gears, the distortion of gear teeth caused by quenching must be removed by precision cutting (skiving) and/or grinding. In the case of large gears with large modules, skiving by a carbide hob is more economical than grinding when the highest accuracy is not required.

In the present investigation, carbide hobs with and without coated TiN layers were used for finishing hardened gears made from carbon and alloy steels. The gears to be skived were hardened by two different methods: induction hardening and carburizing. The induction hardened gears with a hardness of about 600 Hv can be finished easily by a carbide skiving hob without coating. However, the carburized gears with a hardness of about 750 Hv were very difficult to finish due to the severe flank wear and/or chipping at the cutting edges when a carbide hob without coating was used. However, when a carbide skiving hob with coated TiN layer on both the rake face and the flank was used, the tool life increased by a factor of about 10. Even with the skiving hob with the coated layer on the flank only, the tool life increased by a factor of about 7.

It was found that the tool lives of carbide hobs used for finishing hardened gears were governed by the flank wear and/or chipping which occurred on the fixed side (trailing side) of the cutting edges with a tool angle smaller than that of the other side (leading side). Therefore, in order to increase the lives of skiving hobs, it is strongly suggested to produce the coated skiving hobs with helical gashes, which give the same tool angle on both sides of the cutting edges.

Figure 1—Carbide hobs used for cutting tests.



(a) S45C (b) SCM440 (c) SCM415

Figure 2—Transverse section of hardened teeth.

Table 1—Specifications of conventional and skiving hobs used in the experiments.							
Kind of hobs	Hob (A)	Hob (B)	Hob (C)	Hob (D)	Hob (E)	Hob (F)	Hob (G)
Module	8	8	8	8	8	8	8
Pressure angle	20°	20°	20°	20°	20°	20°	20°
Outside diameter (mm)	120	150	120	120	150	150	150
No. of gashes	9	10	10	10	12	12	12
Inclination of cutting edge	0°	0°	30°	30°	30°	30°	30°
Hob material	SKH55	P20	K10	M10	P20	P30	P30
Coating	TiN	none	none	none	none	TiN	TiN

Introduction

In order to increase the load carrying capacity of gear transmissions, it is desirable to use hardened gears. The quenching in the hardening process of the gears brings about heat treatment distortions, resulting in a reduction in the accuracy of the gears. To effectively utilize the gears, we must improve their accuracy after hardening, by using additional finishing operations such as skiving and/or grinding, honing, etc.

The highest accuracy can be obtained when the hardened gears are finished by grinding. One of the authors designed a gear grinding machine capable of making super precision gears with a mirror-like tooth surface using a CBN grinding wheel (Refs. 1–3). However, when the sizes of the gears are large, a long period of time is required to finish the gears by grinding. It is economical to finish the hardened gears by cutting using a carbide hob when the highest accuracy is not required.

Carbide hobs with special geometry (carbide skiving hobs) are very effective for accurately finishing hardened gears (Ref. 4). The lives of gear cutting tools can be increased by coating them with a thin, hard material (Refs. 5–7). The coating technique for the solid-type gear cutting tools made from high speed steel and carbide has progressed remarkably. Coated carbide hobs of the solid type and with a conventional geometry were effectively used for finishing low hardness gears with a small module (Ref. 8). However, it was very difficult to make the solid-type carbide hob economically when the modules of the work gears were large.

Brazed-type carbide skiving hobs without coating have been used for finishing hardened gears with large modules. However, a coated carbide hob with a sufficiently high accuracy for finishing hardened gears with large modules was not found in the market recently. The progress in both coating and brazing techniques makes it possible to produce high accuracy brazed carbide hobs with coating.

Recently, the authors have been able to obtain a coated skiving hob and conducted the cutting tests with some interesting results. The new, unpublished results obtained using non-coated carbide skiving hobs will be presented in this paper.

Cutting Tools and Test Gears

Specifications of Cutting Tools. Table 1 shows specifications of gear cutting tools (hobs) used for the present investigation. Hobs A and B are of the conventional type with a rake angle of 0° for the outside cutting edges. This means that the inclination angle of the side cutting edges is 0° and, therefore, no oblique cutting is conducted in finishing the tooth surface of the gears (Fig. 19a). Hob A is of the protuberance type and made from high speed steel. Hob B is of the carbide, brazed type with no protuberance.

Hobs C–G are of the carbide, brazed type with a special geometry for finishing hardened gears and are called "skiving hobs." No cutting action occurs at the outside edge of the hob blades. The inclination angle of the side cutting edges of these hobs is 30°, which corresponds to a rake angle of –30° in the case of the conventional hob. The whole tooth depth of skiving hobs was made smaller than that of conventional hobs to prevent cutting action at the tooth bottom of the gears to be finished. The carbide blades of Hob F were coated with a TiN layer with a thickness of about 5µm while those of Hobs C, D and E were not coated. The blades of Hob G were coated on the flank only. Figure 1 shows a conventional carbide hob (Hob B), a skiving hob without coating (Hob E) and a skiving hob with coating (Hob G).

Specifications of Test Gears. Kinds of materials and specifications of test gears are shown in Table 2. A 0.45% plain carbon steel (S45C) and a medium carbon alloy steel (SCM440) were used for induction hardening gears while low carbon alloy steels (SCM415 and SCM420) were used for carburizing gears. For cutting tests, spur gears with a module of 8, a pitch circle diameter of 208 mm and a face width of 60 mm were used.

Using the gear blanks with a hardness of about 200 Hv (normalized steel), rough-cut gears were produced by Hob A. The gears were hardened by induction hardening or carburizing.

For induction hardening, a partial coil was inserted in the tooth space and moved in the direction of tooth trace at a speed of about 300 mm/min. to heat over the two facing tooth surfaces. The tooth surfaces were heated to a temperature of about 1,250°K for the plain carbon steel and to a temperature of about 1,150°K for the alloy steel. Quenching of the heated teeth was conducted using water with some additives to prevent occurrence of quenching cracks on the tooth surfaces. After hardening, the gears were tempered at a temperature of about 470°K for two hours to obtain a Vickers hardness of about 600 Hv (Fig. 3).

The carburizing was conducted at a temperature of about 1,200°K in a mixed gas, which consisted of propane gas and alcohol. After carburizing for five-and-a-half hours, the temperature was decreased from 1,200°K to 1,120°K and quenched in non-soluble oil. After hardening, the gears were tempered for two hours at a temperature of about 470°K to obtain a hardness of about 750 Hv.

Figure 2 shows the transverse section of hardened gear teeth of test gears. Figure 3 shows the hardness distribution below the surface of the hardened teeth made from three different materials. The hardness was measured at an indenter load of 9.8 N. The maximum hardness of induction hardened gears is about 600 Hv and the thickness of the hardened layer is about 3 mm. The maximum hardness of carburized gears is about 750 Hv and the thickness of the hardened layer is about 1 mm.

The accuracies of test gears (rough cut gears) deteriorated appreciably by harden-

Table 2—Specifications of test gears and kinds of gear materials.

No. of teeth	Z = 26
Helix angle	0°
Face width	b = 60 mm
Material	S45C, SCM440, SCM415, SCM420
Hardness (Hv)	600, 600, 750, 750

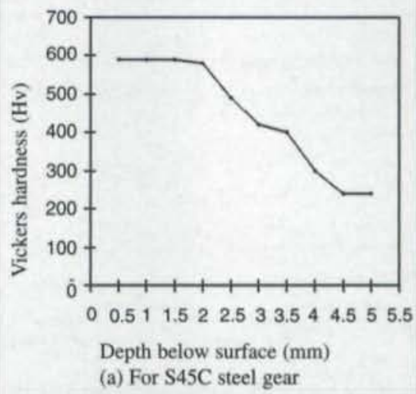


Figure 3a—Hardness of hardened teeth.

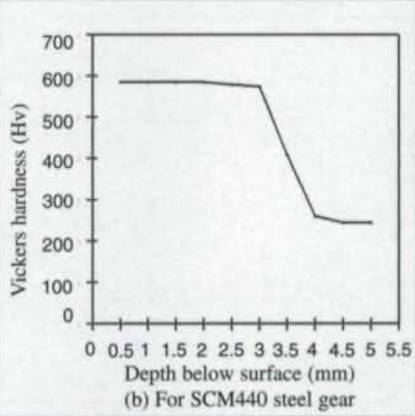


Figure 3b—Hardness of hardened teeth.

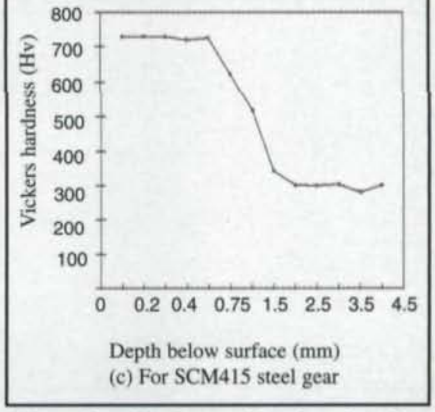


Figure 3c—Hardness of hardened teeth.

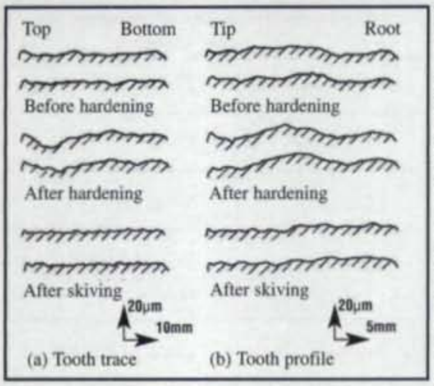


Figure 4—Tooth trace and profile errors of induction hardened gears.

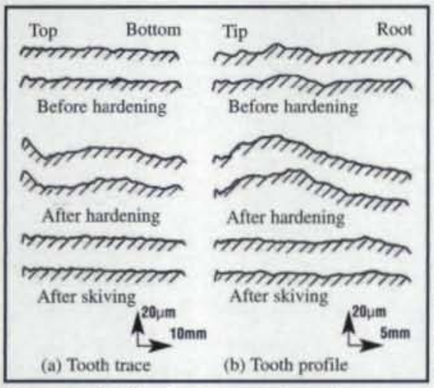


Figure 5—Tooth trace and profile errors of carburized gears.

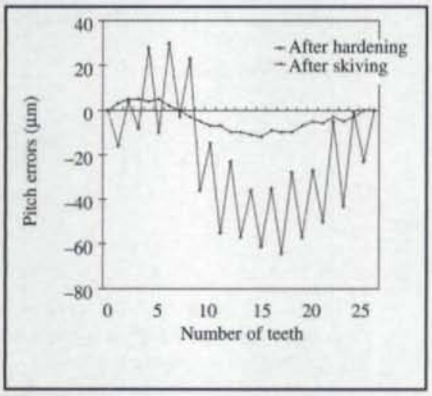


Figure 6—Pitch errors of induction hardened gears before and after skiving.

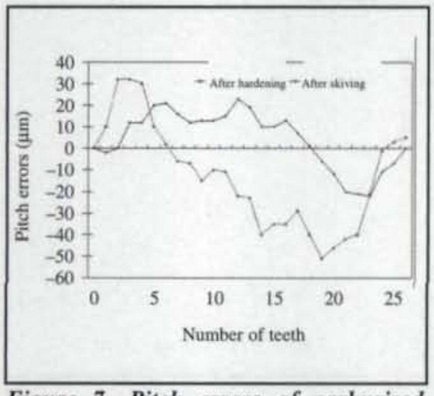


Figure 7—Pitch errors of carburized gears before and after skiving.

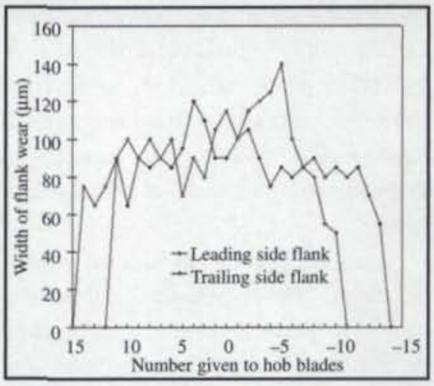


Figure 8—Wear width of all working blades of Hob E without coating used for finishing carburized gears.

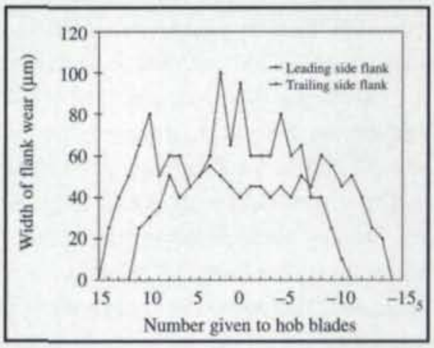


Figure 9—Wear width of all working blades of Hob F used for finishing carburized gears.

ing (Figures 4 and 5). Therefore, hard finishing by carbide skiving hobs becomes very important to economically improve the accuracy of the hardened gears.

Cutting Tests and Tool Wear

Hobbing Machine and Cutting Conditions. For rough and finish cutting of test gears, a hobbing machine with a capacity capable of finishing gears with diameters up to 1,000 mm was used. The machine was made by Kashifuji Co. Ltd. in Japan. Using Hob A made from high speed steel, rough hobbing of nonhardened gears was conducted under the following conditions: a cutting speed of 28 m/min., a hob feed of 2 mm/rev. and a final depth of cut 0.3 mm in the radial direction. The conditions used for skiving of the hardened gears were a cutting speed of 75 or 52 m/min., a hob feed of 2 mm/rev. and a depth of cut 0.3 mm. No cutting fluid was applied.

Changes in Accuracy of Test Gears. Figures 4 and 5 show the accuracies of the tooth profiles and tooth traces of test gears before hardening (after rough cutting), after hardening (before skiving) and after hard finishing (after skiving). For rough cutting, Hob A was used, while Hob F was used for hard finishing (Table 1). Figures 6 and 7 show the cumulative pitch errors of the test gears before and after skiving.

From Figures 4 to 7, it is understood that the decrease in the accuracy caused by the heat treatment was improved by hard finishing for both the induction hardened and the carburized gears.

Effect of Coating on Tool Life. When the coated Hob F was used for finishing the carburized gear at a cutting speed of 75 m/min. and a feed of 2 mm/rev., the flank wear width became greater than 0.2 mm after finishing a single piece of the test gear. Therefore, the cutting speed was reduced from 75 m/min. to 52 m/min. in the following experiments.

When a noncoated hob (Hob E) was used for finishing the carburized gears, the maximum wear width of the hob blades exceeded 0.05 mm after finishing only a single gear. Figure 8 shows the flank wear width on all working blades (side cutting edges) of carbide Hob E after finishing of two carburized gears. Twenty-three blades of the hob were used to finish the gears. The dark mark shows the flank wear width at the left side (leading side) cutting edges while the empty mark shows the wear width at the right side (trailing side) cutting edges.

When coated Hob F was used, 10 carburized gears could be finished before the flank wear reached about 0.1 mm. Figure 9 shows the flank wear width of all working blades of Hob F after finishing 10 carburized gears. Figure 10 shows the effect of the coating on the tool lives of carbide skiving hobs, indicating that the tool lives increased by a factor of seven when the coated hob was used instead of the noncoated hob.

In order to increase the tool lives, it is desirable to use a coated hob such as Hob F with the coated layer on both the rake face and the flank of the cutting edges. However, the coated layer on the rake face is removed completely when the worn cutting edges are sharpened by regrinding.

Recoating of the reground hob may bring about a reduction in the hob's accuracy. Therefore, additional cutting tests were conducted using a skiving hob with the coated layer on the flank only.

Figure 11 shows the flank wear width of all working blades of Hob G after cutting seven carburized gears. By comparing Figures 9 and 11, it can be seen that the coating on the flank only is effective. The tool life becomes shorter by about 30% when compared with that of the hob with the coated layer on both the rake face and the flank (Figure 10).

When Hob G was used for finishing the induction hardened gears with a hardness of about 600 Hv, the tool life increased appreciably in comparison with that of the noncoated hob. Hob G could finish 16 gears before the wear width reached 0.05 mm. Figure 12 shows the flank wear width on all working blades of Hob G after finishing 16 induction hardened gears.

Wear Pattern on Flank. Figure 13 shows wear patterns that were produced on the rake face and the flank of the representative blade of Hob F after cutting 10 carburized gears. Both the rake face and flank of this hob were coated by a TiN layer. Figure 14 shows wear patterns on the flank of Hob G after cutting seven carburized gears. This hob had the coated layer on the flank only. It was estimated that the flank wear on the right side cutting edge was increased appreciably by the occurrence of chipping at the cutting edge. The reason why the flank wear width at the trailing cutting edges is appreciably greater than that at the leading cutting edges is discussed in the next section.

Figure 15 shows wear patterns on the flank of Hob G after cutting 16 induction hardened gears. No chipping occurred at the cutting edges, and the wear width was very small, indicating the effectiveness of the coated layer on the flank. The difference in the wear widths on left side and right side cutting edges is comparatively small because the hardness of the induction hardened gears is lower by about 150 Hv than that of carburized gears, resulting in no chipping at the cutting edge.

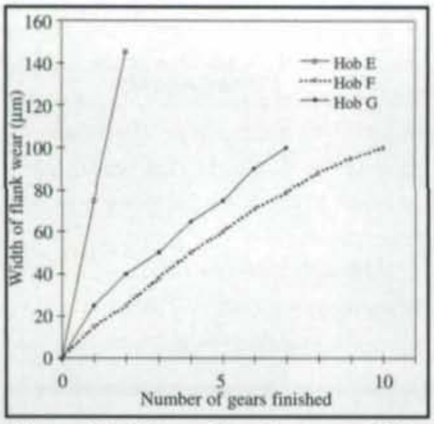


Figure 10—Effect of coating on tool life.

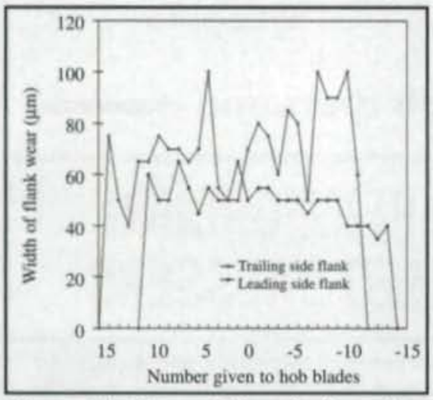


Figure 11—Wear widths of all working blades of Hob G after finishing seven pieces of carburized gears.

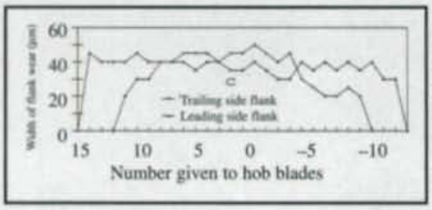


Figure 12—Wear width of Hob G after finishing 16 pieces of induction hardened gears.

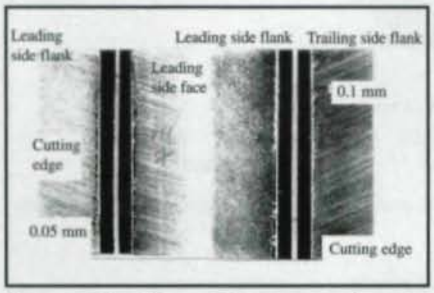


Figure 13—Wear patterns on rake face and flank of coated Hob F after cutting 10 carburized gears.

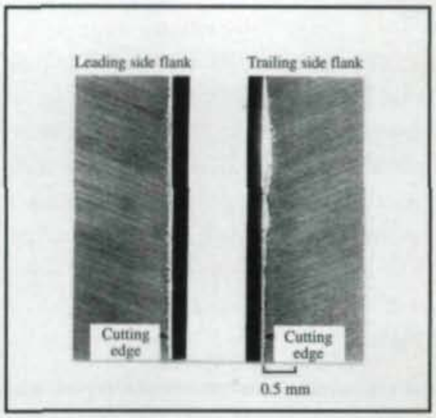


Figure 14—Wear patterns on flank of Hob G after cutting seven carburized gears.

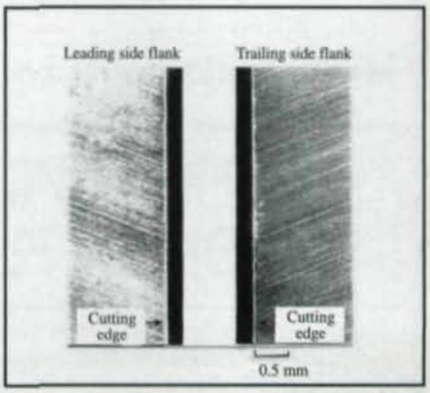


Figure 15—Wear patterns on flank of hob G after cutting 16 induction hardened gears.

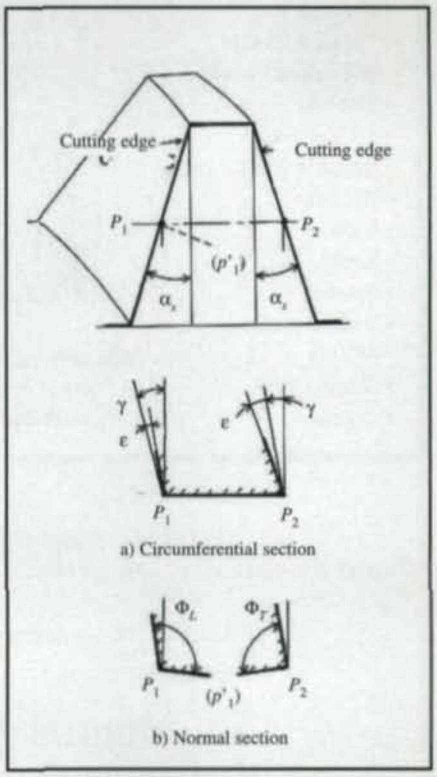


Figure 16—Tool angles of conventional hob with straight gashes.

Discussion

Difference in Wear at Leading Side and Trailing Side Cutting Edges. In the case of gear skiving, the volume of metal on the tooth surface removed by the trailing side cutting edges is almost the same as that removed by the leading side cutting edges. However, it should be noted that the experimental results shown in Figures 8, 9, 11 and 12 indicate that the flank wear at the trailing side cutting edges is greater than that of the leading side cutting edges. Chipping is also apt to occur at the trailing side. The reason for this may be ascribed to the type of gashes given to the hobs used in the present experiments.

Although there are two representative types of gashes utilized for gear cutting hobs, the straight type is commonly used

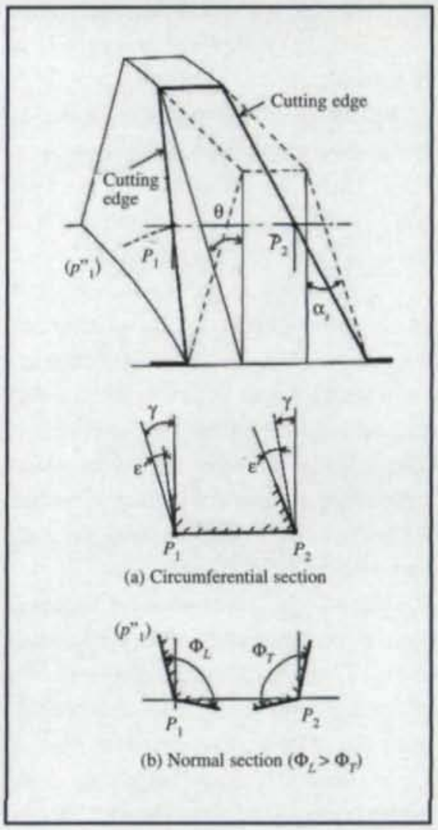


Figure 17—Tool angles of skiving hob with straight gashes.

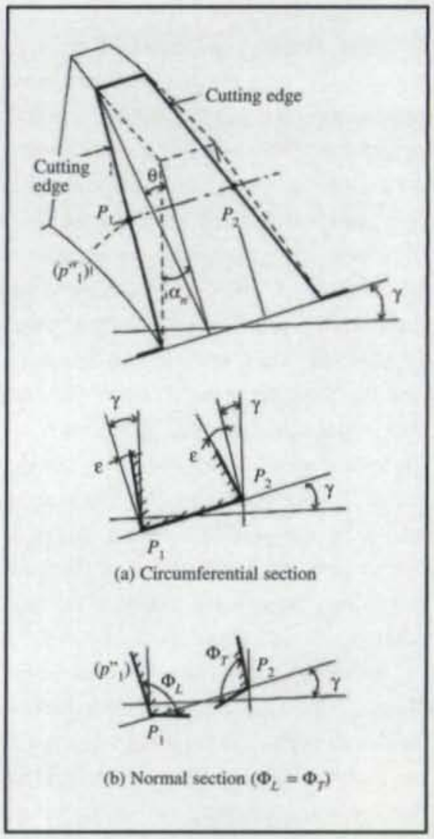


Figure 18—Tool angles of recommended skiving hob with a helical gash.

for the conventional hobs. This is because the accuracy of hobs with straight gashes can be improved with lower manufacturing costs in comparison with that of the hobs with helical gashes. Figures 16 and 17 show the geometrical characteristics of the hob blade in the conventional and skiving hobs.

Figure 17b shows a sectional view of the blade of a skiving hob with cutting edges on a right-hand helical thread and with a straight-type gash. The right-side cutting edge (trailing side cutting edge) gives a smaller tool angle than that of the left-side cutting edge (leading side cutting edge). The greater the tool angle, the smaller the chance of chipping at the cutting edge.

The maximum tool angle is obtained in the section normal to the cutting edge. The maximum tool ϕ_L for the leading side can be calculated from Equation 1 and the maximum tool angle ϕ_T for the trailing side is calculated from Equation 2.

$$\phi_L = 90^\circ + \Delta\phi + \gamma' \qquad (1)$$

$$\phi_T = 90^\circ + \Delta\phi - 2\gamma + \gamma' \qquad (2)$$

where,

$\sin\Delta\phi = (\sin\eta \sin\alpha_n - \tan\varepsilon / \cos\eta)\cos\alpha_n$

$\tan\eta = \tan\theta \cos\alpha_n$

$\tan\gamma' = \tan\gamma / \cos\alpha_n$

Although the process for deriving these equations is omitted due to lack of space, numerical examples are shown as follows. In the case of Hobs F and G, when given geometrical values (pressure angle $\alpha_n = 20^\circ$, lead angle of hob thread $\gamma = 3.6^\circ$, relief angle $\varepsilon = 3.7^\circ$, nominal rake angle $\theta = 30^\circ$) are introduced into Equations 1 and 2, $\phi_L = 98.7^\circ$ and $\phi_T = 91.4^\circ$ are obtained. For the conventional Hob B with $\theta = 0^\circ$ and $\varepsilon = 3.5^\circ$, $\phi_L = 90.6^\circ$ and $\phi_T = 83.3^\circ$ are obtained. These calculated values agree with the measured ones.

From these values for tool angles, it is clearly understood that the chipping hardly occurs on the cutting edges of the skiving hob with $\theta = 30^\circ$ because the maximum tool angle is greater by about 8° than that of the conventional carbide hob with $\theta = 0^\circ$.

The effect of the tool angle on the flank wear of the carbide hob becomes greater when the hardness of a gear is very high, as in the case of carburized gears (Figs. 8 and 9).

Method to Improve Tool Lives of Skiving Hobs. From the present experiments, it is estimated that the tool lives of skiving hobs can be increased when a skiving hob is designed to have the same tool angles for the leading and trailing sides. This is easily realized by changing the types of hob gashes. When the spiral angle of the hob gashes is made equal to the lead angle of hob thread, the maximum tool angles for the leading and trailing sides become the same and are calculated from Equation 3 (Fig. 18).

$$\phi_L = \phi_T = 90° + \Delta\,\phi \qquad (3)$$

When the given geometrical values are the same as those of the above mentioned example excepting for the gashes, tool angle $\phi_L = \phi_T = 94.8°$ is obtained.

The authors estimate that application of coated skiving hobs with helical gashes is very important for finishing fully-hardened carburized gears economically, although with some increase in the manufacturing costs for the hobs.

Advantages Obtained by Oblique Cutting. When the skiving hob was used, the side cutting edge conducts intermittent oblique-cutting (milling) to finish the tooth surface, as shown in Fig. 19b. Although there are some fundamental investigations on the mechanism of the continuous oblique cutting (Refs. 9–10), many problems must be solved to obtain effective equations for calculating changes in the cutting force during the intermittent oblique cutting, such as in gear skiving. Moreover, there are practical problems. For example, the effects of oblique angle on the amount of tool wear, the shape of chips, etc. The authors are conducting some basic investigations to show the effect of intermittent oblique cutting on tool wear and the finished accuracy using a hobbing machine, and the carbide fly tools with and without coating. The results obtained will be published in the near future.

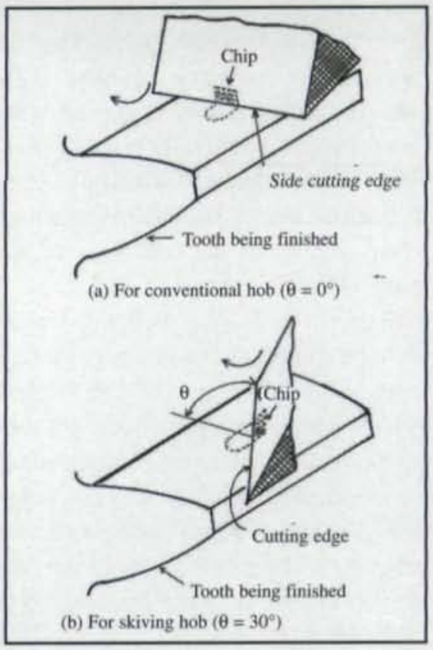


Figure 19—Oblique angle of cutting edges of the two different hobs.

Conclusions

The present investigation was conducted using six kinds of carbide hobs, and the following results were obtained:

1. Induction hardened gears with a Vickers hardness of about 600 Hv could be easily finished by a carbide skiving hob without coating.
2. Carburized gears with a hardness of about 750 Hv were very difficult to finish due to wear and chipping at the cutting edges when skiving hobs without coating were used.
3. When a carbide skiving hob with a coated TiN layer of about 5μm in thick-

ness was used, the tool life increased by a factor of 10 in comparison to the one without coating.

4. The skiving hob with a coated layer on the flank only was effective in increasing the tool life, especially in finishing induction hardened gears with a hardness of about 600 Hv.

5. The flank wear of the trailing side cutting edge was appreciably greater than that of the leading side cutting edge when the hobs were used for finishing carburized gears.

6. The reason for the difference in the wear is explained by calculating the difference in the maximum tool angles of the leading and trailing sides (Fig. 17).

7. It is estimated that the tool life of a skiving hob to be used for finishing fully hardened carburized gears can be increased by introducing coated hobs with almost the same tool angle for leading and trailing sides.

8. The tool angles for the leading side and trailing side cutting edges become the same value when the numerical value of the spiral angle of the hob is made equal to that of the lead angle of the hob tooth thread.

Acknowledgments

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