621.914.5:621-408.8

Paper No. 199-16

Fundamental Research on Hobbed Gear-tooth Surface Roughness*

- Influence of the Built-up Edge -

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Poor surface finish commonly found on the gears used in the as-hobbed condition often leads to a low surface durability. This paper presents detailed investigations about the effect and the formation of a built-up edge (BUE) which is one of the important factors influencing the surface roughness by performing hobbing experiments and simulated-hobbing tests. Moreover, the relation between the BUE and the cutting thickness which is dominated by the hobbing conditions is investigated. From the simulation tests, it is found that definite relationships exist among the size of the BUE formed on the cutting edge, the size of the cutting thickness and the surface roughness. Based on the results, it is clearly confirmed that these relationships are applicable to hobbing also.

1. Introduction

The tooth surface roughness of a gear is one of the important factors influencing the durability of the tooth surface. The effect of this factor increases as the hardness of a gear material increases^{(1)~(4)}. Therefore, the improvement of the tooth surface finish of a hobbed gear is an important problem particularly in the case of large gears and/or hardened and tempered gears (about 350 BHN), which are often used after hobbing with no subsequent finishing being made. However, there are very few papers^{(5)~(6)} on this subject.

Table 1 shows the factors influencing the tooth surface roughness. The built-up edge (BUE) is the most important among these factors, because the range of the cutting speeds (20~30 m/min) often applied to hobbing large gears produces large sized BUEs. Moreover, the formation of BUEs is influenced by many factors as shown in Table 2. Among those factors, the cutting thickness, which can be obtained by the numerical calculation method⁽⁷⁾ of hobbing the unfinished gear space, varies largely with the cutting conditions and/or the specifications of the hob and gear. In the previous papers,^{(8)~(10)} the relationship between this theoretical cutting thickness and the formation of the BUE, and that between the BUE and the tooth surface roughness in gear hobbing have been reported. However, the distinction of the influence of BUEs from that of various other factors on the surface roughness is very difficult,

because hobbing is a very complicated cutting process.

This paper investigates the influence of the BUE on the tooth surface roughness in detail by making single-point fly-tool cutting experiments which simplify the hobbing action and reduce the effects of other factors. Moreover, from the experimental results, the relationship between the cutting thickness and the surface roughness in hobbing is made clear.

Table 1 Factors influencing the tooth surface roughness of the hobbed gear

Table 2 Factors influencing the BUE formation

2. Fundamental experiments using fly-tool

2.1 Cutting conditions

During hobbing, the tooth surface is generated by the side cutting edges of the hob teeth, and the cutting thickness differs from tooth to tooth and from position to

* Received 6th March, 1980

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Fig.3 BUEs remaining attached on the cutting edge

2.2.2 Relation between the size of BUE and surface roughness

Figure 4 shows the size of the BUE attached on the tool relief surface protruding out of the cutting edge at the end of one cut, and the resulting surface profile obtained therein. The fly-tool cutting is carried out in such a way that any BUE which occurs and becomes attached to the tool with every revolution of cut continues to be removed after every corresponding cut, until that particular cut where the measurement of the BUE is taken, under the cutting conditions shown in Fig.5. The portion of finished surface cut by the cutting tool where no BUE exists is quite smooth but, the one cut by the tool where BUE remains attached is seen to be considerably rough. Thus the size of the BUE formed and the surface roughness obtained are found to be closely related to each other. It can be considered that the surface profile is formed by the BUE in these cutting conditions. Figure 5 shows the scanning electron microscope photographs of the same machined surface as the one shown in Fig.4. The photos A,B,C,D correspond to the places A,B,C,D on the surface as indicated. On the left hand side region of photo A, scratches can be seen which are caused by the BUEs. The starting portion of these scratches is shown enlarged in photo B where the adhering particles that are regarded as BUE are clearly visible. Photo C shows the end portion of the scratch. The particles here are larger than those in B. In photo D, the particles are seen as having been ploughed at the end region of cut bordering the machined and the unmachined surfaces. From these photographs, it becomes clear that the particles formed at the beginning of cut are smaller in both quantity and size, and they become larger with the progress of the cutting process.

Figure 6 shows the surface roughness (measured perpendicular to the cutting direction) for different positions along the length of cut. The surface becomes rougher towards the end of cut.

In the case of the up cut of the milling, the machined surface remains from the beginning of cut until the region of the feed-length and the following region is cut away at the next cut. Therefore, the size of the BUE attached on the tool just before the next cut influences the surface roughness as shown in the above results. But in the case of the down cut, as the machined

Fig.4 BUE on the fly-tool and the resulting surface profile

Fig.5 The SEM photographs of the machined surface

Fig.6 The surface roughnesses along the length of cut

surface remains in the region of the feed-length at the end portion of cut, the BUE formed during the cutting influences the surface roughness. In any case, it can be considered that the size of the BUE attached on the tool after one cut influences the surface roughness.

2.2.3 Effect of the cutting speed and workpiece hardness on the surface roughness

Figure 7 shows the surface roughnesses and the area ratios obtained under different cutting speeds and different workpiece hardnesses. In Fig.8, a specimen of machined surface is shown, in which scratches due to the BUEs can be seen. From Fig.7, it can be said that the surface becomes smoother and the proportion of scratches becomes smaller with an increase in cutting speed and hardness. Patterns of BUE formation under these conditions are given in Fig.9. It will be clear from the figure that BUEs tend to separate off from the cutting edge as the cutting conditions gradually become severe.

Figure 10 shows the back side photographs of the chips in different cutting conditions. The surface in (a) is considerably smooth with hardly any formation of BUE or most of them, if formed, have been carried away by the chips flow. However, in (b) the formation of BUEs can be seen which remain attached on the back side face of the chip. Because of these BUEs, the quality of the machined surface deteriorates.

Fig.7 Effect of the cutting speed and the workpiece hardness on the surface roughness

Fig.8 The specimen of machined surface

Cutting condition		No. of cuts required	BUE on the tool
Hb210	V=20 m/min	3	fully attached
	V=48 m/min	3	full & partial attachment
Hb312	V=20 m/min	15	full & partial attachment
	V=48 m/min	25	only partially attached

* No. of cuts so required as to have the tool attached with BUE for 3 times

Fig.9 Patterns of BUE formation

(a) Hb312 V=48m/min

(b) Hb210 V=20m/min

Fig.10 The back side photographs of the chips

From the above results, it can be concluded that machining a hard material at a high cutting speed gives rise to a condition in which the formation of the BUE is suppressed and the attached BUEs tend to fall off with the chips.

2.3 Relation of the cutting thickness to the size of the BUE and the surface roughness

From the results (a) of the calculation using the numerical analysis method,⁽⁷⁾ it is found that the theoretical cutting thickness lies in the range of approximately 1~40μm, and the theoretical cutting length, in the range of approx. 3~5mm at the side cutting edge in the involute-generating region in hobbing with a module 3 hob under the conditions given in Table 3. Here fly-tool tests are performed to simulate, as closely as possible, those cutting thicknesses and cutting lengths. From these tests, the relation of the cutting thickness to the size of BUE and the surface roughness is investigated. The results are shown in Fig.11. The sizes of the BUEs plotted in the figure are those of BUEs attached on the rake face, measured and given by "h" as shown. Although the sizes of BUEs attached on the tool relief surface would normally be expected to directly affect the surface finish, these values are not used here, because they are considerably small in size, making it difficult to obtain accurate measurement. Moreover, it can be considered that the size of BUEs on the rake face "h" would be in pro-

Fig.11 Relationships among the cutting thickness, the size of BUE and the surface roughness

Fig.12 Relation between the cutting thickness and the area ratio

portion to that of BUEs on the relief face to a certain extent and hence those "h" are used. The sizes of BUEs and the surface roughnesses are the average values obtained after repeating the experiment several times.

As shown in the left part of Fig.11, the size of BUE is almost directly proportional to the cutting thickness and the influence of the cutting length seems to be small in the case of cutting speed 20m/min. Comparing the two figures, it is seen that both the roughness and the BUE curves have similar trends with an abrupt rise in slope at around a cutting thickness of 20μm. The BUE becomes relatively large in size at a higher cutting speed of 48m/min. Although this change in speed has almost no effect on the surface roughness in the case of the cutting length $a=3\text{mm}$, the surface roughness is influenced by the cutting speed and becomes considerably larger in the region of longer cutting length of 6mm.

In Fig.12, the relationship between the cutting thickness and the area ratio is shown. Here also, an abrupt rise in the area ratio and hence that in the quantity of scratches can be seen when the cutting thickness exceeds the 20μm range. This trend is quite similar to that in the case with surface roughness. It can also be observed that, although the area ratio decreases considerably with an increasing hardness, there is no change in the trend of the area ratio in the region of 20μm.

The overall results are obtained as follows; (1) The effect of the BUE on the surface roughness increases in the region of the cutting thicknesses of about 20μm and over. (2) The change of the cutting speed in the range of 20~48m/min has hardly any effect on the surface roughness in the region of smaller cutting thicknesses and shorter cutting lengths that correspond to those at the leading side cutting edges of the hob teeth in hobbing under the conditions shown in Table 3 and the reverse will be the case with trailing cutting edges. (3) The cutting length has small effect on the formation of the BUE and the surface roughness in the region of about 20m/min.

3. Hobbing experiments

The results of hobbing experiments are compared with those of fly-tool tests. The specifications of the hob and gear used in these hobbing experiments are the same as those shown in Table 3. The cutting conditions are shown in Table 4 and related figures.

Fig.13 BUEs remaining attached on the hob tooth

Table 4 Hobbing conditions

Cutting speed	20 m/min
Feed	3.0 mm/rev.
Cutting method	climb hobbing
Cutting oil	mineral oil added with inactive chlorinated fatty oil
Hobbing machine	Kashifuji KR-600
Surface measuring instrument	Talysurf type 4

3.1 Interrelationship among the cutting thickness, the BUE and the surface roughness

3.1.1 Relation between the size of BUE and the tooth surface roughness

The relation between the size of BUE attached on the hob teeth which generate the involute-profile and the surface roughness obtained is investigated.

Hobbing being an intermittent cutting process, the BUEs attached on the cutting edges after one cut remain when the hob is quickly disengaged from the gear blank by rapidly drawing the table of the hobbing machine backward during hobbing. The photograph of the hob tooth obtained in that way is shown in Fig.13. To obtain accurate relation between the size of the BUE and the tooth surface roughness in this hobbing test, the BUEs protruding toward the relief surface of the trailing side cutting edge are investigated, because the cutting thicknesses removed by this side are comparatively large resulting in large sized BUEs.

Figure 14 shows the surface roughness profile from the root to the tip along the involute of a trailing side gear tooth flank in this hobbing test. Here, 0 is the tooth of generating center, teeth with negative Nos. are the preceding teeth, and those with positive Nos. are the following teeth. Thus, the root portions of the trailing side flanks are generated by the preceding teeth and the tip portions by the following teeth respectively. As seen from the profile-graph, surface roughness varies along the tooth profile, the tip region having a smooth sur-

Fig.14 Surface roughness profile at the trailing side flank

Fig.15 Relation between the size of BUE and the tooth surface roughness

face and the root region having a rough surface.

In Fig.15, the relation between the size of the BUEs and the surface roughness for each number of the cutting teeth is shown. The size of the BUE projecting out on the relief surface "h'" is measured at the generating portion of each tooth. The roughness R_{max} at the place corresponding to that particular tooth is measured and plotted. From this figure, it can be seen that the two curves are very much alike, thus showing a direct proportional relation between the size of BUE and the surface roughness in gear hobbing.

In Fig.16, the maximum theoretical cutting thicknesses calculated at the involute-generating portions of the hob teeth under the hobbing conditions with various feeds are shown. Comparing the cutting thicknesses in the case of the climb-hobbing with the feed rate of 3.0mm/rev with the surface roughnesses in Fig.15, can be seen the trend that the surface on the root side cut by the preceding teeth which produce the chips with larger thicknesses is rough.

The tooth surface roughness curve in Fig.15 has an abrupt rise in slope at the vicinities of cutting teeth numbering 6 and -4. This trend can be seen on the other surfaces in the same gear. Although the cause of such trend may be the change of the cutting amount due to the eccentricity of the hob or the vibration by a large amount of cut, it is not very clear yet.

The cutting thickness near the cutting tooth numbering 13 is very small, and on the cutting tooth are hardly observed the BUEs. The surface roughness corresponding to the cutting tooth numbering 13 is about 4-5 μ m, and this result is in agreement with that of the surface roughness produced by the "BUE-FREE" cutting edge in Fig.2.

The overall results show close relationship between the size of the BUE and the tooth surface roughness. Moreover, they show that the increased cutting thicknesses are accompanied by an increase of the tooth surface roughness. However, it is very difficult to say that the theoretical cutting thickness of each tooth relates closely to the surface roughness corresponding to that particular tooth.

3.1.2 Relation of hob feed to the cutting thickness and the surface roughness

Fig.16 Maximum theoretical cutting thickness by the side cutting edge near the involute-generating portion

Fig.17 Relation between the feed and the tooth roughness

Generally a change in hob feed changes the amount of cut for each hob tooth, particularly the change of the cutting thickness is large as shown in Fig.16. Consequently, a significant change in the BUE formation and finally a change in the tooth surface roughness condition are expected to happen. These are results of hobbing experiments at three different feed rates in both conventional and climb hobbing methods.

The tooth surface roughnesses obtained in these hobbing tests are shown in Fig.17. The surface roughnesses are the average values of R_{max} on three different points (tip-side, near the pitch point, root-side) along the involute profile.

Figure 18 shows the photographs of the tooth surfaces in the case of climb hobbing for each hob feed.

Comparing the tooth surface roughnesses with the maximum cutting thicknesses as shown in Fig.16, the following are obtained. (1) At a feed rate of 0.5mm/rev, the theo-

Fig.19 Comparison of the surface roughness on the tip side and the root side flanks

m3 $\beta=0^\circ$ V=20m/min CLIMB SCM435 Hb210

Fig.18 Tooth surface photographs

Fig.20 The size of BUEs on the hob teeth in various feed rates

retical cutting thicknesses for both conventional and climb hobbings are less than 20μm contributing to a high degree of surface finish as fine as under 10μm in both trailing and leading flanks. This result is in agreement with those by the fly-tool cutting tests shown in Fig.11 and in Fig.12.

(2) In the case of the conventional hobbings with feed rates of 1.5 and 3.0mm/rev, cutting thicknesses in the trailing side in both of the cases from following teeth side until generating center tooth are much the same

size. But those at a feed rate of 3.0mm/rev in the region of the preceding teeth side are larger.

In Fig.19, the surface roughnesses of the tip side teeth cut by the following teeth of the hob and those of the root side teeth cut by the preceding teeth of the hob on the trailing flank in these hobbing tests are separately shown. The differences in the root side tooth roughnesses are larger than those in the tip side. This trend of the surface roughness is in agreement with that of the size of the cutting thickness. The difference of the roughness in the region of the root side contributes to that of the roughness in Fig.17.

(3) In the case of climb hobbing with feed rates of 1.5 and 3.0mm/rev, the cutting thicknesses at the feed rate of 3.0mm/rev are larger from the vicinity of the cutting tooth numbering 5 upto the preceding side teeth than those at 1.5mm/rev in the trailing side. The difference of roughness on the trailing side is also larger, comparing with those under similar conditions in the case of the conventional hobbings with the same feed rates.

In Table 5, the sizes of the BUEs that correspond to "h" in Fig.11 in the climb hobbing with three different feeds are shown. Trailing sides which remove relatively larger cutting thicknesses (in the hobbing of spur gear) are found to be attached with considerably larger BUEs at each feed rate. Moreover, with an increase of the feed, the size of the BUEs increases particularly on the trailing side cutting edges, and the surface roughness also increases. These results imply that;

- (1) The size variation of cutting thickness directly corresponds with that of the BUEs.
- (2) The size variation of cutting thickness is also closely related to that of the surface roughness.
- (3) With the attainment of cutting thickness as small as 20μm, the resulting tooth surface finish becomes very smooth, being almost free from scratch marks.

3.1.3 Effect of two-stage finishing hobbing

To improve the tooth surface finish, hobbing is frequently performed in stages.

Figure 20 shows the maximum theoretical cutting thicknesses removed during two-stage hobbing experiments at various feeds in conventional hobbing. Here a full depth of 6.75 mm is reached in two cuts with a second-

Fig.21 Maximum theoretical cutting thickness in finish hobbing

Fig.22 Relation between the feed and the tooth roughness in finish hobbing

stage (final-stage) finishing allowance of 0.25mm fed across the tooth profile. From this figure it can be seen that the feed rate has hardly any influence on the cutting thickness at the involute-generating portion of each hob tooth, and all cutting thicknesses in both trailing and leading sides are well below 20μm.

Figure 21 shows the tooth surface roughnesses under these hobbing tests. The roughnesses of the leading side flanks hardly differ from those in Fig.17, because the thicknesses remain the same as those removed in hobbing with the full-depth of 6.75mm in one cut. Thus the two-stage hobbing improves the tooth surface finish on the trailing side flank in the hobbing of spur gear. Considering the results of the fundamental experiments using a fly-tool and those of hobbing, it can be said that setting a depth of cut which gives the cutting thicknesses of less than 20μm, will be the better cutting condition.

3.2 Effect of cutting speed and hardness of workpiece

Figure 22 shows the surface roughnesses in the case of the single-stage and two-stage hobbings. The surface roughness in

Fig.23 Relationships among the cutting speed, the gear blank hardness and the tooth roughness

both of the cases at the cutting speed of 50m/min for the workpiece hardness of 210BNH is the greatest. This range may be in the region of the cutting temperatures which produces large sized BUEs. Although the difference in the surface roughnesses corresponding to that particular cutting condition is smaller than that in the case of the fly-tool tests shown in Fig.7, the trends of the surface roughnesses are in agreement with each other.

4. Conclusions

The relation between the BUEs attached on the cutting edges and the surface roughnesses is found out strictly and quantitatively by performing fundamental cutting experiments with a fly-tool. Moreover, it is made clear that this relation can be applied for the hobbings.

Consequently the following are concluded;

- (1) The BUEs have very strong influence on the tooth surface roughnesses of hobbled gears in the region of cutting speeds 20~50 m/min.
- (2) The cutting thicknesses have close inter-relationship with the size of the BUEs and the tooth surface roughnesses.
- (3) In the region of the cutting thicknesses less than 20μm the scratches caused by the BUEs hardly remain on the surface, resulting in a more smooth surface finish.

This fundamental interrelationship among the cutting thickness, the BUE and the tooth surface roughness can be applied for hobbing of not only spur gears but also helical gears. As regards the hobbing of helical gears, the same is reported in other papers. (8)(9)(10)

However, it has not become clear yet whether the results of this paper can be applied when the kinds of the workpieces and the cutting conditions vary widely or large gears are hobbled. Moreover, the use of the cutting oil suitable for the improvement of tooth surface can be considered by a practical means. At present further studies on such subjects are in progress by performing both hobbing and fly-tool cutting experiments.

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