On Tooth Form Accuracy of Roll-finished Involute Helical Gears*

(4th Report, Use of Die-wheel with Longitudinal

Tooth Form Correction (Crowning))

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In order to improve the tooth form of roll-finished involute helical gears, roll-finishing by a die-wheel with longitudinal tooth form correction, i.e. crowning, was investigated. The simulated and the measured results indicate that the use of a crowned die-wheel enables roll-finishing under lower applied loading than the use of a die-wheel without correction, and brings a high tooth form accuracy. Even in case of roll-finishing of work-gears with large face width, a fairly good tooth form over a whole tooth flank can be also obtained by using the crowned die-wheel, if the condition of axial feed of work-gear is selected properly in consideration of the amount of crowning correction of die-wheel.

Key words : Gear, Roll-finishing, Low Load, Tooth Form Accuracy, Crowning Correction, Face Width

1. Introduction

The tooth form of a roll-finished involute helical gear shows commonly a somewhat concave shape deviating from the true involute profile at the position near the pitch point (1)-(5), because the change of the distributed load on work-tooth flank is remarkable as the die-wheel is pressed to and meshed with the work-gear under very high load. The uneven load distribution on tooth flank is due to the change in the number of pairs of teeth in simultaneous contact during meshing and also due to the uneven compliance of a work-gear tooth for its deformation. If the roll-finishing is worked under lower loading, it is expected that a better tooth form will be obtained. The authors have developed therefore a roll-finishing in a crossed axes system in which contact between die-tooth flank and work-tooth flank occurs geometrically only at one point. The feature of this method has been reported (6).

In case of roll-finishing in an ordinary parallel axes system, if a die-wheel with crowning correction is used instead of a die-wheel without crowning, the geometrical condition of tooth contact will resemble that in a crossed axes system. So, roll-finished tooth form will be improved.

In this report, as the first step of investigation, it is discussed about whether the tooth form quality of a roll-finished gear can or cannot be improved by lowering the applied load for roll-finishing : The computer simulation was made for a case when the compliance of work-tooth flank for contact deformation was set lower, whereby the compliance of work-tooth for bending deflection remained constant. On basis of the simulation results, experiments of roll-finishing by use of a die-wheel with crowning correction were carried out, and the validity of the die-wheel with crowning correction was shown by comparing the results with those of the conventional uncorrected die-wheel.

Some fundamental conditions to improve the quality of the roll-finished helical gears were investigated, revealing the factors which should be considered in the roll-finishing by a die-wheel with crowning correction.

2. Improvement of Tooth Form Accuracy by Roll-finishing under Lower Loading

In order to improve the tooth form quality of roll-finished gears the effects of applying load on tooth form accuracy were investigated : Using the simulation

* Received 7th May 1974.

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program reported in the previous report⁽²⁾, the roll-finished tooth form was calculated for a case that only the compliance of work-tooth flank for contact deformation was reduced. The reduction of the contact compliance induces a considerable plastic deformation of work-tooth flank even when the applied load is small. As the result, roll-finishing under lower loading would give higher tooth form accuracy. Die-wheel and work-gear used for the simulation were error free and their specifications are listed in Table 1.

Figure 1 shows the calculated transverse tooth forms of the gears roll-finished by a die-wheel with no crowning correction under the applied load of 11kN { =1120kgf }. Tooth form curves S1, S2 and S3 show the transverse tooth form at a distance of 3.2mm from the leading side end of tooth, at the center of face width and at a distance of 3.2mm from the trailing side end respectively. Figure 2 shows the calculated transverse tooth forms of gears roll-finished under a lower load of 4kN { =408kgf }, when the compliance of tooth flank for contact deformation

is reduced to a quarter of the previous case (Fig.1) under the same compliance for tooth bending deflection. This value of the applied load was selected to get almost equal plastic deformation of work-tooth flank to that of a case of Fig.1.

In case that work-gear has such a low contact compliance as in the case of Fig.2, enough amount of plastic deformation is induced even under lower applied loading, while the elastic bending deflections of die- and work-tooth are small and the change in the contact pressure between die- and work-tooth flank is equally small. So, the transverse tooth forms show a very slight concave shape near the pitch point in comparison with those in case of Fig.1. Thus, it is expected that the tooth form accuracy of roll-finished gear will be improved, if the roll-finishing under lower loading can be realized.

3. Roll-finishing by Die-wheel with Crowning Correction

One actual method to reduce only the compliance for contact deformation keeping tooth rigidity for bending deflection constant, or to reduce the ratio of contact compliance to bending compliance of a mating tooth pair, is to realize point contact instead of line contact. The roll-finishing in a crossed axes system is one practical method for it⁽⁶⁾. Contact between die- and work-tooth flanks occurs at one point geometrically also in parallel axes roll-finishing, when crowning correction is made of die-wheel teeth. The applied load concentrates on small area, then the same effect may be expected as in case of roll-finishing in a crossed axes system.

The computer simulation of a roll-finished tooth form is carried out for roll-finishing by a crowned die-wheel in

Table 1 Specifications of die-wheel and work-gear

	DIE	WORK
tooth form	normal	
module (mm)	2	
press. angle (deg.)	20	
number of teeth	80	34
addendum modification coefficient	0	0
helix angle (deg.)	23LH	23RH
face width (mm)	30	12
amount of crowning (μm)	70,130	—
material	SKS3	S45C
flank hardness (H_{RC})	62	12
quality	JIS M0	(hobbed)

Fig. 1 Calculated transverse tooth forms of gears roll-finished under the applied load of 11kN

Fig. 2 Calculated transverse tooth forms of gears which have a quarter value of compliance of tooth flank for contact deformation roll-finished under the applied load of 4kN

the conventional parallel axes system. On basis of the knowledge obtained, the results of experiments are analyzed and the prospects of this roll-finishing are discussed.

The simulation program (2) used in this study assumes the followings: The sum of the pressing direction components of the distributed loads on all meshing tooth flanks is equal to the applied load for roll-finishing. The torque on work-tooth flank owing to the distributed loads on tooth flanks is zero. Roll-finishing of the tooth flank of work-gear proceeds only by the plastic deformation of the work-gear owing to indentation of die-tooth flank under this distributed load on tooth flank calculated.

Specifications of die-wheel and work-gear used in the investigation are shown in Table 1. In calculations, in order to judge whether roll-finishing proceeds enough or not enough, a convex tooth form error of $10\mu\text{m}$ was given on a work-tooth. In experiments, a work-gear of JIS Quality 4 was used. Roll-finishing machine used in this study is a two die-wheels and constant loading type⁽¹⁾. Crowning correction was given only on one of the die-wheels and the other was used as a support-gear to prevent the deflection of the axis of work-gear. The rotational speed of die-wheel was 25rpm and the roll-finishing time was 5sec.

Figure 3 shows the calculated transverse tooth forms of the gears roll-fin-

Fig. 3 Calculated transverse tooth forms of gears roll-finished using die-wheel with crowning correction ($\delta=70\mu\text{m}$) under the applied load of 7kN

Fig. 4 Calculated transverse tooth forms of gears roll-finished using uncorrected die-wheel under the applied load of 11kN

δ	0 μm		δ	70 μm		δ	130 μm	
Load	Driven	Followed	Load	Driven	Followed	Load	Driven	Followed
7 kN	Hobbed Tip 16	17	5 kN	Hobbed 26	22	3 kN	Hobbed 16	16
	Finished 7	12		Finished 7	5		Finished 14	13
11 kN	Hobbed 15	17	7 kN	Hobbed 17	16	5 kN	Hobbed 16	16
	Finished 7	8		Finished 4	6		Finished 4	5
13 kN	Hobbed 27	27	9 kN	Hobbed 17	15	7 kN	Hobbed 17	14
	Finished 14	10		Finished 17	15		Finished 13	11

Fig. 5 Measured tooth forms of gears roll-finished using die-wheel with crowning correction

ished using the die-wheel with crowning correction of $70\mu\text{m}$. The applied load for roll-finishing is 7kN . Then the convex tooth form given to work-gear is almost corrected, i.e. the roll-finishing has been well done. Figure 4 shows the calculated transverse tooth forms of the gears roll-finished using an uncorrected die-wheel. The applied load is increased to 11kN in order to make roll-finishing proceed enough. The high load brings about a little concave shape near the pitch point. Such a concave shape is observed but to lesser extent in case of using a die-wheel with crowning correction (Fig.3), because the roll-finishing proceeds enough under lower loading of 7kN . This shows

that, even in roll-finishing in the conventional parallel axes system, if a die-wheel with crowning correction is used, the roll-finishing proceeds enough under lower loading and a fairly good tooth form of roll-finished gear is expected.

In order to make clear the influences of the amount of crowning correction of die-wheel and of the applied load to the roll-finished tooth form, experiments of roll-finishing were carried out under various applied loads using two kinds of die-wheels whose amounts δ of crowning correction are $70\mu\text{m}$ and $130\mu\text{m}$.

Figure 5 shows the tooth forms of the hobbed and the roll-finished work-gears. Numbers in this figure indicate the maxi-

Fig. 6 Calculated longitudinal tooth forms of gears roll-finished using die-wheel with crowning correction ($\delta=70\mu\text{m}$) under the applied load of 7kN

Fig. 7 Calculated longitudinal tooth forms of gears roll-finished using uncorrected die-wheel under the applied load of 11kN

δ	$0\mu\text{m}$		δ	$70\mu\text{m}$		δ	$130\mu\text{m}$	
	Driven	Followed		Driven	Followed		Driven	Followed
7 kN	Hobbed 12 L.S. T.S.	12 T.S. L.S.	5 kN	Hobbed 11 L.S. T.S.	12 T.S. L.S.	3 kN	Hobbed 22 L.S. T.S.	16 T.S. L.S.
	Finished 12	10		Finished 10	9		Finished 22	10
11 kN	Hobbed 11 L.S. T.S.	12 T.S. L.S.	7 kN	Hobbed 14 L.S. T.S.	10 T.S. L.S.	5 kN	Hobbed 16 L.S. T.S.	18 T.S. L.S.
	Finished 7	7		Finished 3	4		Finished 5	6
13 kN	Hobbed 9 L.S. T.S.	16 T.S. L.S.	9 kN	Hobbed 16 L.S. T.S.	10 T.S. L.S.	7 kN	Hobbed 12 L.S. T.S.	14 T.S. L.S.
	Finished 13	16		Finished 16	7		Finished 10	14

L.S.: Leading Side of Meshing
T.S.: Trailing Side of Meshing

Fig. 8 Measured longitudinal tooth forms of gears roll-finished using die-wheel with crowning correction

imum tooth form error in μm . For comparison, the tooth forms of the gears roll-finished by an uncorrected die-wheel ($\delta=0\mu\text{m}$) are also shown. These were measured at the same position as S2 in the calculated ones.

Referring to Fig.5, the optimum tooth form was obtained under 7kN loading in case of $\delta=70\mu\text{m}$ and under 5kN loading in case of $\delta=130\mu\text{m}$. In case of less loading than these values, the hobbed tooth form of work-gear remained after roll-finishing and the roll-finishing did not proceed enough. On the other hand, under higher loading, the roll-finished tooth form showed a large concave shape near the pitch point, i.e. over-roll-finishing was observed. On the contrary, roll-finishing with an uncorrected die-wheel ($\delta=0\mu\text{m}$) needed 11kN loading to obtain the optimum tooth form, and the roll-finishing could not proceed enough under the same loading as in a crowned die-wheel. It is therefore clear, when a die-wheel with crowning correction is used, that low loading operation is possible and an increase in the amount of crowning correction of die-wheel makes the required load lower. More accurate tooth form is obtained by a die-wheel with crowning correction than by an uncorrected die-wheel, because roll-finishing can proceed well under low loading, i.e. the change in distributed load and the deflection of gear tooth can be reduced.

Figures 6 and 7 show the calculated longitudinal tooth forms (in face width direction) corresponding to Figs.3 and 4 respectively. The curves L1, L2 and L3 show longitudinal tooth forms (tooth trace forms) at distances of 2.4mm, 4.8mm (corresponds to pitch point) and 7.2mm from the tooth tip on the plane of action respectively.

It seems intuitively that the longitudinal tooth forms roll-finished by the crowned die-wheel show a concave shape at the position near the center of face width. Actually a dull-rounding down at the both side ends of tooth flank, which was observed in Fig.7 (uncorrected die-wheel), was hardly observed in case of

using the crowned die-wheel (Fig.6), and better longitudinal tooth forms were obtained. The reason seems to be as follows: When the mating tooth pair has no form correction, the distributed load between die- and work-tooth flanks has maximum value at the free end of tooth. Using the crowned die-wheel, the same as the one in case of a crossed axes system, the applied load distributes convexly on the contact line i.e. the amplitude of distributed load on tooth flank becomes smaller at the both side ends of tooth flank where the compliance for contact deformation i.e. the resistance to plastic deformation is smaller than at the position near the center of face width.

Figure 8 shows the measured longitudinal tooth forms (tooth trace forms) corresponding to Fig.5. The measured position corresponds to L2 in the calculated tooth form. It is clearly admitted that better longitudinal tooth form without dull-rounding down near the both side ends of tooth can be obtained by an adequately crowned die-wheel. The results coincide well with the simulation results, Figs.6 and 7. It was revealed that roll-finishing proceeds under lower loading by the die-wheel with crowning correction than by an uncorrected die-wheel, and better transverse and longitudinal tooth forms are obtained, if the amount of crowning correction of die-wheel is properly selected. When the amount of crowning correction is too large or when the work-gear with very large face width is roll-finished, the applied load concentrates near the center of face width and roll-finishing may proceed there excessively. Then the quality of a roll-finished gear will be deteriorated. In these cases, therefore work-feed in its axial direction seems to be necessary.

4. Roll-finishing of Work-gear with Large Face Width

Roll-finishing of work-gears which have larger face width b of 18 or 24mm than one of 12mm in the previous section

Fig. 9 Measured transverse tooth forms of gears roll-finished without work-feed

Fig. 10 Measured longitudinal tooth forms of gears roll-finished without work-feed

were carried out. Figure 9 shows the transverse tooth forms of the hobbed work-gears and the roll-finished ones. The die-wheels with crowning correction of 70 or 130 μm were used under the applied load W of 7 or 5 kN, which can be regarded as the optimum load for each die-wheel. In this figure, three tooth form error curves from top to bottom correspond to that at a distance of 3mm from the leading side end of meshing, that at the center of face width and that at a distance of 3mm from the trailing side end of meshing respectively. In case of roll-finishing of the work-gear with face width of 18mm by a die-wheel with crowning correction of 70 μm , a good tooth form was obtained. But in the other cases, roll-finishing proceeded only near the center of face width and did not proceed enough near the both side ends of tooth flank and the hobbed tooth form remained.

Figure 10 shows the measured longitudinal tooth forms (tooth trace forms) corresponding to Fig.9. A good longitudinal tooth form was obtained in roll-finishing of work-gear of 18mm face width by a die-wheel with crowning correction of 70 μm , and a dull-rounding down near the

both tooth side ends was hardly observed. In other cases, longitudinal tooth forms showed a concave shape near the center of face width. Roll-finishing proceeded only there.

At the roll-finishing of work-gear which has large face width using the crowned die-wheel, feeding action of work-gear in its axial direction seems to be effective to roll-finish the whole tooth flank uniformly. The work-gears which had face width of 18 or 24mm were roll-finished with the axial work-feed using a die-wheel with crowning correction of 130 μm under the applied load of 5kN. The feed started at the position where the leading side end of meshing of work-gear coincided with the center of face width of die-wheel and ended at the position where the trailing side end of meshing of work-gear coincided with the center of face width of die-wheel (i.e. the amount of feed was equal to the face width of work-gear). The rate of feeding was 2mm/s.

Figures 11 and 12 show the measured transverse and the longitudinal tooth forms. When the work-feed was so designed that the whole face width of work-gear mated with the center of face width of

Fig. 11 Measured transverse tooth forms of gears roll-finished with work-feed from one side end of tooth to the other end ($\delta=130\mu\text{m}$)

Fig. 12 Measured longitudinal tooth forms of gears roll-finished with work-feed from one side end of tooth to the other end ($\delta=130\mu\text{m}$)

Fig. 13 Measured transverse tooth forms of gears roll-finished with work-feed whose extent is decided in consideration of amount of crowning correction of die-wheel ($\delta=130\mu\text{m}$)

die-wheel, good transverse tooth forms were obtained over the whole face width of 18 or 24mm (Fig.11). The longitudinal tooth forms did not show a concave shape at the center of face width which was observed in Fig.10 (b), but they showed a dull-rounding down at the both side ends of face width. The cause of this dull-rounding down seems to be as follows: The both side ends of face width of work-gear, where the compliance of tooth for contact deformation is small, contact with the center of face width of the crowned die-wheel. Then plastic deformation becomes large. To obtain an accurate tooth trace curve by roll-finishing using the crowned die-wheel, the axial work-feed should be made with careful selection of the starting and the ending points and the amount of work-feed, considering the distributed compliance of work-tooth for contact deformation.

Fig. 15 Measured transverse tooth forms of gears roll-finished with work-feed whose extent is decided in consideration of amount of crowning correction of die-wheel ($\delta=70\mu\text{m}$)

Fig. 14 Measured longitudinal tooth forms of gears roll-finished with work-feed whose extent is decided in consideration of amount of crowning correction of die-wheel ($\delta=130\mu\text{m}$)

In the previous section the best longitudinal tooth form was obtained when a die-wheel with crowning correction of $70\mu\text{m}$ was used for a work-gear with face width of 12mm. For trial here, the starting and the ending positions of work-feed were so decided that the local amount of crowning correction of die-wheel at the positions where it came into contact with the both side ends of face width of work-gear was greater than or equal to $10\mu\text{m}$ regardless of the total amount of crowning correction of die-wheel. That is, in case of a $130\mu\text{m}$ crowned die-wheel, the work-feed was started when the face center of die-wheel contacted with the work-gear at a position 4mm distant from the leading side end and was ended when the die-wheel center contacted with the work-gear at a position 4mm distant from the trailing side end of

L.S.: Leading Side of Meshing
T.S.: Trailing Side of Meshing

Fig. 16 Measured longitudinal tooth forms of gears roll-finished with work-feed whose extent is decided in consideration of amount of crowning correction of die-wheel ($\delta=70\mu\text{m}$)

the work-gear.

Figures 13 and 14 show the transverse and the longitudinal tooth forms of the gears roll-finished with such a work-feed as mentioned above at feeding rate of 2mm/s under the applied load of 5kN. As shown in Fig.13, a fairly good transverse tooth form was obtained over the whole face width. And it is noticed from Fig.14 that a concave shape of longitudinal tooth form near the center of face width seen in Figs.6 and 7 and a dull-rounding down near the tooth side ends seen in Fig.12 are hardly observed. Thus a fairly good longitudinal tooth form was obtained.

And, as shown in Fig.10, the longitudinal tooth form of the roll-finished gear with large face width of 24mm showed concave shape near the center of face width and roll-finishing did not proceed enough on the whole face width. Then roll-finishing of work-gear with face width of 24mm was carried out using a 70 μ m crowned die-wheel with work-feed in the same manner as in the above mentioned case, i.e. the local amount of crowning correction of die-wheel at the side ends of work-tooth was 10 μ m. In this case, the work-feed was started from a distance of 6mm from the leading side end of meshing and was ended at a position 6mm distant from the trailing side end of meshing. And the extent of feed was 12mm.

Figures 15 and 16 show respectively the transverse and the longitudinal tooth forms of the work-gears roll-finished under the applied load of 7kN with work-feed at a rate of 2mm/s. As shown in these figures when the extent of work-feed is selected in consideration of the amount of crowning correction, roll-finishing proceeds well over the whole face width and a fairly good tooth form is obtained. A concave shape near the center of face width and a dull-rounding down of longitudinal tooth form near tooth flank side ends are not observed. Thus, even if the work-gear has large face width, the work-feed will produce a fairly good tooth form over the whole face width, when the starting and the ending points of the feed are selected in consideration of the resistance of work-tooth to contact deformation at the tooth side end.

5. Conclusions

In order to confirm the prospect of roll-finishing of involute helical gears

using a die-wheel with crowning correction computer simulations and experiments were carried out. Then the following facts were revealed :

(1) When a die-wheel with crowning correction is used, roll-finishing can proceed well under much lower loading than in case of using an uncorrected die-wheel. As the change in the contact loads during meshing becomes smaller, a more accurate tooth form can be obtained.

(2) Work-gears which have rather small face width are roll-finished well using a die-wheel with small amount crowning correction. A fairly good longitudinal tooth form can be obtained without remarkable dull-rounding down at tooth flank near the both side ends of tooth, because the contact loads become small near the side ends where the resistance of tooth to contact deformation is small.

(3) When the crown of a die-wheel is too large and/or a work-gear of large face width is roll-finished, roll-finishing proceeds only at the center of face width and hardly at the side ends. In these cases, to improve the accuracy of roll-finished gears the work-feed in its axial direction is effective.

(4) In case of roll-finishing with work-feed in its axial direction, a fairly good tooth form is obtained, if the starting point and the extent of work-feed are decided in consideration of the amount of crowning correction of die-wheel.

Acknowledgement

Sincere gratitude is extended to Mr. Y. Toko-o, an engineer of Kyoto Institute of Technology and Mr. S. Hirayama, Mr. T. Shinoki and Mr. T. Yamamoto, students of K. I. T., for their help in the experimental work of this investigation.

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