Profile and Longitudinal Modification of a Roll-Finishing Die-Wheel*

Ichiro MORIWAKI**, Takashi OKAMOTO**,
Aizoh KUBO*** and Hisashi YAMADA**

Computer simulations of roll-finishing by a die-wheel with profile and longitudinal modifications were carried out to determine the optimum tooth form of a die-wheel. The simulation results revealed that a die-wheel should be modified by hollowing the tooth form at the position corresponding to the hollowed part of a tooth form roll-finished by an unmodified die-wheel, and so was projected at the position corresponding to this corresponding position. Then, the experiments of roll-finishing were carried out using the modified die-wheel. The results of these experiments showed that the profile and longitudinal modifications of a die-wheel were very effective if altered in the manner mentioned above; such a die-wheel gave a fairly good tooth form. Further more, the experimental results showed that an interference between the tooth tip of die-wheel, and the tooth root and bottom of work-gear should be prevented, e. g., by tip relief of the die-wheel.

Key Words: Gear, Roll-finishing, Profile and Longitudinal Modification, Tooth Form Accuracy

1. Introduction

In the roll-finishing of involute helical gears, a die-wheel is pressed to and meshed with a work-gear. As a result, a variation in the load distribution on a tooth flank, due to the change in the number of pairs of teeth in simultaneous contact during the meshing, causes a concavity of the roll-finished tooth form, i. e., the tooth form deviates from the true involute profile at the position near the pitch point. In addition, the compliance for contact deformation of the tooth flank, i. e., the resistance to plastic deformation of the tooth flank, is small at the position near the free end of the tooth. Thus, the roll-finished tooth form also shows a rounding down at the tooth tip and both tooth edges. In order to study these problems, a computer simulation program for the roll-finishing of involute helical

gears has been developed⁽¹⁾. This simulation program reproduces the roll-finishing process well, permitting analytical and experimental studies⁽²⁾⁻⁽⁴⁾.

In the present report, profile and longitudinal modifications of die-wheel are discussed with a view to producing a roll-finished error-free work-gear. As the first step, a computer simulation reveals the effects of profile and longitudinal modifications of the die-wheel on a roll-finished tooth form, and also determines the optimum modified tooth form of a die-wheel. Experiments of roll-finishing were carried out using a die-wheel with these profile and longitudinal modifications. The experimental results show the validity of such a modified die-wheel. These investigations will give us vital informations upon roll-finishing with a modified die-wheel.

2. Determination of Die-Wheel Modifications by Computer Simulation

The tooth form of a roll-finished gear is hollowed at the position near the pitch point and rounded down at both tooth edges. Hence, the tooth form of a die-wheel should be hollowed out at the position corresponding to the hollowed part of a work-tooth form

* Received 19th June, 1987. Paper No. 86-1387 A

** Department of Mechanical and Production Engineering, Kyoto Institute of Technology, Goshokaido-cho, Matsugasaki, Sakyo-ku, Kyoto, 606, Japan

*** Department of Precision Mechanics, Kyoto University, Yoshidahonmachi, Sakyo-ku, Kyoto, 606, Japan

roll-finished by an unmodified die-wheel. From this presumption, a modified tooth form of die-wheel determined by a computer simulation of roll-finishing. Specifications of die-wheel and work-gear are listed in Table 1.

Figure 1 shows the calculated tooth profiles and tooth traces of the work-gear roll-finished by an unmodified die-wheel. This calculation was carried out on conditions that an applied load was 9 kN, the tooth form of work-gear before the roll-finishing was a true involute, the rotational speed of the die-wheel was 25 rpm, and the roll-finishing time was 5 s. The tooth curves S 1, S 2 and S 3 show tooth profiles at a distance of 3.2 mm from the leading side of the meshing, at the center of the face width, and at a distance of 3.2 mm from the trailing side of the meshing, respectively. L 1, L 2 and L 3 show the tooth traces at distances of 2.4 mm, 4.8 mm (corresponding to the pitch point), and 7.2 mm from the tooth tip on the plane of action, respectively. These tooth forms are concave near the pitch point and rounded down at the tooth tip and both tooth edges. This is generally the case for roll-finished tooth forms.

The modified tooth profile was determined using the tooth form curve S 2 in Fig. 1; it was hollowed out at the position near the pitch point and the tooth bottom. This tooth profile was given uniformly to a die-wheel at the all positions along the face width. The modified tooth trace was determined similarly, using the tooth form curve L 2 in Fig. 1. It was rounded down at both tooth edges. This tooth trace was given uniformly over the profile. Figure 2 shows the modified tooth profiles and tooth traces of this die-wheel. Using such a modified die-wheel, we calculated the roll-finished tooth form.

Figure 3 shows the calculated tooth forms of work-gear roll-finished by this modified die-wheel. The applied load for the roll-finishing was decreased to 8 kN. This was due to longitudinal modification of the die-wheel resembling crowning. If a crowned die-wheel is used, then roll-finishing will proceed satisfac-

torily under a lower loading⁽³⁾. Thus, under this applied load, plastic deformation of the work-tooth flank was almost equal to that shown in Fig. 1. In Fig. 3, longitudinal modification of a die-wheel was effective for a roll-finished tooth trace; the tooth trace is fairly good and it is not rounded at both tooth edges. However, a profile modification of a die-wheel has only a small effect on the roll-finished tooth profile; this tooth profile still shows a slight concavity at the position near the pitch point and a slight rounding down at the tooth tip.

The calculation was then made for a roll-finishing by a die-wheel with both the tooth profile and tooth trace accumulatively hollowed out, using the tooth form curves S 2 and L 2 in Fig. 3. Figure 4 shows the modified tooth profiles and tooth traces of a die-wheel determined in such a way. Similarly, this tooth profile was given uniformly to the die-wheel at the all posi-

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 mod. coef.	0	0
helix angle (deg.)	23LH	23RH
face width (mm)	30	12

Fig. 1 Calculated tooth form of a gear roll-finished by an unmodified die-wheel

Fig. 2 Tooth form of a die-wheel with profile and longitudinal modifications

Fig. 3 Calculated tooth form of a gear roll-finished by a die-wheel with modifications

Fig. 4 Tooth form of a die-wheel with accumulative modifications

tions along the face width, and this tooth trace was given uniformly over the profile.

Figure 5 shows the calculated tooth profiles and tooth traces of work-gear roll-finished by such a die-wheel. The applied load for the roll-finishing was further decreased to 7 kN, because the amount of crowning in the die-wheel became larger. Under this applied load, the plastic deformation of the work-tooth flank was almost equal to that shown in Fig. 1. Referring to Fig. 5, although the tooth profile at the position near both tooth edges was still slightly worse, at the center of face width (S2) it was sufficiently improved, and showed a fairly good tooth profile without a concavity at the position near the pitch point. The tooth trace was also sufficiently improved. As a result, we were able to obtain a fairly good tooth form.

The tooth form of a modified die-wheel should be determined by repeating the procedure mentioned

above, i.e., with a view to producing a roll-finished error-free gear, a tooth form of die-wheel should accumulatively be hollowed out at the position corresponding to the hollowed part of a tooth form of the roll-finished gear. If a tooth form of a modified die-wheel is determined in such a manner, we can expect then tooth form of a roll-finished gear to be fairly good.

3. Experiments of Roll-Finishing by a Modified Die-Wheel

For the study, we manufactured a modified die-wheel. The tooth form of this die-wheel was determined from simulation results mentioned previously. The experiments on roll-finishing were carried out using this modified die-wheel.

Figure 6 shows the measured tooth profiles and the tooth traces of the die-wheel with profile and longitudinal modifications. These tooth profiles are concave at the position near the pitch point and are hollowed out at the position near the tooth bottom which the tooth tip of work-gear contacts. The tooth traces have a modification resembling crowning. The roll-finishing machine used in the present study consisted of two die-wheels with constant-loading⁽⁵⁾. The roll-finishing conditions were the same as used in the

Fig. 5 Calculated tooth form of a gear roll-finished by a die-wheel with accumulative modifications

Fig. 6 Measured tooth form of a die-wheel with profile and longitudinal modifications

computer simulations, i.e., the applied load for roll-finishing was 7 kN, the rotational speed of die-wheel was 25 rpm, and the roll-finishing time was 5 s. Specifications of the die-wheel and work-gear are listed in Table 1. The die-wheel was fabricated from SKS 3 steel ($H_{RC}=60$) and the work-gear from S 45 C steel ($H_{RC}=12$). The work-gear (JIS Quality, 0) was ground, since the change of tooth form of a work-gear must be clarified when roll-finished by a modified die-wheel.

Figure 7 shows examples of the measured tooth profiles and tooth traces of work-gear roll-finished by this modified die-wheel. This figure shows fairly good roll-finished tooth traces without a rounding down at both tooth edges. However, the tooth profiles showed a hollowed part at a position near the tooth bottom. This was induced by an interference between the tooth tip of the die-wheel, and the tooth root and bottom of the work-gear. This interference caused a deterioration of the tooth profile over the whole region. The depth of this hollowed part was larger on the followed tooth flank than on the driven tooth flank, because, on the followed tooth flank, the tooth contact starts at the tooth root of the work-gear.

(a) tooth profile

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

(b) tooth trace

Fig. 7 Measured tooth form of a ground work-gear roll-finished by a die-wheel with modifications

This interference may be induced by a large projection of a modified die-tooth form at a position near the tooth tip. Hence, a tip relief was given to a modified die-wheel corresponding to the depth of this hollowed part. Figure 8 shows the measured tooth profiles of a die-wheel given the tip relief. The amount of the tip relief in the normal direction was 10 μm on the drive side and 20 μm on the coast side.

Figure 9 shows examples of tooth profiles and tooth traces of work-gear before and after roll-finishing by this modified die-wheel under the same roll-

Fig. 8 Tooth profile of a modified die-wheel with tip relief

(a) tooth profile

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

(b) tooth trace

Fig. 9 Measured tooth form of a ground work-gear roll-finished by a modified die-wheel with tip relief

finishing conditions as mentioned above. If the tip relief is given to a modified die-wheel, then interference is hardly induced, and a fairly good roll-finished tooth form can be obtained. This result shows a qualitative agreement with the simulation result. Hence, profile and longitudinal modifications of a die-wheel should be determined by gradually correcting a die-tooth form corresponding to a roll-finished tooth form.

We must finally verify the validity of such a modified die-wheel for an actual roll-finishing, i. e., a roll-finishing of hobbed gears. For this purpose, experiments for hobbed work-gears (JIS Quality, 6) were carried out using a modified die-wheel with the tooth form determined by the method mentioned above.

Figure 10 shows the measured tooth profiles and

(a) tooth profile

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

(b) tooth trace

Fig. 10 Measured tooth form of a hobbed work-gear roll-finished by a modified die-wheel with tip relief

tooth traces of a hobbed gear which was roll-finished under the same roll-finishing conditions as mentioned above. In this figure, three tooth profiles from top to bottom are shown at the position near the leading side of the meshing, at the center of the face width, and at the position near the trailing side of the meshing. They correspond to the calculated tooth profiles S 1, S 2 and S 3, respectively. With reference to the tooth profile at the center of the face width shown in this figure, although a large tooth form error was observed in a hobbed tooth form, in a roll-finished tooth form it was hardly observed; this tooth profile was fairly good, exhibiting no concavity at the position near the pitch point or a rounding down at the tooth tip. The tooth trace also was fairly good.

Roll-finished tooth profiles, however, were not improved at the positions near the leading and the trailing side of the meshing in comparison to the center of the face width. They showed a slight concavity at the position near the pitch point and a slight rounding down at the tooth tip. The reasons for this are as follows: Profile and longitudinal modifications of the die-wheel were determined from a roll-finished tooth profile at the center of the face width, and a tooth trace at the pitch point. A tooth profile determined in such a manner was given uniformly to a die-wheel at the all positions along the face width, and a tooth trace was given uniformly over the profile. As a result, the tooth profile except at the center of the face width, and the tooth trace except at the pitch point, do not give the optimum tooth form for producing a roll-finished error-free gear. In order to obtain a fairly good tooth profile over the whole face width, an optimum tooth profile at each longitudinal position must be given to a die-wheel along the face width. This optimum tooth profile should be determined from a roll-finished tooth form at each corresponding position. A longitudinal modification also must be given to a die-wheel in the same manner. Hence, an optimum die-tooth profile will differ with the longitudinal position, and an optimum tooth trace will differ with the transverse position. However, in this study, a modified tooth profile was given uniformly to a die-wheel along the face width, and a modified tooth trace also was given uniformly over the profile. This is because such a modification of a die-wheel cannot be satisfactorily realized at this time. Recently, however, a new gear grinding system⁽⁶⁾ has been developed to take into account a topological modification of tooth flank. Hence, the use of such a grinding system will produce a die-wheel with an optimum tooth form for giving a true involute profile to a roll-finished gear.

4. Conclusions

With a view to producing a roll-finished gear with a true involute profile, calculations and experiments of roll-finishing by die-wheels containing various modifications were carried out to determine profile and longitudinal modifications of a die-wheel. The following facts were revealed.

(1) When an optimum tooth form of a die-wheel is determined by a computer simulation, the die-tooth form should gradually be corrected corresponding to a roll-finished tooth form, i.e., the die-tooth form should be accumulatively hollowed out at the position corresponding to a hollowed part of a roll-finished tooth form, and should similarly be projected at the position also corresponding to that of a projected part of a roll-finished tooth form.

(2) In an actual operation, the tip relief must be given to a die-wheel so as to prevent interference between the tooth tip of the die-wheel, and the tooth root and bottom of the work-gear. However, it is difficult to simulate such interference.

(3) Whereas, in the present study, a die-tooth form was determined only from a tooth profile at the center of the face width and a tooth trace at the pitch point of a roll-finished gear, a die-tooth form should, in practice, be determined from the whole region of a roll-finished tooth form. This determination of a die-wheel modification will enable us to obtain a fairly good tooth form over the whole tooth flank.

In the present report, a required tooth form of a roll-finished gear was a true involute. The use of the determination method of die-wheel modifications recommended in this report will enable the production

of a gear with an arbitrarily required tooth form. This point will be discussed in the next report.

Acknowledgments

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

References

- (1) Okamoto, T., Nagashima, H. and Kubo, A., On Tooth Form Accuracy of Roll-finished Involute Helical Gears, *Bull. JSME*, Vol. 23, No. 185 (1980), p. 1913.
- (2) Okamoto, T., Kubo, A., Moriwaki, I. and Ohkubo, H., Roll-finishing of Involute Helical Gears in Crossed Axes System, (1st Report, Fundamental Investigation), *Bull. JSME*, Vol. 27, No. 227 (1984), p. 1018.
- (3) Moriwaki, I., Okamoto, T., Kubo, A., Shishiyama, H. and Fujii, N., On Tooth Form Accuracy of Roll-finished Involute Helical Gears, (4th Report, Use of Die-wheel with Longitudinal Correction (Crowning)), *Bull. JSME*, Vol. 29, No. 249 (1986), p. 975.
- (4) Moriwaki, I., Okamoto, T. and Kubo, A., On Tooth Form Accuracy of Roll-finished Involute Helical Gears, (3rd Report, Effect of Loading Process and Die-wheel Approach), *Bull. JSME*, Vol. 29, No. 249 (1986), p. 966.
- (5) Okamoto, T., Experimental Study on Tooth Form Accuracy of Roll-finished Gears (in Japanese), *Proc. 8th Jpn. Soc. Mech. Eng. Symp.*, No. 750-9 (1975) p. 307.
- (6) Maag Technical Information ES-422.