Improvement of Gear Accuracy in Gear Hobbing*

(2nd Report, Investigation of the Causes of Tooth Profile Errors by Comparing Computed Tooth Profile Errors with Measured Ones)

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The causes of tooth profile errors in gear hobbing are investigated by comparing computed tooth profile errors with measured ones, for manufacturing accurate gears. Under various hobbing conditions, gears are cut and measured. Spheroidal graphite cast iron is used as the hobbled test material because built-up edges hardly occur. From these comparisons, it is found that tooth profile errors are mainly caused by geometrical errors and the eccentricity of the hob. Tooth profile errors caused by dynamic errors of the hobbing process are very small under these conditions, though they are observed more or less in the case of helical gear hobbing. It is also confirmed that the method of calculating tooth profile error, which is discussed in the first report, is useful in analyzing gear accuracy.

Key Words: Hobbing, Tooth Profile Error, Hob Accuracy, Setting Error of Hob, Dynamic Effect of the Hobbing Process, Separation of Errors

1. Introduction

The tooth profile errors of hobbled gears are influenced by various factors such as hob accuracy, vibration of the hobbing machine and built-up edges, etc. It is, therefore, very difficult to separate tooth profile errors caused by static factors, such as hob accuracy and setting error of the hob, and those caused by dynamic factors, such as vibration of the hobbing machine, from measured tooth profile errors. As a result, the hobbing conditions necessary to reduce tooth profile errors are difficult to determine.

This study aims at manufacturing highly accurate gears by hobbing, from the knowledge of the effects of factors influencing the accuracy of hobbled gears. In this paper, by comparing tooth profile errors calculated using the analytical method shown in the first report, with the measured tooth profile errors of gears hobbled under various hobbing conditions, the validity of the analytical method is investigated and, more-

over, the effects of static and dynamic factors influencing tooth profile errors are discussed.

2. Test conditions

The specifications and the errors of the hob used in these tests, and the hobbing conditions, are given in Tables 1 and 2, respectively. In Fig. 1, the measuring positions of eccentricity of the hob set are shown.

After hobbing tests, tooth profile errors are mea-

Table 1 Specifications and errors of the hob used

Module	6	No. of threads	1, RH
Pressure angle	20°	No. of gashes	12,
Outside dia.	115.7		straight
Rake angle	0°	Material	SKH55
Length	110		
Tooth profile error	L.S.		4.6µm*
	T.S.		8.0µm*
Lead variation tooth	L.S.		4.0µm*
to tooth	T.S.		5.8µm*
Accumulative error	L.S.		7.0µm*
in 1 convolution	T.S.		11.0µm*
Single gash spacing error			37µm**
Accumulative gash spacing error			70µm**
Radial alignment of cutting face			20µm*
Gash lead error			15µm*
L.S.:Leading side, T.S.:trailing side,			
*:JIS class 0, **:JIS class 1.			

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sured using a base-circle disk type gear tester, and then measured tooth profile errors are compared with those analyzed by the method shown in the first report.

The gear material is spheroidal graphite cast iron (JIS FCD40), which has a good machinability⁽¹⁾ and rarely experiences built-up edges. The tooth surfaces of this gear material after hobbing are very smooth, with only about 5 μm in maximum height of roughness and, therefore, the traces of cutting of the hob teeth clearly remain on the tooth surfaces. The hobbing machine is a Kashifuji KS-600, and the cutting fluid is a mineral oil containing an inactive fatty oil.

3. Test results and discussions on the tooth profile error

Figures 2 and 3 show the measured and computed tooth profile errors of the hobbed spur and helical gears, respectively. In the computed tooth profile errors, the hob errors and the setting error are considered.

After comparison, tooth profile errors are discussed in the following sections.

3.1 Correspondence between computed and measured tooth profile errors

Computed tooth profile errors correspond very well to the measured ones in each hobbing test, as shown in Fig. 2. Therefore, static factors such as hob errors appear to have a large influence on tooth profile errors under these hobbing conditions. From a detailed comparison of the computed and measured tooth profile errors, the following results are obtained.

(1) The correspondence between the computed and the measured tooth profile errors at the trailing side is better than that at the leading side.

(2) The correspondence between both errors at the leading side is better in the case of full depth hobbing (Exp.2) and climb hobbing (Exp.5) than in the case of finish hobbing (Exp.1) and conventional hobbing (Exp.1), respectively.

Generally, one side of the tooth surface protrudes and the other side caves in at positions corresponding to positions of both side edges of the hob tooth which generates both tooth surfaces simultaneously, when the relative displacement between the hob and the work-gear is caused by the cutting force and the torsional vibration in the driving system of the hobbing machine. However, those convexo-concave surfaces were not found in these hobbing tests.

In following sections, the causes of the difference in correspondence between the computed tooth profile errors and the measured ones in leading and trailing

Fig. 1 Measurement of eccentricity in hob setting

Table 2 Experimental numbers and hobbing conditions
($m6$, $\alpha=20^\circ$)

No. of exp.	Gear parameters	Cutting condition				Eccentricity of hob ($\mu\text{m}/\text{deg.}$)	
		Cutting speed	Cutting direction	Feed	Cutting depth (radial direction)		
1	Z=21($\beta=0^\circ$) FCD40,HB180	22.9 (m/min)	Conv.	1,5 (mm/ rev)	0.3 (mm)	3/180°,10/180°	
2	Z=20 $\beta=0^\circ$ FCD40 HB188				Signal side cutting 0.9	Full depth cutting	2/0°,6/75°
3*						0.3	6/90°,10/90°
4*			6/150°,6/150°				
5			2/165°,10/105°				
6			2/150°,10/105°				
7			2/165°,10/105°				
8			Full depth cutting		6/210°,8/210°		
9	0.3		6/270°,10/180°				
10	Z=21($\beta= 0^\circ$) SCM415,HB156	22.9	Conv.	1,5 (mm/ rev)	0.3	6/270°,10/180°	
11	Climb				6.7	4/270°,10/180°	
12					0.9	6/270°,10/180°	
13	Conv.		6/270°,10/180°				
14	Climb		6/270°,10/180°				
15	FCD40,HB207						

Backlash of master worm gear (*: 62 μm , no mark: 40 μm , recommended value: 30–50 μm)
Face width of gears: 35–40mm

tooth surfaces are studied, by investigating the cutting state of both side cutting edges of hob teeth.

3.1.1 Rake angles of both trailing and leading side cutting edges

The rake angle (γ_n) of the side cutting edge is calculated from the following equation.

$$\gamma_n = \tan^{-1}(\tan \gamma \sin \alpha_c / \cos \lambda \tan \lambda \cos \alpha_c)$$

where γ is the rake angle of the top cutting edge, α_c is the normal pressure angle, λ is the lead angle and signs + and - are the trailing edge and leading edge, respectively.

The rake angles of the hob shown in Table 1 are 3.2° at the trailing edge and -3.2° at the leading one.

It is clarified that the trailing side cutting edge is sharper than the leading side one.

3.1.2 Cutting depth of both side cutting edges

For the spur gear hobbing of Exp.1 in Fig.2 and the helical gear hobbing of Exp.15 in Fig.3, the computed tooth profile errors differ from the measured ones, at leading tooth surfaces, to a small extent.

The difference between both errors is large, in particular, in tooth profiles generated by preceding tooth No.12 and following tooth No.6 from the central generating tooth.

Figure 4 shows the calculated undeformed chip

Fig. 2 Tooth profile errors in hobbing spur gears

Fig. 3 Tooth profile errors in hobbing helical gears

ϕ	Cutting edge No. -3										Cutting edge No. 3									
-0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	L.S.										T.S.									

(a) Exp. No. 1

ϕ	Exp. No. 15										Exp. No. 13									
-12.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-11.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-11.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-10.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-10.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-9.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-9.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-8.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-8.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(b) Cutting edge No. -12 in Exp. No. 13 & 15

ϕ	Exp. No. 15										Exp. No. 13									
-9.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-8.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-8.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(c) Cutting edge No. 6 in Exp. No. 13 & 15

Fig. 4 Undeformed chip thicknesses by side cutting edges (unit: μm , ϕ : revolution angle(deg.) of hob)

thicknesses⁽²⁾ in hobbing. Figure 4 (a) shows the undeformed chip thicknesses by both the leading edge of tooth No.-3 and the trailing edge of tooth No.3 that are generated near the pitch points on both tooth surfaces simultaneously in Exp.1; Fig.4 (b) and (c) show the thicknesses by both leading sides of teeth Nos.-12 and 3 in Exp.13 and Exp.15, respectively.

In spur gear hobbing, the undeformed chip by the leading edge is very thin and long, but on the other hand, that by the trailing edge is thick and short.

In the helical gear hobbing of Exp.15, the undeformed chip by the leading edge of tooth No.-12 is less than $10 \mu\text{m}$ in thickness and is long, and only the leading edge works. The undeformed chip thicknesses by the leading edge of tooth No.6 are also very small at the generating position (near $\phi=0^\circ$).

On the other hand, the undeformed chip thicknesses by the leading edges of teeth Nos.-12 and 6 in Exp. 13 are very large, and the cutting amount is also large.

The measured tooth profile error corresponds fairly well to the computed one at the leading tooth surface of Exp.13, as shown in Fig.3.

From the above results, deflection and rubbing are liable to occur between the cutting edges and the work-gear in the case of a small cutting depth of the leading edges.

However, it seems that deflection and rubbing hardly occur in the following cases:

- * In spur gear hobbing, the cutting depth of trailing side edges is larger than that of leading ones.
- * In climb hobbing, the cutting thickness at the start of cutting is large.

Fig. 5 Tooth surface micrographs by back scanning electron image

Fig. 6 Tooth traces

* In full depth cutting, the hob teeth work at the same time with the proceeding and following teeth.

3.1.3 Tooth surface of hobbed gears

Because it is very difficult to directly observe the cutting state of hob teeth during hobbing, the cutting traces of hob teeth, at the feed mark, on tooth surfaces are investigated by using a scanning electron microscope (BSE). Figure 5 shows photographs of tooth surfaces for the finish hobbing of Exp.1, for the full depth hobbing of Exp.2 and for the climb hobbing of Exp.5.

Many traces of rubbing and tearing are seen on the leading tooth surface of Exp.1 in Fig. 5. However, those traces are hardly observed on the trailing tooth surface of Exp.1 and both surfaces of Exp.2 and Exp. 5, though a small adhesion occurs on gear surfaces.

The cutting state can be also inferred from the tooth trace curves shown in Fig.6. The feed marks of the trailing sides can be seen clearly in every experiment. The feed marks of the leading sides appear in Exp.2 and Exp.5 to some extent, though they can hardly be observed in Exp.1.

The above results are summarized as follows. In hobbing by a hob with a small rake angle, it is difficult to leave cutting traces of leading edges on gear tooth surfaces owing to the cutting conditions such as deflection and rubbing. On the other hand, the cutting traces on trailing tooth surfaces result for the opposite reason. As a result, it is found that the cutting state is one of the important factors influencing tooth profile errors.

3.2 Influence of static errors of the hobbing process on tooth profile errors

As an example, the influence of static errors, such as hob and setting errors, on tooth profile errors of the hobbed gear in Exp.9 is investigated in detail.

Figure 7 (a) shows the computed tooth profile error and the measured one in Exp.9. Figure 7 (b) ~ (e) show the computed tooth profile errors arising from individual errors of the hob such as the setting error, the lead variation tooth to tooth and the single spacing error, and the feed and radial alignment of the cutting face.

As shown in Fig.7, the effect of the lead variation tooth to tooth and the single spacing error of the hob on the tooth profile error are most remarkable among the factors involved in the hobbing condition concerned. Moreover, the tooth profile and setting errors of the hob affect the tooth profile error of hobbed

gears in the same manner, yet the feed and radial alignment of the cutting face have hardly any influence.

The results show that the method of analyzing tooth profile errors shown in the first report is very useful for understanding the effects of static errors of the hobbing process on tooth profile errors.

3.3 Influence of dynamic errors of the hobbing process

In the hobbing process, the fluctuation in cutting forces is very large owing to the intermittent cutting and the fact that the driving system of the hobbing machine is very complex. In this section, the effects of dynamic errors caused by the fluctuation in cutting forces, the accuracy of the driving system, the rigidity of the hobbing machine and the built-up edges, etc., on tooth profile errors of hobbled gears are investigated.

3.3.1 Influence of the deflection of the hob and work arbors and the deviation of the hob toward its axis

In hobbing, displacement between the hob and the work-gear occurs with the deflection of the hob and work arbors and the deviation of the hob toward its axis.

Generally, the radial force on a work-gear is relatively large among three components, i.e., radial force, hob axial force and tangential force, and moreover, the bending rigidity of the hob and work arbors is low, with the result that the deflection of the hob and work arbors has a great influence not only on the tooth profile error but also on the tooth trace.

If the thrust rigidity of a hob arbor is low, the tooth profile error in simultaneous finish hobbing of both tooth surfaces and that in finish hobbing of only one tooth surface should probably differ from each other. As shown in Fig.2, the tooth profile errors in the cases of different radial forces and different thrust forces are investigated by comparing computed tooth profile errors of trailing sides with measured ones in

both full depth (Exp.1) and finish hobbing (Exp.2), conventional (Exp.1) and climb hobbing (Exp.5), respectively. Moreover, the measured tooth profile errors of both sides in the finish hobbings of both tooth surfaces (Exp.1) and only one tooth surface (Exp.4) are compared with the computed tooth profile errors as an example of different thrust forces.

As a result, the computed and the measured tooth profiles of trailing tooth surfaces resemble each other well, and both tooth profiles of leading surfaces in Exp.1 and Exp.4 are also very similar. Further, the tooth traces shown in Fig.6 are straight, and it is clear that the hob and work arbor of the hobbing machine have enough rigidity under these hobbing conditions that their deflection hardly affects the tooth profile errors.

3.3.2 Influence of torsional vibration in the driving system of the hobbing machine

In general, some change should appear in the tooth profiles of hobbled gears with a change in hob revolution (cutting speed) and cutting force, if torsional vibration occurs in the driving system of the hobbing machine. First, the effects of torsional vibration on spur gear hobbing are investigated in both cases of various cutting speeds (Exp.1,6 8 and Exp.2, 9) and various cutting depths (Exp.1,2 and Exp.3,4). In spur gear hobbing, the computed and measured tooth profile errors are much the same regardless of cutting speed or cutting depth. However, as cutting speeds increase, the number of small notches increases in the tooth profile curve. Under these hobbing conditions, it is found that the tooth profile errors arise from the static errors of the hob.

Next, the effects of torsional vibration in helical gear hobbing are investigated in the cases of Exp.12 and 15 shown in Fig.3. The correspondence between the computed tooth profile errors and the measured ones in helical gear hobbing is worse than in spur gear hobbing. Moreover, the tooth traces in helical gear

Fig. 7 Tooth profile errors arising from individual errors among static errors of the hob

Fig. 8 Tooth profile errors in hobbing steel gears

hobbing are also worse than in spur gear hobbing, as shown in Fig.6. In helical gear hobbing, the following causes are considered.

(1) The circumferential force, which is a component of the main cutting force to the work-gear, is very large.

(2) The deviation and deflection of the differential gear and feed system by torsional vibration affect the tooth profile, because the tooth profile of a helical gear is generated during a few revolutions of the work table.

The maximum tooth profile error caused by torsional vibration is less than $3\sim 4\ \mu\text{m}$, in any case, under these hobbing conditions. It seems that the dynamic property of the driving system of the hobbing machine used is very good.

3.3.3 Influence of the backlash of the table master worm gear

The backlash of the table master worm gear of the hobbing machine is changed to $40\ \mu\text{m}$ and $62\ \mu\text{m}$ in Exp.2 and Exp.3, respectively. The computed tooth profile errors and the measured ones in Exp.2 and Exp. 3, shown in Fig.2, are about the same, though some differences appear in the notches of the tooth profile. Furthermore, the computed tooth profile errors are compared with the measured ones in the cases of simultaneous finish hobbing of both tooth surfaces under various cutting depths (Exp.1 and Exp.2) and in the case of finish hobbing of only one tooth surface (Exp.4). There is little difference between the measured tooth profile error and the computed one in each experiment.

From the above results, it is found that the backlash of the master worm gear, within a specified standard range, hardly affects the tooth profile errors.

3.3.4 Influence of the tooth surface roughness

Figure 8 shows the computed and measured tooth profile errors of hobbing steel gears in Exp.10

and Exp.11. It appears that the waves of the measured tooth profile error curve resemble the waves of the computed tooth profile error curve in both cases. In steel gear hobbing, particularly in the case of a large cutting depth such as in Exp. 11, the tooth surfaces become rough⁽³⁾ owing to the built-up edge attached to the hob teeth, resulting in large tooth profile errors.

Therefore, it is necessary to use an exclusive finishing-hob⁽⁴⁾ and a hobbing procedure for reducing the occurrence of built-up edges, in order to improve the tooth profiles of hobbled gears.

4. Conclusion

The validity of the method of analyzing the tooth profile error of hobbled gears, shown in the first report, is demonstrated by the comparison with measured tooth profile errors under various hobbing conditions.

The following results are summarized:

(1) The tooth profile errors under the hobbing conditions concerned arise mainly from static errors such as hob errors. Among the static errors, the lead variation tooth to tooth and single spacing error of the hob have a large influence on tooth profile errors.

(2) Computed tooth profiles of the trailing tooth surface correspond very well with measured ones, but some differences between both tooth profile errors exist in leading tooth surfaces. This is considered to be caused by the cutting conditions such as deflection and rubbing between the cutting edge and the work-gear.

(3) In hobbing steel gears, the tooth surfaces become rough owing to the built-up edge, resulting in large tooth profile errors.

(4) Under the hobbing conditions in this paper, the hobbing machine used has a sufficient dynamic rigidity and very accurate driving system. Moreover, the backlash of its table master worm gear within a specified standard range hardly affects tooth profile

errors.

(5) Basic information for improving the accuracy of hobbed gears can be obtained by comparing computed tooth profile errors with measured ones.

The authors intend to investigate the influence of dynamic errors in the hobbing process on tooth profile errors.

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