621 CROWNING PROCESS OF P/M GEARS FOR AUTOMOTIVE TRANSMISSIONS BY FINISH ROLLING USING SCREW-SHAPED TOOL

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Summary

The purpose of this study is to examine a practical application of a finish rolling process using a screw-shaped tool to consolidate the surface layer of sintered Fe alloy gear and to improve the tooth profile accuracy and the load carrying capacity simultaneously. These objectives are almost attained in the previous paper except the crowning in tooth trace direction, which is the essential matter for gears in automotive transmissions. In this paper, a numerical control finish rolling machine is developed to enable the crowning process. In this new apparatus, the amount of radial feed of the tool is synchronized with the axial feed of the workpiece to put a specified crowning on the gear teeth. A simple calculation method is proposed to decide the rolling orbit for crowning. The crowning profile predicted in the analysis agree well with the experimental ones. Gears with a good tooth profile and a good surface finish can be obtained.

Keywords: finish rolling, burnishing, P/M gear, screw-shaped tool, numerical control, crowning, rolling orbit, consolidation, accuracy, surface roughness

1 Introduction

At present, sintered Fe alloy gears (called P/M gears hereafter) in automotive transmissions are produced by HIP or hot forging after sintering the preforms, finished by gear shaving and carburized. Those processes are very time consuming and relatively high costs. If these P/M gear shaped preforms can be finished by some economical and high-speed plastic forming method, the number of production process can be drastically shortened and the total production cost is reduced by half.

The authors proposed a new method of finish gear rolling using a screw-shaped tool^[1,2]. In the previous paper^[3], preliminary finish rolling experiments are carried out to examine the basic rolling characteristics of P/M gears. The void rate in the surface layer of the gear teeth can be decreased to the desired level and gears with a good tooth profile accuracy and a good surface finish can be produced only in one rolling pass. But, it is impossible to put a crowning on the gear teeth using this equipment, since the distance between the tool and the work is kept constant during rolling.

In order to solve this problem, we developed a numerical control finish rolling machine in which the positioning of gears during rolling is controlled with servo mechanics. The basic rolling characteristics of this new apparatus are firstly examined. A simple calculation method of the rolling orbit for crowning is proposed and evaluated experimentally.

2 Experimental apparatus, procedures and conditions

2.1 Numerical control finish rolling machine

Figure 1 shows the upper view of the newly developed finish rolling apparatus. The two servomotors control the motion of the gear during rolling. Hence, the amount of the radial feed X of the gear is numerically changed at each position in tooth trace direction Z to put a specified crowning on the gear teeth. The position of the gear in both directions is set at an interval of $1\mu\text{m}$, though the minimum controllable unit in this apparatus is $0.1\mu\text{m}$. The rolling orbit of the gear during rolling is approximated by linear interpolations as shown in **Figure 2**. **Figure 3** shows the photograph of the screw-shaped tool and the P/M gear installed in the apparatus. The tool rotates the gear freely which mechanism resembles to the generating motion in the finish gear hobbing. The rotating direction of the tool is the same as the axial feed direction of the gear (climb rolling).

2.2 Gears and screw-shaped tool

The gears used in this experiments are made from the sintered Fe alloy preform disks. The manufacturing process of the P/M disks is changed from 1 times press 1 times sintered^[3] to 2 times presse 2 times sintered to improve the load carrying capacity of the gear. This operation reduces the mean void rate of the preforms by half. The chemical compositions and properties of P/M materials are shown in **Table 1**. Since a full density of this material is 7.80g/cc , the mean void rate is about 5% in volume. **Table 2** shows the dimensions of workpiece spur gears. The gears are cut by the standard hob and rolled by

Figure 1: Experimental apparatus

Figure 2: Scheme of finish gear rolling process for crowning

Figure 3: Configuration of the tool and the gear installed in the apparatus

Table 1: Chemical composition and properties of P/M materials

P/M materials			
Density (g/cm ³)	Void rate (%)		Hardness (Hv)
7.41	5.00		180
Compositions (%)			
Fe	C	Ni	Mo
Bal.	0.06	0.55	1.03

the modified screw-shaped tool. The rolling tool is a right-hand screw shaped tool of SKH51 of 76.6mm in outer diameter. The surface of the tool is ground and coated by TiN. The surface roughness of the tool is finished by $R_z < 2.0\mu\text{m}$. **Figure 4(a)** and **(b)** show the tooth trace and the tooth profile shape of the target products. We intend to put not only about $30\mu\text{m}$ crowning on the teeth trace but also about $30\mu\text{m}$ modification on the tip of the gear teeth profile by finish rolling. **Figure 5** shows the screw shaped tool with a modified tooth profile designed for this object.

2.3 Finish rolling conditions

A tool revolution speed of 260rpm and a gear feed rate of 1mm/rev are employed. A commercial press-oil named DAPHNE DYNADRAW LF-7 (made in Idemitsu Kosan Co. Ltd.) is used as a lubricant.

3 Calculation method of rolling orbit for crowning process

3.1 Basic experiments

The rolling experiments are firstly carried out under the condition of a constant amount of rolling stock to examine the basic characteristics of the new apparatus. The amount of radial feed of the tool Z_0 is set at $450\mu\text{m}$ and $600\mu\text{m}$ to achieve the sufficient consolidation in the surface layer of the gear teeth^[3]. **Table 3** shows the relationship between the amount of rolling stock S_0 and the amount of stock rolled ΔS . As ΔS increases in proportion to S_0 , the rolling rate $\Delta S/S_0$ is almost kept constant about 60%. Hence, the calculation method of the rolling orbits for crowning is constructed based on the assumption of the rolling rate constancy.

Table 2: Dimensions of spur gears

Module	m	3mm
Pressure angle	α	20°
Number of teeth	z	26mm
Face width	b	20mm

Figure 4: Ideal tooth trace and tooth profile of the product gear

Figure 5: The modified tooth profile of the screw-shaped tool

Table 3: Decrease and rate of decrease in tooth thickness

(Unit : μm)			
Z_0	S_0	ΔS	$\Delta S/S_0$ (%)
450	150	85	56.7
600	200	120	60.0

3.2 Calculation method of rolling orbit

The rolling orbit for crowning is calculated according to the following procedures.

1st-step: The tooth trace profiles on both sides near the pitch point of the rolled gear are measured by CLP at an interval of 15 μ m. The highest point in a measurement data is defined as the reference point (RP). Then we can obtain the relationship between X_n (the distance from a data point to RP) and H_n (the height difference between a data point and RP) as shown in **Figure 6(a)**. In this paper, the amount of radial feed of the tool at the tooth trace center is set to 450 μ m hereafter.

2nd-step: If the amount of stock rolled at RP (ΔS) is assumed to be equal on both sides, we can calculate the distribution of rolling rate R_n at X_n with the next equation.

$$R_n = \frac{\Delta S + H_n}{Z_0 \cdot \sin \alpha} = \frac{\Delta S + H_n}{S_0} \quad (1)$$

Figure 6(b) shows an example of R_n . It is observed that the distribution of R_n on follower side is smaller than that on driven side especially at both ends.

3rd-step: Since we put an assumption that R_n is independent from the amount of rolling stock, we can calculate the rolling orbit Z_n with the next equation.

Figure 6: Calculation method of rolling orbit for crowning process

Figure 7: Rolling orbits by several straight-lines interpolation

$$Z_n = \frac{\Delta S + C_n}{R_n \cdot \sin \alpha} \quad (2)$$

Here, C_n is the ideal height difference at X_n calculated from the tooth trace profile shown in Figure 4(a). However, Z_n cannot be decided uniquely at this stage, because R_n is different on both sides and is not optimized yet. In this paper, we select R_n on follower side as first approximation and determine Z_n as shown in Figure 6(c).

4 Results and considerations

Since the rolling orbit calculated by equation (2) consists of the coordinate data above 1,300 points, it is very tedious and time consuming to input all these data into the NC program. Then, the actual rolling orbit Z_n' is approximated by several linear interpolations. **Figure 7** (a)~(c) show the examples of the rolling orbit interpolated by 3, 5 and 7 straight lines respectively. **Figure 8** (a)~(c) show the comparison of the tooth trace curves of gears rolled by those linear interpolated orbits. The broken lines show the ideal tooth trace profile. Comparing these results on follower side, the tooth trace curves gradually approaches to the ideal one as the number of interpolation lines increases. The tooth trace profile of 5 lines interpolation satisfies the target accuracy, and the tooth trace profile of 7 lines interpolation entirely agrees well with the ideal one. The tooth trace profile on driven side also becomes gradually smooth as the number of interpolation lines increases, but the tooth profile error is hardly improved especially near the left side end. This is because the rolling rate on driven side is considerably larger than that on follower side around this portion. It is necessary to consider this difference of rolling rate to optimize the crowning profile on both sides. The tooth trace profile after rolling can be predicted with the next equation.

$$Q_n = Z_0 \cdot R_0 - Z_n' \cdot R_n \quad (3)$$

Here, R_0 is the rolling rate at the

Figure 8: Comparison of the tooth trace curves in each linear interpolation method

Figure 9: Comparison of tooth trace curves between experiment and calculation

reference point. **Figure 9** shows the comparison between the tooth trace curves obtained in experiment and that in calculation in the case of 7 lines interpolation. Both results agree well on both sides, indicating that our basic concept is correct and this calculation method has enough approximation accuracy on practical use.

Figure 10 shows the comparison of the tooth profile curves in each cross sections of the rolled gear. It is found from these figures that the tooth profiles on both sides are hardly affected by crowning process and their accuracies satisfy the desired level of JIS 3~4 grade. **Table 4** shows the comparison of the surface roughness of gears between before and after rolling. Those in both directions are greatly improved up to the same degree of the surface roughness of the screw-shaped tool.

Figure 10: Comparison of tooth profile curves in each cross-section rolled by the modified tool

Table 4: Comparison of the surface roughness (Unit : μm)

Z_0	Toot profile direction		Tooth trace direction	
	D	F	D	F
Before rolling	4.64	4.58	2.56	2.46
After rolling	1.22	1.31	0.26	0.51

D : Driven side F : Follower side

5 Conclusions

A numerical control finish rolling machine using screw-shaped tool is developed to enable the crowning process for P/M gears. The basic characteristics of this new apparatus are firstly examined. The rolling rate is found to be hardly affected by the amount of rolling stock. A simple calculation method of the rolling orbit for crowning is proposed on the assumption of the rolling rate constancy. The actual rolling orbit is approximated by several linear interpolations. The crowning shapes predicted in the analysis agree well with the experimental ones. Tooth profile accuracies and the crowning shapes of the rolled gear teeth satisfy the desired accuracies of JIS 3~4 grade.

References

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