Crowning Process of P/M Gears for Automotive Transmissions by Finish Rolling Using Screw-Shaped Tool*

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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 gears and to improve the tooth profile accuracy and the load carrying capacity simultaneously. These objectives are almost attained in the previous works 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 rolled gear teeth. A simple calculation method is proposed to decide the rolling orbit for crowning. The crowning profiles predicted in the analysis agree well with the experimental ones. Gears with a good tooth profile and a good surface finish can be obtained.

Key Words: Plastic Working, Gear, Powder Metallurgy, Accuracy, Surface Roughness, Finish Rolling, Screw Shaped Tool, Crowning, Void, Consolidation

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 realize full consolidation and ensure the enough load carrying capacity of P/M gears. However, their total production costs are comparable to or higher than those for conventional steel gears. If these P/M gear shaped preforms can be finished by

some economical and high-speed plastic forming method, the number of production processes can be drastically shortened and the total production costs are reduced by half.

The authors proposed a new method of finish gear rolling using a screw-shaped tool^{(1),(2)}. The objective of this study is to replace the HIP and gear shaving process by this rolling to reduce the production costs of P/M gears drastically. In the previous papers⁽³⁾ preliminary finish rolling experiments are carried out to examine the basic rolling characteristics of P/M gears. The void ratio in the surface layer of gear teeth can be decreased to the desired level only in one rolling pass. Gears with a good tooth profile and a good surface finish can be produced using a screw-shaped tool with a concave tooth profile. But, it is impossible to put a crowning on gear teeth by the conventional equipment, since the distance between a tool and a workpiece is kept constant during rolling.

In this paper, to solve this problem, we developed a numerical control finish rolling apparatus, using servo mechanics to control the amount of rolling stock at each position in tooth trace direction during rolling. The basic rolling characteristics of this new

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apparatus are firstly examined. A simple calculation method of a rolling orbit for crowning is proposed and evaluated experimentally.

2. Experimental

2.1 Numerical control finish rolling machine

Figure 1 shows the schematic drawing of the newly developed numerical control finish rolling apparatus. The two servomotors control the motion of a gear during rolling. Hence, the amount of radial feed Z of a gear can be numerically changed at each position in tooth trace direction X to put a specified crowning on the rolled gear teeth. The position of a gear in both directions is set at a division of $1\mu\text{m}$ during rolling, though the minimum controllable unit in this apparatus is $0.1\mu\text{m}$. In an actual rolling experiment, the orbit for crowning calculated by the analysis is approximated by a several straight lines interpolation as shown in Fig. 2. Figure 3 shows the photograph of a screw-shaped tool and a P/M gear installed in the apparatus. The tool rotates the gear freely which mechanism resembles to the generating motion in a finish gear hobbing. The rotating direction of the tool is the same as the axial feed direction of the gear, that is the climb rolling.

Fig. 1 Schematic drawing of experimental apparatus

Fig. 2 Finish rolling process for crowning

2.2 Gears and screw-shaped tool

Gears used in this experiments are made from sintered Fe alloy preform disks. The manufacturing process of P/M disks is changed from 1 time press 1 time sintering⁽³⁾ to 2 times press 2 times sintering to improve the load carrying capacity of gears. This operation can reduce the mean void ratio of preforms by half. Material properties and chemical compositions of P/M gears are shown in Table 1. Since a full density of this material is 7.80 g/cc , the mean void ratio is about 5% in volume. Table 2 shows the dimensions of workpiece spur gears. Gears are cut by a standard hob and rolled by a modified screw-shaped tool. The rolling tool is a right-hand screw-shaped tool of SKH51 of 76.6 mm in outer diameter. The surface of the tool is ground and coated by TiN. The surface roughness of the tool is finished by $R_z < 2.0\mu\text{m}$. Figures 4(a) and (b) show the tooth trace and the tooth profile shape of the target gear product. We intend to give not only about $30\mu\text{m}$ crowning on the

Table 1 Material properties and chemical compositions of P/M gear

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

Table 2 Dimensions of spur gears

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

Fig. 3 Configuration of tool and gear installed in apparatus

Fig. 6 Calculation method of rolling orbit for crowning process

very tedious and time consuming to translate all of these data into the NC program called GM code. Then, in this experiment, the actual rolling orbit Zn' is approximated by linear interpolations as mentioned before. Figures 7(a)-(c) show the examples of the rolling orbit interpolated by 3, 5 and 7 straight lines respectively. Figures 8(a)-(c) show the comparison of the tooth trace curves of gears rolled by those linear interpolated orbits. The broken lines are the ideal tooth trace profile. Comparing these results in the follower side, the tooth trace profile 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 in the driven side also becomes gradually smooth as the number of interpolation lines increases, but the tooth profile error is hardly improved especially around the left side end. This is because the rolling rate in the driven side is considerably larger than that in the follower side around this portion. It is necessary to consider this difference of the rolling rate to

Fig. 7 Rolling orbits approximated by several straight lines interpolation

optimize the crowning profile on the whole.

We can predict the tooth trace profiles after rolling using the next Eq.(3).

$$Qn = Z_0 \cdot R_0 - Zn' \cdot Rn \quad (3)$$

Here, R_0 is the rolling rate at the reference point. Figures 9(a) and (b) show the comparison of the tooth trace profiles between experiment and 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.

4.2 Accuracies and consolidation

Figure 10 shows the comparison of the tooth profiles in each cross section of the rolled gear. Figures 11(a) and (b) show the tooth profile and the lead 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

Fig. 8 Comparison of tooth trace profiles rolled by each linear interpolation orbit

Fig. 9 Comparison of tooth trace curves between experiment and calculation

satisfy the desired level of JIS 3-4 grade. Table 4 shows the comparison of the surface roughness of the rolled gear teeth between before and after rolling. Those in both directions are much improved up to the same degree of the surface roughness of the screw-shaped tool.

Figures 12(a) and (b) show the distributions of the void ratio in the surface layer near the pitch point after rolling. From these figures, the material consolidation on both sides is intensively promoted in the surface layer of 1.0 mm in depth. The void ratio in the follower side decreases to 1% or less and that in the

Fig. 10 Comparison of tooth profiles in each cross section of rolled gear

driven side becomes almost 0%.

5. Conclusions

A rolling machine with axis intersection type controlled by servo mechanics is developed to enable the crowning process for P/M gears. The conclusions are summarized as follows.

(1) 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.

(2) A simple calculation method of the rolling orbit for crowning is proposed based on the assumption of the rolling rate constancy. The actual rolling orbit is approximated by a several straight lines interpolation. The crowning shapes predicted in the analysis agree well with the experimental ones.

Table 4 Comparison of surface roughness

Z_0	(Unit : μm)			
	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

(a) The driven side

(b) Follower side

Fig. 11 Tooth profile and lead

(3) The tooth profile accuracies and the crowning shapes of the rolled gear teeth satisfy the desired level of JIS 3-4 grade.

(4) Gears with a good tooth profile and a good

(a) The driven side

(b) Follower side

Fig. 12 Distribution of void ratio in surface layer

surface finish can be obtained.

(5) The void ratio of the rolled gear teeth is decreased to 1% or less in the surface layer of 1.0 mm in depth by only one rolling pass.

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