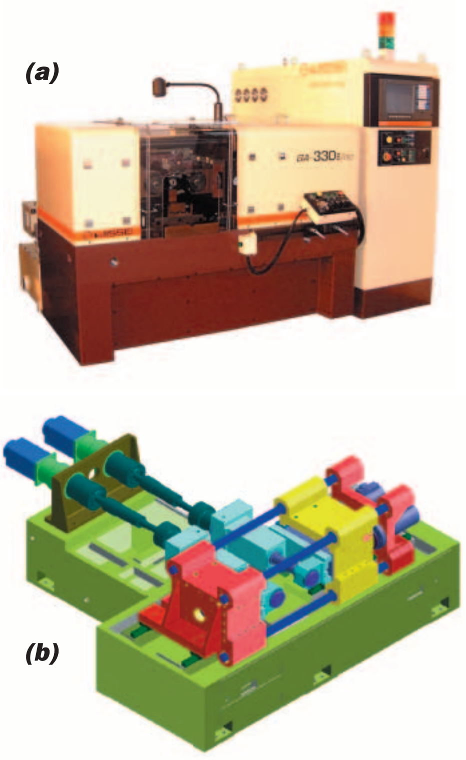
fORM ROLLiNG for Finishing Powder Metal GEARS

For many years researchers have struggled to refine the process of using powder metal to form lower-cost and higher-quality gears.

Nissei describes its work in bringing that dream one step closer to reality.

Figure 1 — CNC thread rolling machine GALAXY
(a) Front view
(b) Schema of appearance figure



by Teruie Takemasu, Ph.D.,
and Toshinaka Shinbutsu

In this article we introduce a finish rolling process for sintered Fe alloy gears using a new CNC form rolling machine: the Galaxy, which has been developed by Nissei Co. Ltd. The Galaxy is a two-roller dies plunge feed type in which seven axes are numerically and simultaneously controlled during rolling, reaching the highest precision currently available in this type of machine.

First we will show the machine's unique structure for thread, screw, and gear rolling. Second, we will describe the finish rolling experiments of sintered Fe alloy gears—referred to as "P/M," for powder metal gears, from this point forward—that we have conducted. Gears with good tooth profile accuracy and surface finish are produced using a tool with a modified tooth profile. We have also confirmed that the tooth surface and the fillet at the root of the gear teeth can be rolled simultaneously in one rolling process. The consolidation level in the surface layer of rolled gear teeth can be achieved to the desired level by adjusting the amount of rolling stock normal to the tooth surface up to 150µm. The results of roller fatigue tests prove that the surface fatigue durability is improved by 80 percent or more by finish rolling.

Keywords: Form rolling, CNC, two-roller dies plunge feed type, burnishing, P/M gears, modified tool, tooth profile accuracy, surface roughness, simultaneous rolling, consolidation, surface fatigue durability.

Introduction

Many researchers have studied various methods of the gear rolling process since World War II, the main purpose having been to establish a mass production process in plastic forming for high-strength precision gears. Finish gear rolling by the two-roller plunge feed type is actually in practical use, most widely within the automotive industry. This is because finish gear rolling has many advantages, such as short manufacturing time, suitability to automation, long tool life, good surface finish, and improvement of the tooth surface strength by work hardening. However, there are still a number of challenges to be met, such as low flexibility, poor tooth profile accuracy, and the simultaneous rolling of the tooth surface and fillet at the root. The tooth profile of the tool used in finish gear rolling must be modified to obtain a gear with a high tooth profile accuracy. This is because the contact pressure fluctuates due to the change in the number of contacting points and the elastic deflection of gear teeth during rolling. We believe—and our tests indicate—that the Galaxy machine has the potential to solve these problems.

Sintered Fe alloy is used prominently as the material for gears used in manufacturing automobile transmissions. Since P/M gears can drastically reduce the number of production processes, it is estimated that the total production costs of gears will be cut by about half. For this article, preliminary finish rolling experiments of P/M gears using the Galaxy machine were first conducted to examine the basic rolling conditions. A gear-shaped tool with an unmodified tooth profile was used. Secondly, simultaneous rolling experiments using the tool with a modified tooth profile were carried out to obtain a gear with good tooth profile accuracy. Finally, the two-rollers contact fatigue tests were done to confirm the effects of finish rolling on the surface fatigue durability.

A High-Precision CNC Rolling Machine

Motivation to Develop Galaxy

Many believe that high-precision threads and gears should be produced by the cutting and grinding method, and that thread rolling machines are only used for making threads or screws. We have found, however, that thread rolling is an excellent production method in terms of cost, material savings, pollution reduction, production speed, and uniform quality.

The Galaxy CNC form rolling machine, shown in Figure 1, has allowed for a change from the normal machine parts production method from cutting to form rolling. The machine's development was in response to a great demand in the industry for low-cost and environmentally-benign production. There is no doubt that metal deforming is the best way to make parts, but applications for high-precision parts such as gears are still limited.

Description of Techniques

Figure 2 shows the overview structure of the Galaxy. The machine has four tie rods for rigidity, so that the load during forming is distributed evenly among the tie rods shown in the figure. Accordingly, the CNC system can operate efficiently by reading the exact distance between the right and left spindles by means of a bridge-like linear sensor mounted on spindle heads. The right and left spindle approach the workpiece simultaneously. The spindle approach is controlled by a servo valve at the resolution of 1 micrometer, and the tilt of the spindle is controlled to 1/1,000 of a degree.

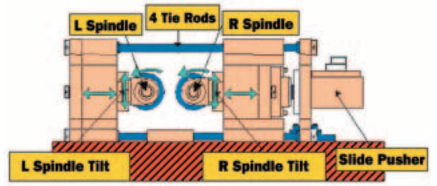


Figure 2 — Structure of developed machine

Synchronicity deviation between the two spindles' rotation is less than 1/100 degree because of the full closed control system. Controllable axes are seven in total, as shown in Figure 3. The use of special optical data transmission by means of international standard "SERCOS" and program language means that a motion control card is not necessary in this system.

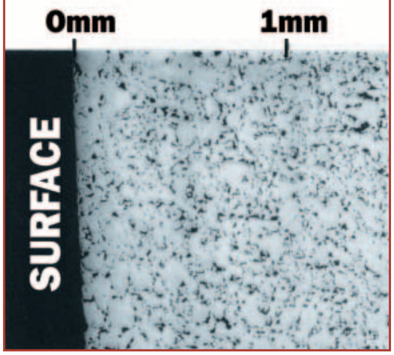
Figure 3 — 7 controllable axes

Finish Rolling Experiments of P/M Gears

Research Background

At present, P/M gears in automotive transmissions are produced by HIP or hot forging after sintering the preforms, finished by gear shaving and carburization. These processes result in full consolidation and ensure sufficient load carrying capacity of the gears. However, their total production costs are comparable to, or higher than, those for conventional steel gears. The authors proposed a new production process of finish gear rolling using a newly developed form rolling machine, with the objective being to replace the HIP and gear shaving process to drastically reduce the production costs of P/M gears.

Figure 4 — Microscopic photograph of P/M gear texture in a cross section before rolling



Experimental Conditions

The workpiece used in these experiments was of sintered Fe alloy gear shaped preforms. Two kinds of manufacturing processes are employed to produce those preforms. One is "1 press, 1 sintered" and another is "2 presses, 2 sintered." The latter operation can reduce the initial void ratio of preforms by half. Figure 4 shows a microscopic photograph near the surface of the workpiece before rolling. The chemical compositions and properties of P/M gears are shown in Table 1. Since a full density of this material is 7.80g/cc, the mean void ratio of 1P1S is about 10 percent in volume, and 2P2S about 5 percent. The workpiece was a standard spur gear: three-module, 20 degree pressure angle, 26 teeth number, and 20mm face width.

The rolling tool was a spur gear of SKH51. Two kinds of tools were prepared. One was an unmodified tool with a standard tooth profile (as shown in Figure 5), and another was a modified tool with a concave tooth profile (Figure 9), which is explained in detail later. The teeth surfaces of both tools are finished by grinding by $Rz<2.0\mu m$. The accuracy of those tools meets JIS class 1. The amount of rolling stock (T_0) normal to the tooth surface of gear teeth can be calculated by the equation of $T_0=S_0 *\sin\alpha$ (α: pressure angle).

A tool revolution speed of 60 rpm and a tool radial feed rate of 0.167 mm/rev were employed. A commercially available Daphne Dynadraw LF-7 (made by Idemitsu Kosan Co. Ltd.) was used as a lubricant. Figure 6 shows the contact state between the tool and the gear during rolling. In this article, the tooth surface driven by the tool is called the "driven side," and the opposite surface is referred to as the "follower side." In the driven side, the tool first contacts with the tip of the gear marked with an "x," and the contact area moves to the root. The tool tip corner also first contacts with the fillet surface of the gear marked with ▼, and the contact between the tool and the gear finishes at point △. In the follower side, the tool first contacts with the root surface of the gear marked with ●, and the rolling proceeds in both directions of ③ and ④.

Rolling Experiments with an Unmodified Tool

Preliminary finish rolling experiments of P/M gears using the unmodified tool are firstly done to examine the rolling

Table 1 — Material compositions and properties of P/M gears

P/M Gears

Compositions (%)			
Fe	**C**	**Ni**	**Mo**
Bal.	0.06	0.55	1.03
	Density (g/cm^3)	Void ratio (%)	Hardness (Hv)
1P1S	7	10.25	100
2P2S	7.41	5	120

Table 2 — Variation of tooth thickness

(Unit : mm)

S_0	T_0	ΔT	$\Delta T/T_0$(%)
225	75	61	80.7
300	100	83	82.5
450	150	121	80.7

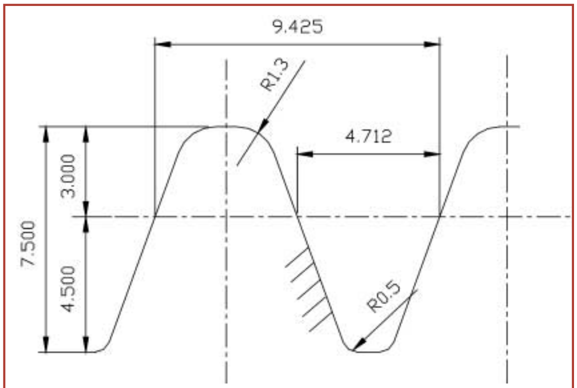


Figure 5 — Tooth profile of an unmodified tool

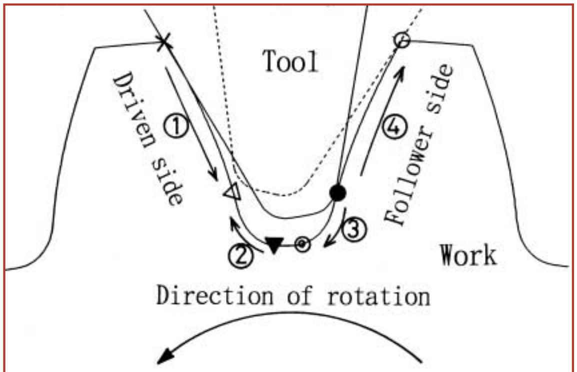


Figure 6 — Contacting state during rolling

characteristics of P/M gears and the basic rolling conditions. The unmodified tool is 3.0mm in addendum and 4.5mm in dedendum to allow the maximum amount of radial feed of the tool (S_0) up to 750µm (T_0 = 250µm). Here, the amounts of radial feeds of the tool are set to 225µm, 300µm and 450µm. Thus, the corresponding amounts of rolling stock T_0 are 75µm, 100µm and 150µm respectively.

Table 2 shows the relationship between the amount of rolling stock T_0 and the amount of stock rolled ΔT. Figure 7 shows the distributions of the amount of stock rolled, and examples of the tooth profile curves are shown in Figure 8. The average amounts of stock rolled ΔT on both sides are almost equal in each radial feed of the tool, and ΔT increases in proportion to T_0. Therefore, the ratio of $\Delta T/T_0$ is almost kept constant. All of the distribution curves are convex near the pitch point, that is, the tooth profile curves become depressed by about 40mm at the pitch point. This is because both sides of the gear tooth contact with the tool near the pitch point at the same moment and the amount of elastic deflection of the gear tooth is depressed.

Rolling Experiments with a Modified Tool

In the previous rolling experiments using the unmodified tool, tooth profiles of the rolled gears became heavily concave around the pitch point. There are two methods to solve this problem. One is rolling gears with a convex tooth profile by the unmodified tool, and another is rolling gears with a standard tooth profile by the modified tool. For this article, the latter method was employed.

The rolling experiments of steel gears proved that the rolled tooth profiles by this method are not much affected by the amount of rolling stock, though it is generally difficult to optimize the concave tooth profile of the modified tool. Figure 9 shows the tooth profile of the modified tool. The concave shape of the tool is designed to reflect the concave shape of the gear rolled by the unmodified tool using three straight lines approximation. The addendum of the modified tool (3.3mm) is set longer than that of the unmodified tool by 0.3mm in order to roll the tooth and the fillet surface of gear teeth in one rolling process, which is called simultaneous rolling. Since this rolling process can consolidate not only the tooth surface but also the root fillet near the critical point, it is expected that both the surface fatigue strength and the bending fatigue strength can be improved simultaneously. Three levels of radial feed of the tool—450µm, 540µm, and 600µm—were employed to achieve sufficient consolidation of the surface layer of the rolled gear teeth.

The ratio $\Delta T/T_0$ was kept constant (=0.8) in each radial feed of the tool during this experiment. Figure 10 (a)~(c) shows the examples of the tooth profile curves after rolling. Comparing these results, the concave amounts of rolled gears on both sides were scarcely affected by the amount of rolling stock. Observed in detail, all of the tooth profiles in the driven side are slightly concave. This is due to the fact that the concave amount of the modified tool is not enough on this side, and the appropriate amount of concavity of the tool is assumed to be about 40µm. While the tooth profile curves in the follower side are entirely flat, a little convexity, about 5µm in depth, is observed near the pitch points. However, it should be easy to correct these convexities by modifying the tooth shape of the tool.

Figure 7 — Distribution of the amount of stock rolled

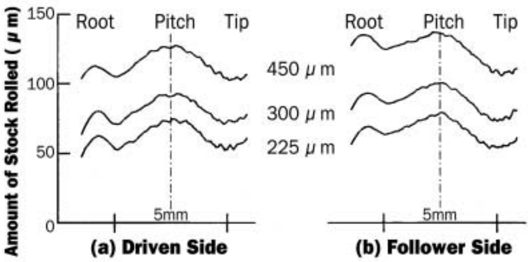
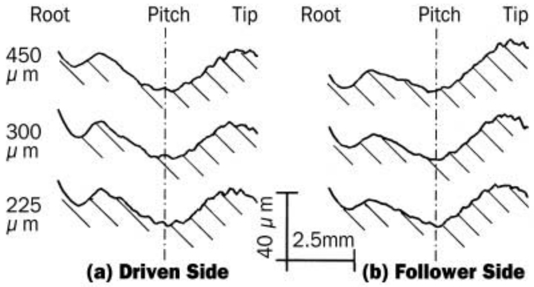


Figure 8 — Tooth profile curves rolled by standard tool



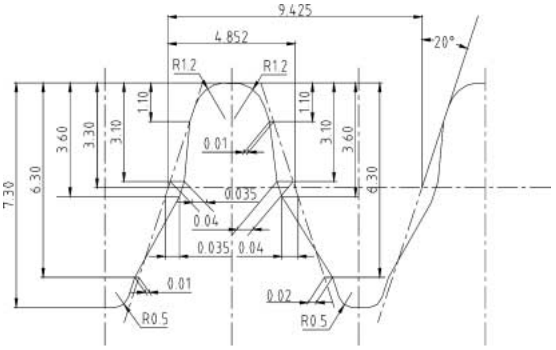


Figure 9 — Tooth profile of modified screw-shaped tool

Figure 11 shows examples of the tooth trace curves of S_0=600μm. The leads of the rolled P/M gears became almost flat on both sides, though the material droops slightly at both ends for the sake of the edge effect.

The distribution of the amount of stock rolled on the rolled tooth surface is shown in Figure 12. The fillet surfaces in the root near the most critically stressed point, calculated by Hofer's 30 degree tangent method, are successfully rolled to the same extent as that of the tooth surface.

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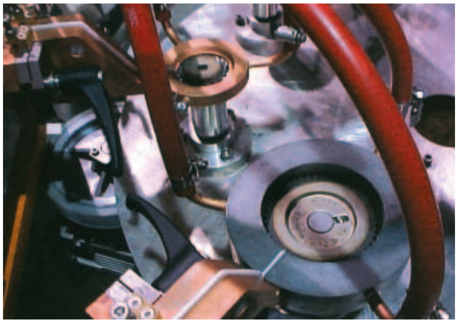

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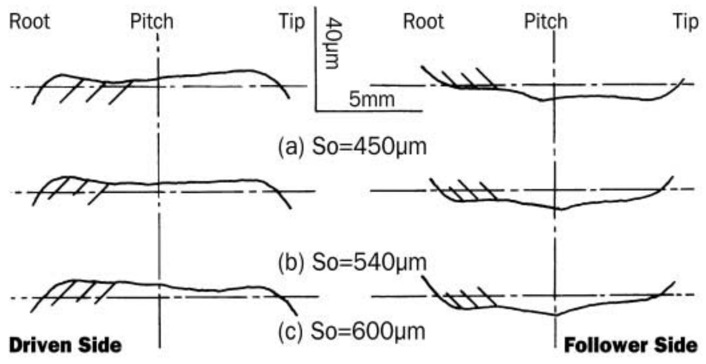
Figure 10 — Tooth profile curves rolled by modified tool

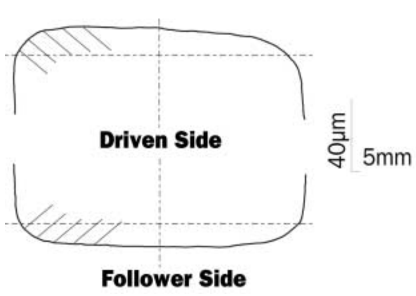


(a) So=450µm

(b) So=540µm

(c) So=600µm

Figure 11 — Tooth trace curves after rolling



Consolidation in Surface Layer

We also examined the distributions of the void ratio near the surface layer by image analysis to evaluate the state of consolidation of P/M texture more precisely. The void ratio is calculated in a cross section 15mm in width (axial direction) and 2.5mm in depth from the outer surface at an interval of 0.04mm (radial direction). Figure 13 (a) and (b) show the comparison of distributions of the void ratio near the pitch point of S_0=600µm between 1P1S and 2P2S. It is observed from these figures that the consolidation of the material is intensively promoted in the surface layer of 1.0mm in depth for both materials, and the void ratio in this area of 2P2S becomes almost zero.

Rolling Experiments and Two-Rollers Contact Fatigue Tests for P/M Rollers

Figure 14 shows the dimensions of 1P1S P/M rollers used in the rolling experiments and two-rollers contact fatigue

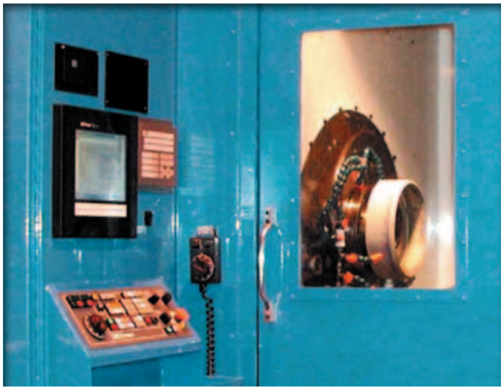

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Figure 12 — Distribution of the amount of stock rolled

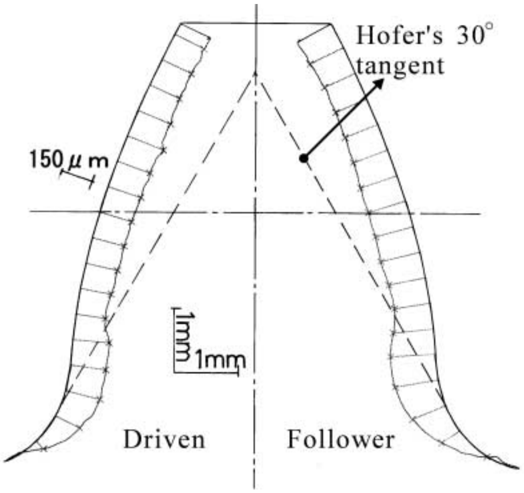


Figure 13 — Void ratio in surface layer after rolling
(a) 1P1S
(b) 2P2S

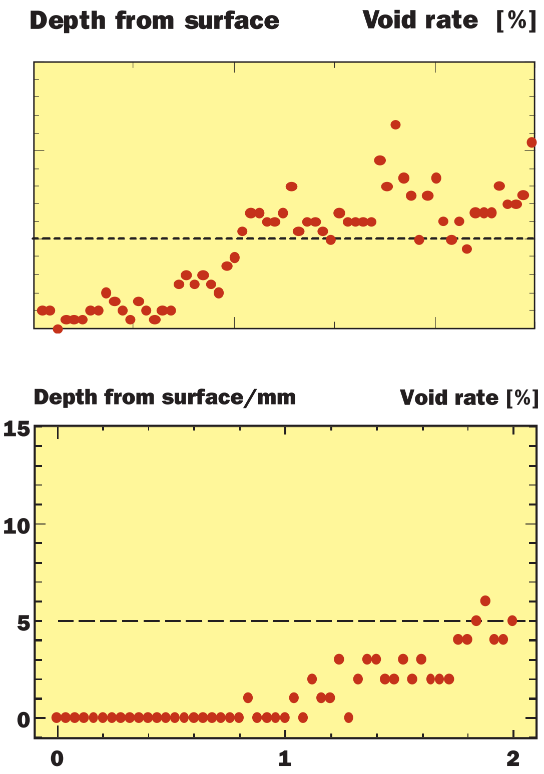


Figure 14 — Shapes of test rollers

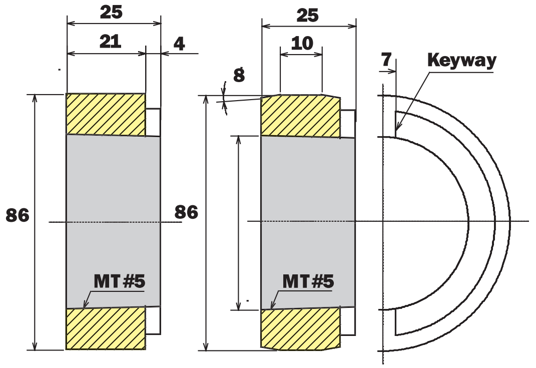
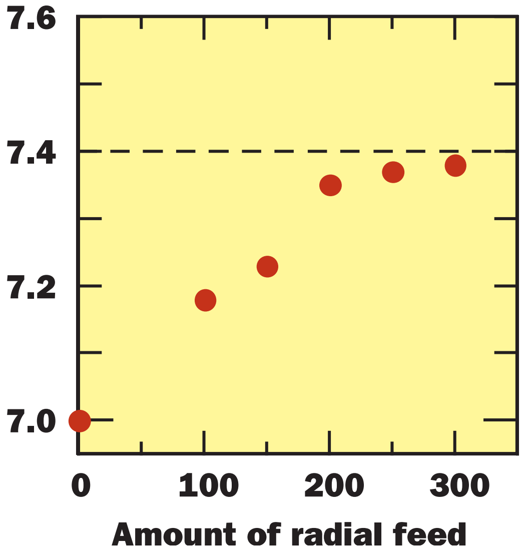


Figure 15 — Void ratio in surface layer



tests. Figure 15 shows the relationship between the mean density near the surface layer of the workpiece (r) and the amount of depth of indentation of the tool (S_0). S0 is varied from 100µm to 300µm at an interval of 50µm, and "ρ" is measured by the γ-ray method. The range of measurement is the surface area of 1.5mm in depth (radial direction) and 15mm in width (axial direction). "ρ" increases in proportion to S_0 when S_0<200µm, but saturates when S_0>200µm. We assign here the target value of the void ratio to 5 percent (=7.41g/cc) or less in the surface layer of 1.0mm in depth. This value is satisfied when S_0>200µm.

The two-rollers contact fatigue tests were carried out with three kinds of roller specimens called Group-A, Group-B and Group-C. They are carburized at 930°C and the outer

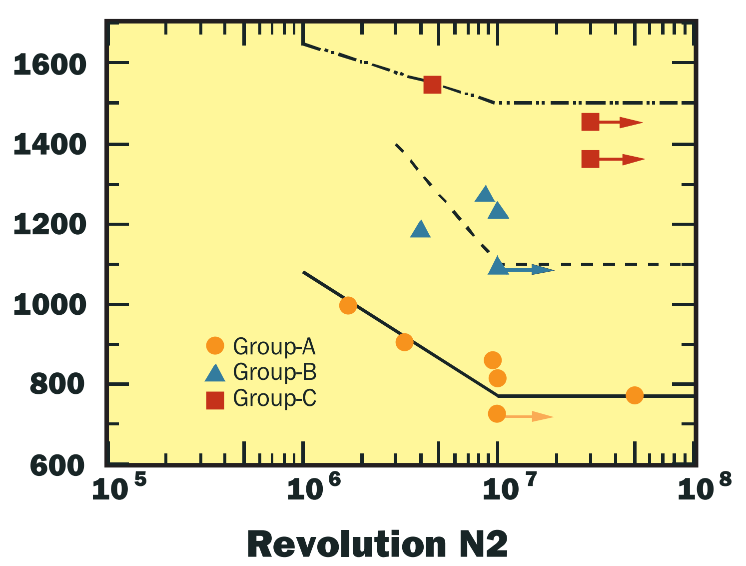


Figure 16 — S-N curves for surface fatigue test

surfaces are ground to Ry<0.2μm. Group-A is the unrolled rollers of which carburizing depth is about 1.0mm. Group-B and Group-C are the rolled rollers of S_0= 300μm, of which carburizing depths are about 0.6mm and 1.0mm respectively. Figure 16 shows the results of the two rollers contact fatigue tests. The representative damage of these P/M rollers is scoring. The surface durability of Group-A is about 800Mpa, and the scoring depth is about 0.3~0.4 mm from the surface. The surface durability of Group-B is about 1,200Mpa, and the scoring depth is about 0.6mm, which coincides with the carburizing depth. The surface durability of Group-C is about 1,500Mpa, and the scoring depth is about 0.3~0.4 mm. These results show that the surface fatigue durability is greatly improved: 80 percent or more by finish rolling. However, it is necessary to improve the material properties and to make the higher consolidation in the surface layer, since the present target value of the surface fatigue durability for transmission gears is above 2,000MPa.

Simultaneous rolling can be successfully done and can produce gears with good tooth profile accuracy and good surface finish using the tool with a modified tooth profile. A desired consolidation in the surface layer of the P/M gears can be achieved, and the surface fatigue durability is greatly improved by this finish rolling process.

Conclusions

Simultaneous rolling can be successfully done and can produce gears with good tooth profile accuracy and good surface finish using the tool with a modified tooth profile. A desired consolidation in the surface layer of the P/M gears can be achieved by setting the amount of rolling stock normal to the tooth surface more than 150μm. The surface fatigue durability is greatly improved by this finish rolling process.

From the above results, we conclude that the finish gear rolling process utilized by the Galaxy machine is a very powerful and efficient way to obtain high-strength and high-precision P/M gears.

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