Precision Gear Profile with Chromium Alloyed Steel

Teruie TAKEMASU	Dept. of Mechanical and System Design, Tokyo Univ. of Science, Suwa 5000-1 Toyohira, Chino, Nagano 391-0292, Japan
Takao KOIDE	Dept. of Mechanical Engineering, Tottori University 4-101 Mimami, Koyama-cho, Tottori 680-8552, Japan
Yoshinobu TAKEDA	Höganäs Japan K.K. Akasaka Shasta East 2-19, Akasaka 4-chome, Minatoku, Tokyo 107-0052, JAPAN
Sven BENGTSSON	Hoganas AB SE-263 83 Höganäs, Sweden

ABSTRACT

A preform of 1.5Cr-0.2Mo PM steel having density of 7.55 g/cc was surface rolled using a high precision transverse rolling machine to form a spur gear. The rolling was designed to get good surface densification and tight tolerances on the gear profile. After rolling, casehardening was conducted. Pore distribution and endurance limits in both bending fatigue and rolling contact fatigue were investigated. The results support the feasibility of using transverse rolling of high density P/M materials to obtain high precision spur gears with strength comparable to wrought steel.

INTRODUCTION

Finish gear rolling using two-roller transverse rolling is widely used today within the automotive industry. This is because finish gear rolling has many advantages, such as short manufacturing time, suitability to automation, long tool life, delivers good surface finish on flanks and improvement of the load carrying capacity of rolled gears. Powder Metallurgy technology is especially suitable for producing complex shaped parts such as gears. PM gear preforms lack the extremely tight tolerances often requested by automotive industry. The fatigue strength is also limited due to the porosity, but it has been demonstrated that with surface densification by transverse rolling, PM gears can be manufactured with a narrow tolerances on the tooth profile, very good surface finish and highly improved load carrying capacity grace to the surface densification provided by transverse rolling.

It has been demonstrated that a high density and high performance PM gear has successfully been made using 1.5Cr-0.2Mo material and a high precision transverse rolling machine; FA-20/CNC developed by Nissei Co. Ltd. The purpose of this study is to demonstrate a high precision PM spur gear equivalent to finish rolled gears of wrought steel with respect to contact fatigue and bending fatigue performance.

EXPERIMENTAL

Fig. 1 shows the overview of the transverse rolling machine FA-20/CNC. This machine has a four tie rod structure for rigidity, and the forming loads are distributed evenly among these rods. Fig. 2 shows the configuration of two rolling tools and a PM gear in between the tools. In this process, the right side tool is pushed into the PM gear until a pre-set center distance between the right and left tool spindles is reached. The CNC system can effectively operate the spindles to the exact distance with a resolution of +/- 0.5μm. Synchronicity deviation between the two spindles' rotation is less than 0.02 degree thanks



Fig. 1: CNC Transverse rolling machine

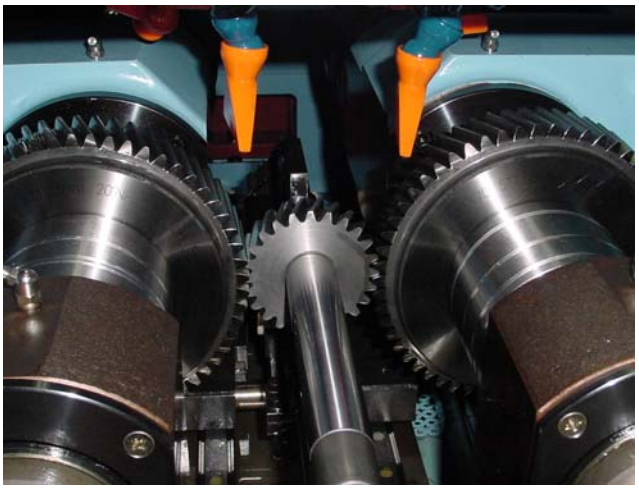


Fig. 2: Configuration of tools and gear

Table 1: Chemical composition (wt. %) of the test gears and test rollers

Material	C	Ni	Mo	Cr	Cu	Fe
A: Fe-Cu-C	0.80	-	-	-	2.00	Bal.
B: Fe-Ni-Mo-C	0.06	0.54	1.02	-	-	Bal.
C: Fe-Mo-C	0.40	-	0.80	-	-	Bal.
D: Fe-Cr-Mo-C *	0.23	-	0.20	1.50	-	Bal.

* Höganäs AB

Table 2: Comparison of PM preform characteristics

Material	Manufacturing process	Density [g/cm^3]	Porosity [%]	Hardness [HRB]
A	1P1S	6.88	11.8	77
B	1P1S	7.00	10.3	62
C	1P1S	7.17	8.1	73
D	1P1S	7.55	3.2	85

P: Press, S: Sinter

to the closed loop control system.

Table 1 shows the chemical compositions of tested PM materials. The comparison of PM preform characteristics in each material is shown in Table 2, which indicates that material-D has very high density compared to the other materials.

In this article, two kinds of rolling experiments were carried out; one is the finish gear rolling using PM spur gears as shown in Fig. 2 and the other is the fundamental surface densification test using PM roller specimens as shown in Fig. 3(a). PM rollers were also used in the surface durability tests explained later. The gear dimensions are summarized in Table 3. Two kinds of hobs were prepared to cut the PM spur gear teeth. One was the unmodified standard hob (HOB-0) and the other was the modified hob (HOB-1), which is designed to obtain PM gears having a pronounced convex tooth profile around the pitch point. The maximum involute crowning, Cα, on the modified gear tooth was set to 160 μm. The rolling tool was a spur gear with a standard tooth profile, meeting an accuracy of DIN 4. A tool



Fig. 2: PM spur gear

Table 3: Dimensions of PM spur gear

Gear parameters	Unit	Value
Module, m	mm	3
Pressure angle, α	degree	20
Number of teeth, z	-	26
Teeth width, b	mm	10.0
Outside diameter, dt	mm	84.0
Pitch diameter, d	mm	78.0
Root diameter, dr	mm	70.5
Addendum modification coefficient, x	mm	0.0

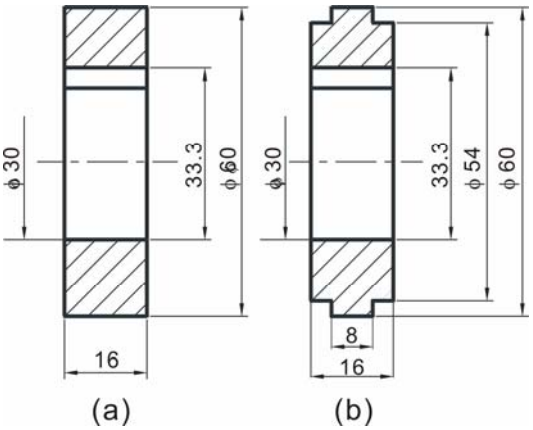


Fig. 3: PM roller specimens

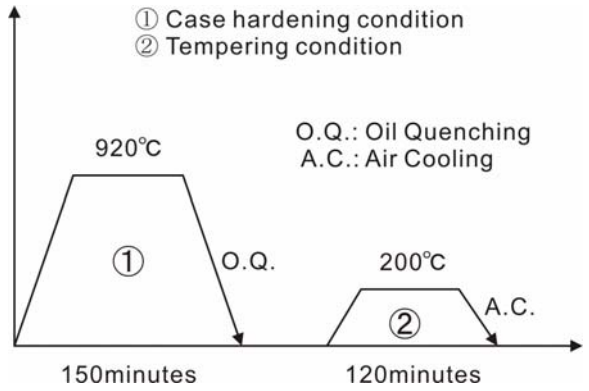


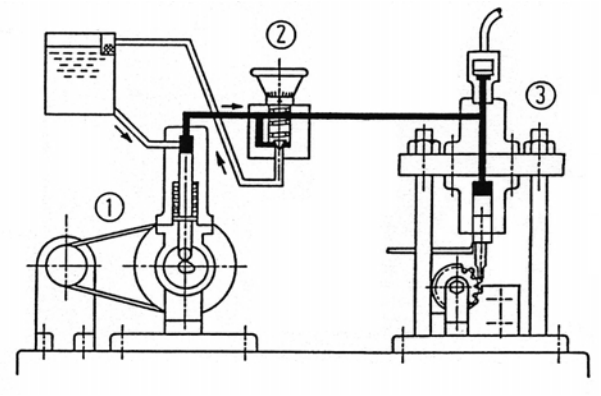
Fig.4: Case hardening condition

speed of 60 rpm and a tool radial displacement of 0.167mm/rev were employed.

For investigation of the load carrying capacity of PM materials, single tooth bending fatigue (STBF) tests and rolling contact fatigue (RCF) tests were carried out. Fig.5 shows the scheme of the STBF test machine (pulsator). The load was applied at the tooth tip of the gear in compression and the operating speed was set to 710 cycles per minute. The test was stopped at $5x10^6$ cycles and considered a non-failure if the tooth was not broken. RCF tests were conducted using the two roller contact fatigue test machine as shown in Fig. 7, which features full EHD lubrication and negative slip of 24 %. Fig. 3(b) shows the shapes and dimensions of RCF test rollers, which outer surfaces were ground to Rz < 0.2 μm. RCF-life failure criteria is when the damaged area of the roller surface became more than 2 % and the RCF run-out limit was set to $5x10^7$. All of the PM test gears and rollers were case hardened under the condition shown in Fig. 4 to achieve about 1.0 mm carburizing depth.

RESULTS

Fig. 8 shows examples of involute and lead profiles after finish gear rolling. This is for the case of PM gear preforms of material-D cut by HOB-1. As the amount of tool radial displacement r_0 increases, the tooth profiles gradually align with the involute. PM gears with good involute tooth profile on both driven and follow sides can be obtained by optimizing r_0. On the other hand, the tooth lead profiles are kept almost flat regardless of r_0. The same tendencies have been observed for the other PM materials.



① Pulse Hydraulic Pump

② Pressure Regulator

③ Loading System

Fig. 5: Schema of single tooth bending fatigue test machine (pulsator)

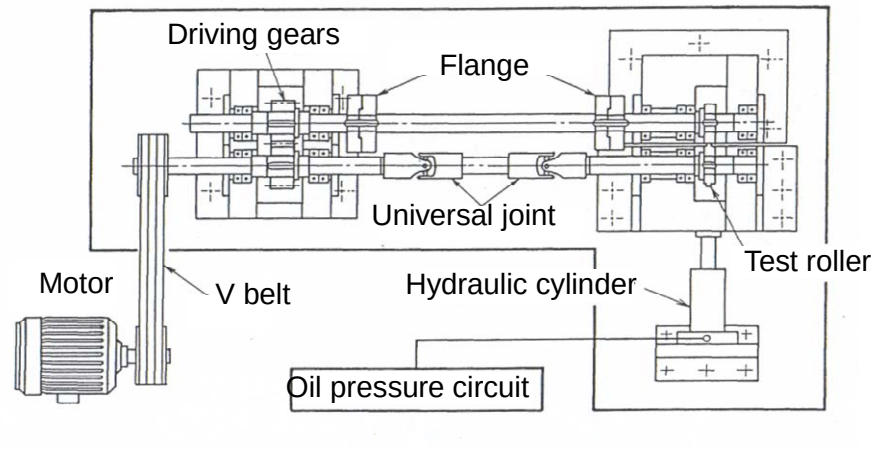


Fig.7: Layout of rolling contact fatigue test machine

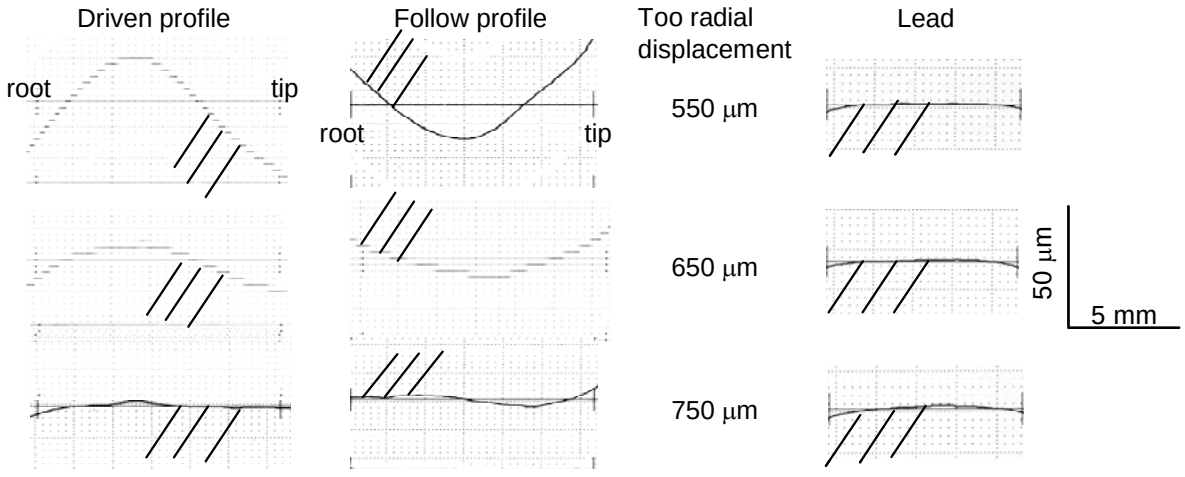


Fig. 8: Tooth profiles and leads after rolling

Fig. 9 shows the relationships between the amount of actual reduction in radius Δr and the amount of tool radial displacement r_0 for each material in the surface densification experiments of PM rollers. Δr increases in proportion to r_0 for every material, although the ratio of Δr / r_0 reduces as the density of the PM material becomes higher. This is because the young's modulus, the yield stress and the amount of elastic deformation of PM materials tend to increase in proportion to the material density.

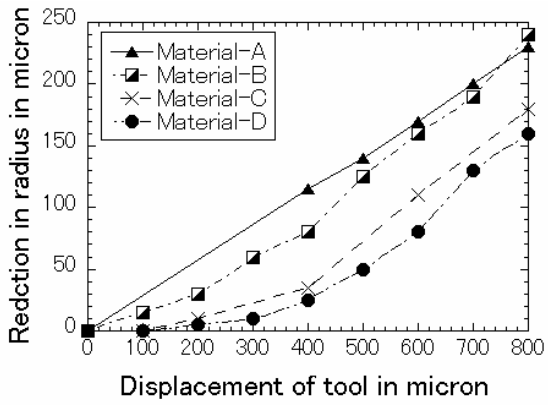


Fig. 9: Comparison of reduction in radius

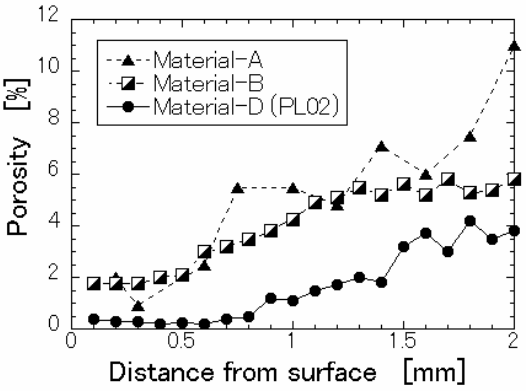


Fig. 10: Comparison of porosity distribution

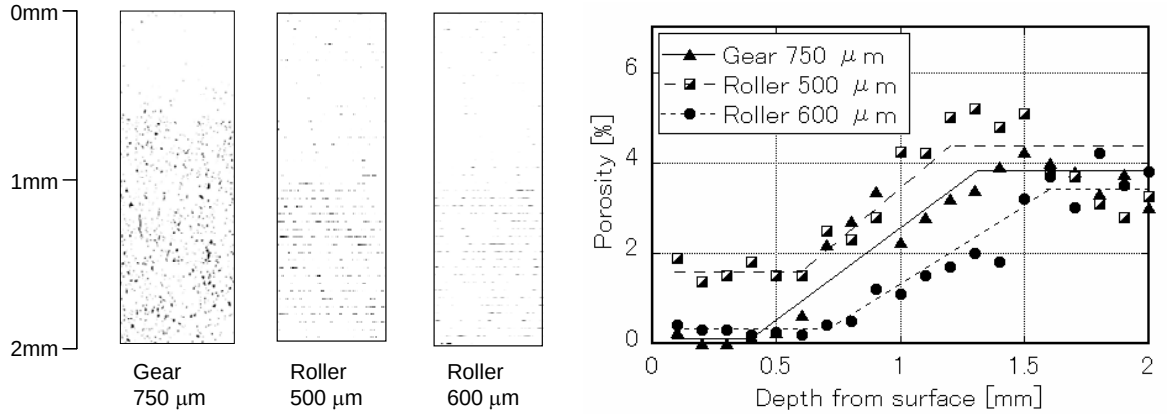


Fig. 11: Comparison of porosity distribution between gear (flank) and rollers

Fig. 10 show the comparison of the porosity distribution in the surface layer for three kinds of PM rollers when Δr = 100 μm. The densification level of material-D is much higher than for the other PM materials. Specifically, at the surface and to a depth of approximately 0.8 mm, the densification properties of material-D are very benign and the porosity in this area becomes almost zero. This densification property seems ideal to improve RCF strength, since the maximum shear stress in sliding rolling contact typically acts under the surface at depth of 0.1 ~ 0.4 mm depending on contact width and the magnitude of friction.

The porosity distributions around the pitch point of rolled gear teeth are compared with those of rolled rollers as shown in Fig. 11. The densification level of the gear in r_0 = 750 μm is located among that of the roller in r_0 = 500 μm and 600 μm. Note that the material in the gear surface layer at depth of about 0.5 mm is fully dense.

Table 4: Typical wrought steel used for transmission gears

	C	Si	Mn	P	S	Cr	Mo	Ni
JIS-SCM415	0,13-0,18	0,15-0,35	0,60-0,85	0.03	0.03	0,9-1,2	0,15-0,30	-
SAE8620	0.18-0.23	0.15-0.35	0.70-0.90	0.03	0.04	0.40-0.60	0.15-0.25	0.40-0.60
DIN16MnCr5	0.14-0.19	0.4	1.0-1.3	0.035	0.035	0.8-1.1	-	-
DIN18CrMo4	0.15-0.21	0.4	0.6-0.9	0.035	0.035	0.9-1.2	0.15-0.25	

The load carrying capacities of the PM materials are compared with those of a typical wrought steel used for transmission gears, JIS-SCM415 (as shown in Table 4). Fig. 12 and Fig. 13 summarize the test results of STBF and RCF respectively, in which the hatched areas indicate the scope of the

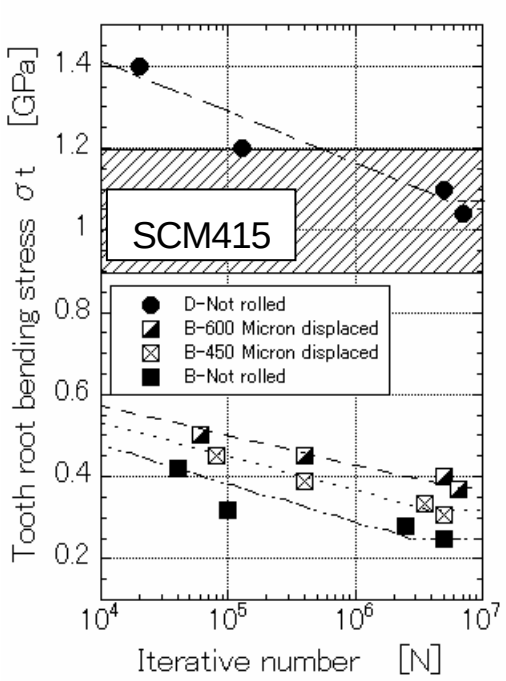


Fig. 12: S-N curves in STBF tests

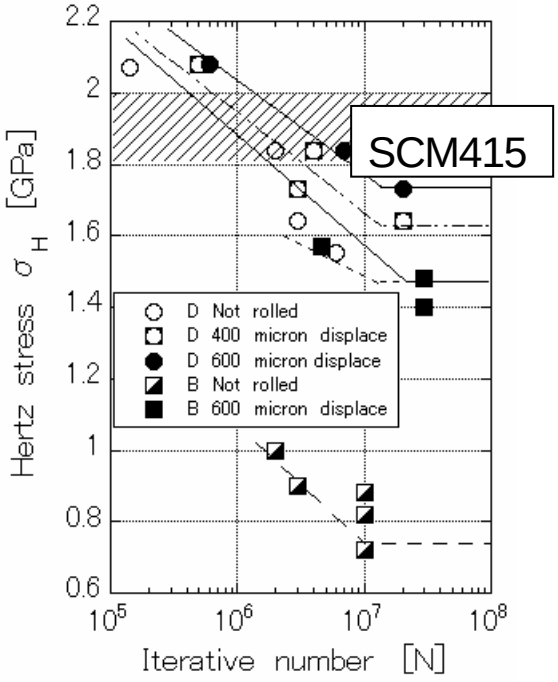


Fig. 13: S-N curves in RCF tests

endurance limit of case hardened SCM415. In STBF test, gears of material-B were rolled to densify the fillet surfaces in the root near the most critically stressed point. The bending fatigue strength of material-B is greatly improved by surface densification. But the endurance limit in the RCF tests, even with 600 micron displacement, is below half of that of the wrought steel gear. On the other hand, the strength level (STBF) of the material-D, as-sintered and case hardened, is equivalent to that of the wrought steel gears. This is thanks to the high density, the closed surface pores and the high performance of the fully pre-alloyed powder used in material-D.

The results of RCF test confirm that the surface densification can substantially enhance the surface fatigue strength of the PM materials. Specifically, the RCF endurance limit of material-D almost matches the wrought steel performance. The representative damages for both PM materials were spalling. But the spalling depth of material-B was about 0.3 ~ 0.4 mm where the shear stress reaches maximum as mentioned previously. On the other hand, the spalling depth of material-D was about 1 mm or more, which coincides with the carburizing depth. Hence, it seems possible to improve the RCF endurance limit of material-D by optimizing the hardening depth.

Conclusion

- The Tooth Root Bending Fatigue durability of high density Cr-Mo PM steel gears matches wrought steel gears.
- The Rolling Contact Fatigue performance of surface densified high density PM Cr-Mo rollers was much improved and almost matches wrought steel gears.
- A high density PM Cr-Mo material has excellent properties for making surface rolled gear with high accuracy gear profiles.
- A high precision CNC form rolling machine enables sufficient control to make spur gears with accurate shape and a fully densified surface layer of at least 1 mm on the gear flank.