Mechanism of Attaining High Strength Sintered and Surface-rolled Gear and Merits of Its Application in Automotive Field

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Abstract

With the aim of expanding the application to automobiles, a study was conducted to determine the applicability of sintered parts to transmission gears that require high fatigue strength. Recent studies have reported that sintered and surface-rolled gears based on pre-alloyed steel powder can achieve fatigue strength equal to or higher than that of conventional wrought steel gears, but the mechanism that enables the former to achieve a fatigue strength higher than that of the latter has not been fully clarified. Hence, Kobe Steel has investigated the factors that may bring higher fatigue strength to sintered and surface-rolled gears in comparison with wrought steel and found that it is attributable to their highly compressive residual stress. Also studied were the advantages of applying sintered and surface-rolled gears. By optimizing the surface-rolling conditions so as to improve the tooth profile accuracy, the same contact-pressure fatigue strength as that of the ground product can be obtained without any grinding, suggesting the possibility of eliminating the grinding process.

Introduction

Recently, the reduction of carbon dioxide emissions has become a major challenge as a measure against global warming, and electrification is rapidly progressing in the field of automobiles. Since sintered parts are mainly used for automotive engines, there is a concern that their use may decrease due to the electrification of vehicles.

Under such circumstances, transmission gears are being considered for a new application of sintered parts. Since high fatigue strength is required for the material of transmission gears, low-alloyed steels for machine structural use, such as SCr420, are mainly used after carburization and quenching. Sintered materials tend to have porosities inside, posing the issue that their fatigue strength is lower than that of wrought steel. Meanwhile, densification of the near-surface by surface rolling processing has achieved a fatigue strength equal to or higher than that of the wrought steel gears.[1), 2)] In particular, Ni-Mo pre-alloyed steel powder that does not contain any easy-to-oxidize elements such as Cr has the advantage that there is little concern about performance degradation due to oxidation even during sintering and heat treatment under the atmosphere of endothermic gas (commonly known as "RX gas"). On the other hand, despite the porosities, which have not been completely removed by surface rolling processing, surface-rolled sintered gears exhibit a fatigue strength superior to that of wrought steel gears, the mechanism of which behind this phenomenon has not been fully elucidated.

Hence, Kobe Steel has conducted a comparative study with wrought steel gears in order to elucidate the factors that increase the fatigue strength of surface-rolled sintered gears. Furthermore, the benefit of replacing wrought steel gears with surface-rolled sintered gears was also examined, with a view to the expansion of applications of the latter. This paper provides an overview.

1. Strengthening mechanism of surface-rolled sintered gears

As for the strength of gears, common practice is to consider bending strength, tooth surface strength, and scoring strength. This section describes the contact fatigue strength of surface-rolled sintered gears.

1.1 Factors affecting contact fatigue strength of gears

Pitting damage is a typical tooth surface damage of gears. Surface hardness, internal defects (inclusion and porosities), the amount of residual austenite, and compressive residual stress are considered to affect the occurrence of pitting.[3)] Transmission gears are used in driving conditions with high contact-pressure load and slippage, and the tooth surface of each gear is subjected to a temperature rise due to frictional heat. It is reported that not only normal temperature hardness (initial hardness), but also the hardness after annealing at 573 K affects the pitting resistance.[4)] A comparative study of these factors has been conducted using a surface-rolled sintered gear and a wrought steel gear.

1.2 Test method

The test material of sintered steel was made from a mixed powder prepared by adding 0.3% graphite powder to 0.5% Ni-1.0% Mo pre-alloyed powder (completely alloyed powder) produced by water atomization. A disk shaped blank with a diameter of 70 mm, a height of 30 mm and a target density of 7.5 g/cm^3 was compacted and sintered at 1,120℃ for 60 min in a N_2-10%H_2 atmosphere. The blank was cut into the shape of the helical gear specified in **Table 1**, surface-rolled, and then carburized and quenched. The surface rolling method was plunge-type rolling, and the amount of surface rolling equaled the tool pushing depth of 1.2 mm. The carburizing and quenching conditions were gas carburizing at 930℃ for 120 min, followed by annealing at 160℃ for 120 min. The test material of wrought steel was JIS SCr420 (hereinafter referred to as SCr420) that was cut into the same helical gear shape as the above sintered-steel test material and was carburized and quenched. The carburization and quenching were performed under the conditions of pulse carburizing at 950℃ for 210 min and annealing at 150℃ for 60 min. In order to minimize the effect of the surface roughness on the strength, the maximum height, Rz, specified in JIS B 0601: 2001, was set to 2 μm or less by a tooth surface grinding finish for all the gears.

Table 1 Specifications of test gears (helical gear)

	Drive	Driven
Material	Evaluation material	SCM420 carburized
Module	3	
Pressure angle (deg.)	20	
Helix angle (deg.)	20	
Number of teeth	16	24
Face width (mm)	6	25
Standard pitch circle diameter (mm)	51.1	76.6

The contact fatigue test was performed on power re-circulating type test equipment. The fatigue limit load was determined as the load for which no damaged area reaches 2% even if the number of load cycles exceeds 1.5×10^7. A PSPC-type micro X-ray measuring apparatus was used to measure the amount of residual stress and residual austenite.

1.3 Test results and discussion

The results of the contact fatigue test are shown in **Fig. 1**. The vertical axis represents the calculated value of the Hertz contact stress at each pitch point. This test has also confirmed that the surface-rolled sintered gear has higher contact fatigue strength than the wrought steel gear.

Table 2 shows the measurement results for surface hardness and the amount of residual austenite. The hardness and the amount of residual austenite of the surface-rolled sintered gear and wrought steel gear were found to be almost the same.

Fig. 2 shows a cross-sectional photograph near the pitch point (broken-line frame in the figure). No coarse inclusion was found in either one of the gears,

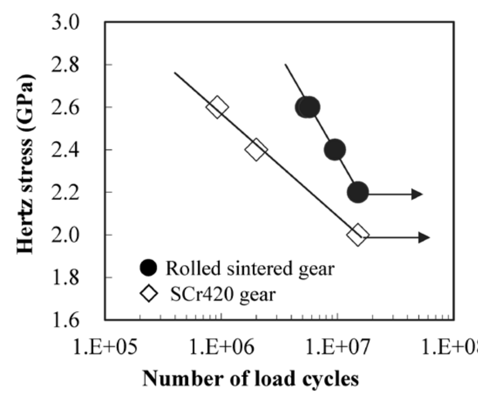


Fig. 1 Results of contact fatigue test

Table 2 Surface hardness and amount of residual austenite

		Rolled sintered gear	SCr420 gear
Surface hardness (HV)	before testing	708	717
	after tempering 573K	656	667
Amount of retained austenite phase (%)		14.1	16.0

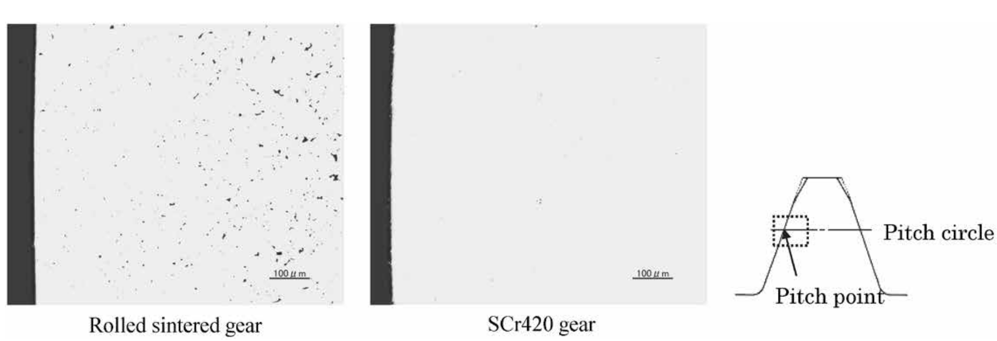


Fig. 2 Porosities and inclusions near pitch point

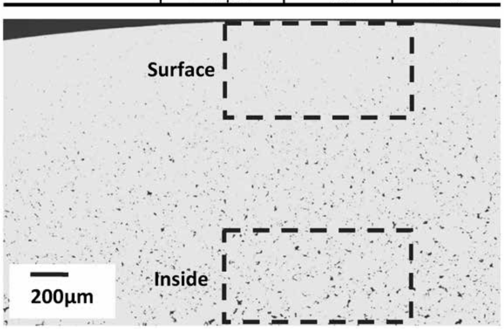
but there were many small porosities in the surface-rolled sintered gear. Here, image analysis has been performed on the near-surface and a part with a width of 1 mm and depth of 0.5 mm inside, about 1 mm from the surface, and the number of porosities included in the area, as well as the equivalent circle diameter of all porosities, were calculated. The results are shown in **Table 3**. In the near-surface area densified by the surface rolling, coarse porosities of 10 μm or more are as few as 0.6% of the total, and also the maximum diameter is as small as 13.4 μm. Therefore, the influence of porosities on the strength is considered to be extremely small.

The near-surface residual stress of the gear tooth was measured by removing the surface in the depth direction by electro-polishing. **Fig. 3** shows the results of the residual stress measurement in the direction of the tooth depth. The surface-rolled sintered gear has been found to have a higher compressive stress remaining in the near-surface compared with the wrought steel gear. Compressive residual stress is known to be effective for improving contact fatigue strength,[5)] and the results of this test suggest that it also contributes to the improvement of the contact fatigue strength of the surface-rolled sintered gear.

It should be noted that there is a difference in the magnitude of residual stress between the surface-rolled sintered gear and the wrought steel gear, which is considered to be attributable to the fact that the surface-rolled sintered gear has a density difference between the near surface layer and the inside. That is, the deformation amount at the time of carburizing and quenching differs between the near-surface, which has been densified by surface rolling, and the interior, in which porosities remain. Therefore, the surface-rolled sintered gear results in a greater compressive residual stress than the wrought steel gear, which has little difference in density distribution. It is inferred that this is the expression mechanism of the excellent contact fatigue strength of the surface-rolled sintered gear.

Table 3 Pore size and distribution of surface-rolled and sintered gear

		Surface	Inside
Mean diameter (μm)		2.8	5.3
Maximum diameter (μm)		13.4	21.6
Ratio of pores (%)	<5μm	89.7	60.7
	5～10μm	9.8	27.5
	>10μm	0.6	11.8



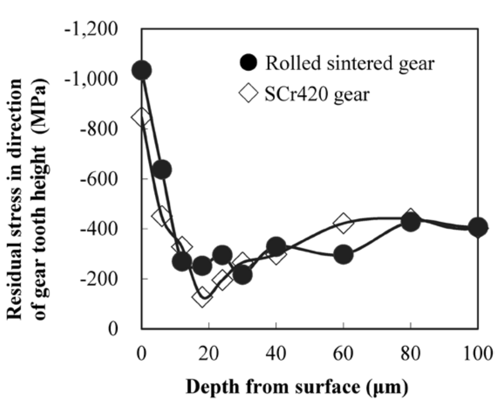


Fig. 3 Near-surface residual stress distribution in tooth depth direction

2. Advantages of applying surface-rolled sintered gear

2.1 Tooth profile adjustment effect in the surface rolling process

For automotive transmissions, downsizing and weight reduction are required for the sake of fuel efficiency improvement, and excellent silence from the aspect of driving comfort. Correspondingly, there is an increasing demand for strength improvement and noise reduction for gears. It is known that the tooth profile accuracy of a gear affects its strength and noise,[6), 7)] and in order to meet the above requirements, the tooth surfaces are more often ground to improve the tooth profile accuracy (hereinafter referred to as gear-tooth grinding).

Fig. 4 shows the production processes of wrought steel gears and surface-rolled sintered gears, respectively, when gear-tooth grinding is performed. In the case of wrought steel gears, the only process step that can adjust the tooth profile accuracy is gear-tooth grinding. In the case of surface-rolled sintered gears, on the other hand, it has been reported that tooth profile adjustment is possible, not only in the gear-tooth grinding process, but also in the surface rolling process,[8)] and it is expected that the gear-tooth grinding step after heat treatment can be eliminated by improving the tooth profile accuracy in the surface rolling step. This section focuses on the possibility of improving tooth profile accuracy and of eliminating the gear-tooth grinding step by improving the surface rolling conditions from the viewpoint of tooth surface strength.

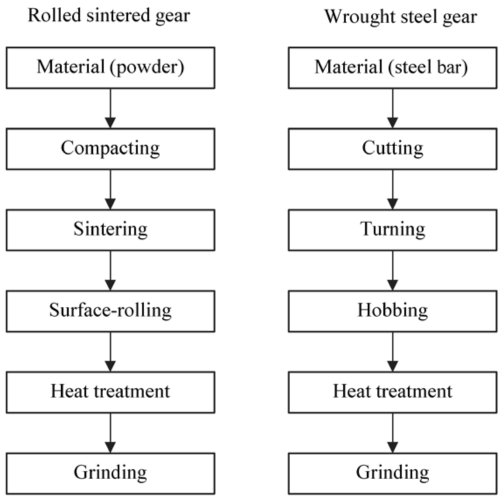


Fig. 4 Comparison of production process between rolled sintered gear and wrought steel gear

2.2 Test method

A 0.5% Ni-1.0% Mo pre-alloyed powder was prepared by water atomization. Graphite powder was added in the amount of 0.3% to prepare a mixed powder for the test. Blanks with a target density of 7.5 g/cm^3 were compacted and sintered in an N_2-10%H_2 atmosphere at 1,120℃ for 60 min. These blanks were cut into the spur-gear shapes specified in **Table 4**, and subjected to surface rolling, followed by carburizing and quenching. Surface rolling was performed on a plunge-type roller under conventional conditions with an amount of stock rolled normal to a tooth flank of 0.14 mm. In addition, as the improved version of these conditions, the amount of stock rolled normal to tooth flank was set to 0.11 mm, and the surface rolling was carried out while the surface rolling die shape was adjusted to improve tooth profile accuracy. Carburizing and quenching conditions were gas carburizing at 930℃ for 120 min and annealing at 160℃ for 120 min. The gear that had been surface-rolled under the conventional conditions was subjected to carburization, quenching and tooth grinding to obtain a tooth profile accuracy of JIS N4-class.

The contact fatigue test was performed on power re-circulating type test equipment and the fatigue limit load was determined as the load when the damaged area did not reach 2% even if the number of load cycles exceeded 1.5×10^7.

2.3 Test results and discussion

Fig. 5 shows the measurement results for the tooth profiles. The tooth profile of the gear that was surface-rolled under the conventional conditions is

Table 4 Specifications of test gear (spur gear)

	Drive	Driven
Material	Evaluation material	SCM420 carburized
Module	3	
Pressure angle (deg.)	20	
Number of teeth	13	26
Face width (mm)	6	10
Standard pitch circle diameter (mm)	39.0	78.0

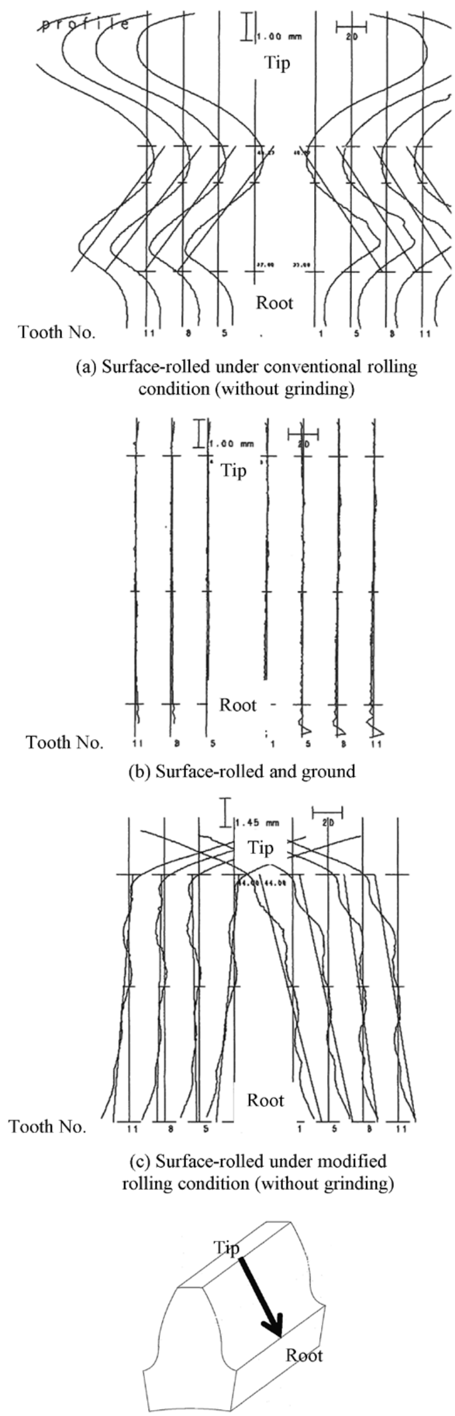


Fig. 5 Comparison of tooth profiles

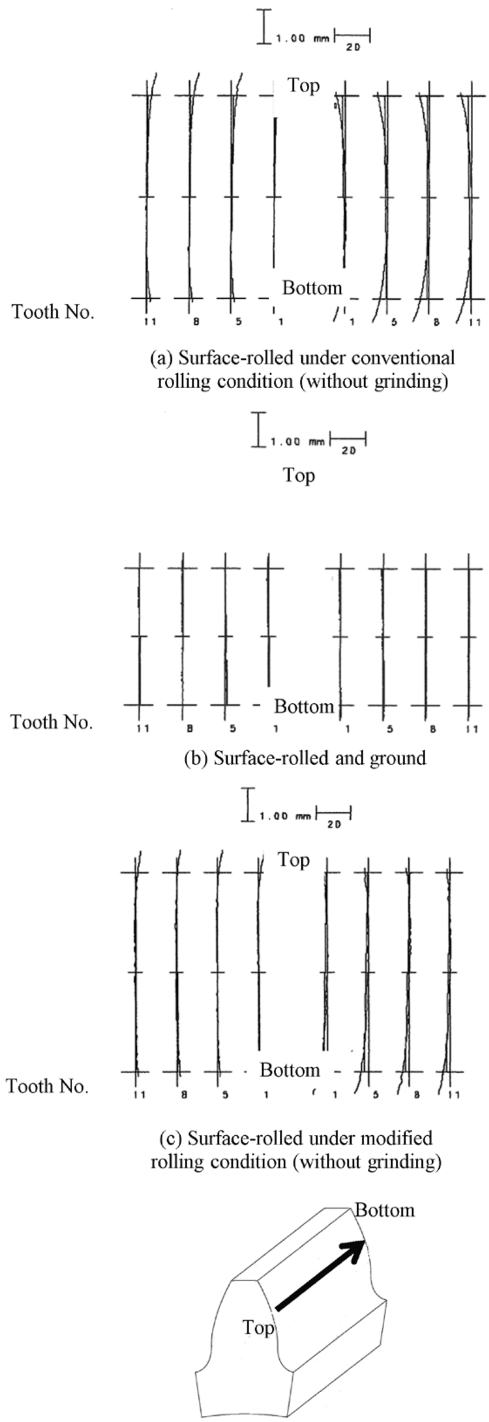


Fig. 6 Comparison of lead profiles

shown in (a), that of the gear surface-rolled under the conventional conditions and ground is shown in (b), and that of the gear surface-rolled under the improved conditions is shown in (c). The gear that was surface-rolled under the improved conditions with the aim of improving tooth profile accuracy had significantly reduced tooth profile errors compared with the one prepared under the conventional conditions. However, it did not reach the same level of accuracy as the tooth ground gear. **Fig. 6** shows the measurement results for the lead

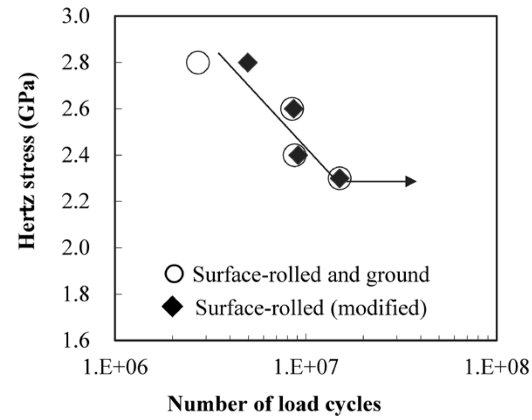


Fig. 7 Results of contact fatigue test

profiles. There was almost no difference in the lead profile error between the surface-rolled gear with or without tooth grinding, and each gear showing a favorable lead profile accuracy.

Fig. 7 shows the results of the contact fatigue test. The gear (a) that had been surface-rolled under the conventional conditions caused severe vibration, which led to an abnormal stopping of the test machine, disabling the evaluation of contact-pressure strength. On the other hand, the gear that had been surface-rolled under the improved conditions indicated no problem during the operation test and had the same contact-pressure fatigue strength as that of the tooth ground gears. It is probable that the gear that had been surface-rolled under the improved conditions had a sufficiently small tooth profile error and did not have a decrease in tooth surface strength. It has been shown that, by adjusting the surface rolling conditions, a tooth surface strength life equivalent to that of the tooth-ground gears can be obtained without performing gear-tooth grinding.

Conclusions

The strengthening mechanism and application advantages of the surface-rolled sintered gear have been studied, and the following results were obtained.

(1) Surface-rolled sintered gears have excellent contact-pressure fatigue strength because surface rolling generates a compressive residual stress greater than that of wrought steel gears.

(2) The surface-rolled sintered gear allows the adjustment of the tooth profile accuracy in the surface rolling process, and even if the gear-tooth grinding process after heat treatment is eliminated by adjusting the conditions, the same contact-pressure fatigue strength as that of the tooth ground gear can be achieved.

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