Improvement of Contact Fatigue Strength of Gears by Tooth surface Modification Processing

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Abstract—I*n this paper, it combined with the caburized gear with the existence of manganese phosphate conversion coating and the gear tooth fatigue experiment of the system gear was conducted using a basic experiment and automatic shift of gear tooth fatigue of a simple substance gear pair. Consequently, it was proved that the gear which gave the manganese phosphate conversion coating had high pitting proof load capability by improvement in the initial familiarity nature of a gear pair, an improvement of lubricating oil holdout, and direct contact prevention of metal. Analysis of the pitting-proof fatigue characteristics of manganese phosphate conversion coating processing specification and the gear tooth wear characteristic etc. performed the engagement gear by one of the two or both in the experiment.*

Keywords: Gear, Manganese Phosphate reatment, Tribology, Fatigue, pitting, Wear

I. Prolusion

In recent years, the power output of automobiles has risen to upgrade driving comfort. At the same time, the automatic transmission (hereinafter AT) requires more gear range, less weight and size reduction to satisfy the fuel economy and environmental protection requirements. This trend has caused stress to the tooth dedendum and the tooth surface contact point to increase at the gear component which is the main structure of the power transmission, resulting in high risk of tooth damage due to dedendum fatigue or pitting fatigue.

Dramatic progress of the shot peening technology has made it possible to implement the appropriate countermeasures to improve the dedendum fatigue life. However, to improve the efficiency of AT power transmission, the oil with lower viscosity tends to be applied resulting in more severe conditions for the pitting fatigue [1]. Therefore, applying only conventional carburizing, quenching and tempering technologies was not enough, and the pitting durability has increasingly becomes the factor governing the gear life [2]. Since the gears for automobiles are produced in very large quantities unlike those of other industrial machines, low costs and stable effects are essential for life improvement measure. Therefore, the authors focused on the improvement of pitting proof load capability by manganese phosphating.

Manganese phosphating was put into practice as anti-rust processing in the 1940s. It is a kind of the chemical conversion treatment which forms crystalline coating on the surface by taking the advantage of the increase of surface pH while etching a metal material. Recently, the technology to control the crystal grain diameter and thickness of the coating has been improved [3] allowing a large amount to be processed at once using the wet method. As a result, the lower cost has been realized and the method has also been applied to the precision part which was difficult in the past.

This report describes the result of the durability test by power recirculation type test machine and AT unit. The effect to the pitting fatigue life by comparing the results with and without manganese phosphating is discussed.

II. Test gears, testing machines and their conditions

II.1 Test gears

The specification and the processing method of the test gears for the power recirculation type test machine are described in **Table1**. The steel grade is chromium steel (SCr420H).

Table 1 Specification of simple test gears

Specification	Drive Pinion	Driven Gear
Normal module (mm)	2.86	
Normal pressure angle (deg)	17.5	
Helix angle (deg)	26.8	
Numuber of teeth	23	66
Material	SCr420H	
Heat treatment	Carbulized	
Surface treatment	Shot Peening	
Tooth surface finishing	Shaving before carburizing	Grinding after carburizing

The small drive pinions of three specifications were used. The first was carburized and quenched after being shaved, the second was ground in the tooth surface after the first type, and the third was coated with manganese phosphate without grinding. Only one specification of driven gear that was carburized and quenched after being shaved has been used. Shot peening was applied to both

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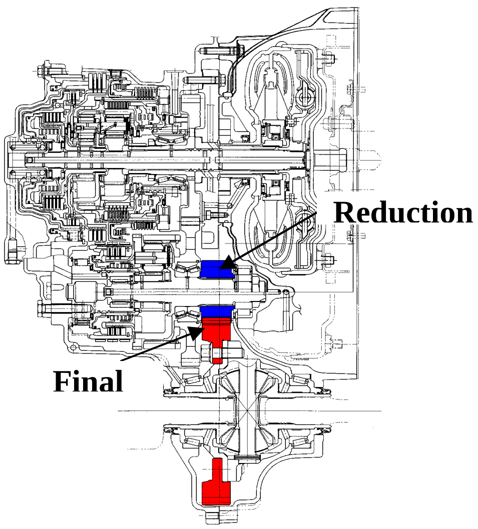


Fig. 1 Cross-sectional view of 5-speed Automatic Transmission

gears. For AT unit, the final transmission gear pair, Reduction gear and Final gear were used, as shown in the **Fig. 1**.**Table2** indicates the gear specifications. The material of the reduction gear is chromium steel, and is carbonitorided. The material of the final gear is chromium steel, and is carburized and quenched. Both gears are processed with shot peening and tooth honing. Furthermore, the specification in which manganese phosphating were applied to both gears, and the specification in which manganese phosphating were applied only to the reduction gear were used in the tests.

Table 2 Specifications of AT system test gears

Specification	Drive Pinion	Driven Gear
Normal module (mm)	2.86	
Normal pressure angle (deg)	17.5	
Helix angle (deg)	26.8	
Numuber of teeth	21	68
Material	SCM	SCr420H
Heat treatment	Carbonitoride	Carbulized
Surface treatment	Shot Peening	
Tooth surface finishing	Honing after carburizing	

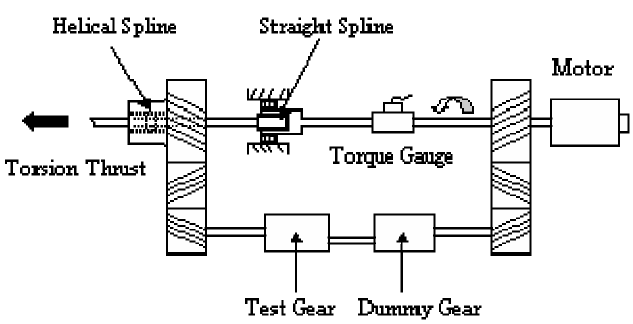


Fig. 2 Power circulation-type gear test machine

II.2 Testing machine and its conditions

The outline of power circulation type gear test machine which was used in the simple substance gear pair experiment is shown in the **Fig. 2**. In the experiment, the drive gear was operated at a speed of 1,500 rpm and oil temperature of 120°C ±2°C. Forced ATF lubrication was applied from the top of the gear mesh region at a rate of 2.5 l/min. Also, an acceleration sensor was used above the bearing of the shaft supporting the gear to detect tooth damage. To determine the pitting fatigue life of the test gears, the gear test machine was stopped at suitable intervals to allow observation of the development of pitting and measurement of the pitting area rate (i.e., the ratio of the pitting area to the effective contact area of the tooth surface). **Fig. 3** shows the outline of the power absorption type gear testing equipment used in the AT unit gear fatigue experiment. Lubrication oil and oil temperature are the same as the simple substance gear pair test. To lubricate the gears, the oil level was maintained at a few mm above the lower end of the final drive gear, and splash lubrication was applied. The reduction gear revolution was set to 900 rpm, and a break-in was conducted before the test. The vibration pickup was attached to the pass-through hole at the top of the unit, and by making the hole close to the reduction gear, the tooth surface was periodically observed so that the pitting and scoring conditions were recorded.

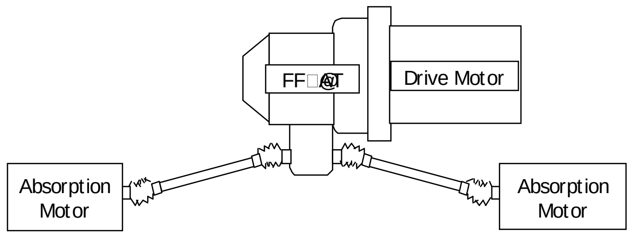


Fig. 3 Outline of a power absorption type gear testing equipment

III. The experimental results

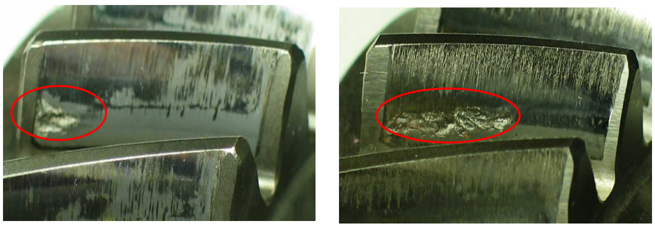
III.1 Pitting fatigue life by simple substance gear pair experiment

Table3 indicates the test combination in the simple gear pair experiment.

Table 3 Combination of the gear specification of an experiment

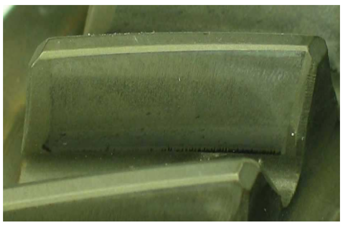
Gears	Drive Pinion	Driven Gear
test 1	shaving before carburizing	shaving before carburizing
test 2	Grinding after carburizing	
test 3	Grinding and M.Pn treatment after carburizing	

In **Fig. 4**, the conditions of pitting produced by the experiment are shown. In the initial stage of pitting, small pits (micro-flaking) are developed on the tooth surface in the mesh onset area near the dedendum. As the number of load cycles increased, the pitting expanded toward the tooth trace direction, and then it developed toward the tip, resulting in the flaking of small fragments there. **Fig. 5** shows the SEM photo of the pair of gears, smaller gear side with shaving and driven gear side with manganese phosphating, after 1.1 x 10^7 revolutions. No tooth surface pittings are observed. **Fig. 6** shows the result of pitting progressing under the condition of the stress of the tooth surface contact point Pmax = 2000 Mpa and the maximum sliding speed at the dedendum = 7.8 m/s. The horizontal axis indicates the meshing cycles, and the vertical axis shows the pitting area rate at each cycles. This shows that when both gears were shaved it lasted approximately 3 times longer than when only the smaller gear side was grinded. When the smaller gear side was grounded and the driven gear side was manganese phosphated, it lasted twice as long as before.



Shaving/shaving 7×10^6rev   Grinding/shaving 3×10^6rev

Fig. 4   Pitting condition after testing



Grinding+P.mn processing □1.1×10^7rev

Fig. 5   P.Mn Processing after testing

III.2 Pitting fatigue life in AT unit test gear

Fig. 7 shows the results of the durability evaluation test on AT unit. The stress of tooth surface contact point Pmax = 2000 Mpa, and the maximum sliding speed at the dedendum is 3.2 m/s. The experiment results show that both gears with manganese phosphating, when compared to the gears without processing has more than twice the pitting durability. Also, the gear pair with manganese phosphating on only the reduction gear, showed the longest durability life.

III.3 Dedendum wear and residual stress at tooth surface

Fig. 8 shows the amount of dedendum wear after the test in relation to the meshing cycles. Tooth surface wear mainly occurred near the dedendum, and the amount of wear increased as the number of meshing cycles increased. **Fig. 9** shows the residual stress at the meshed tooth surface of the drive pinion and the unmeshed (equivalent

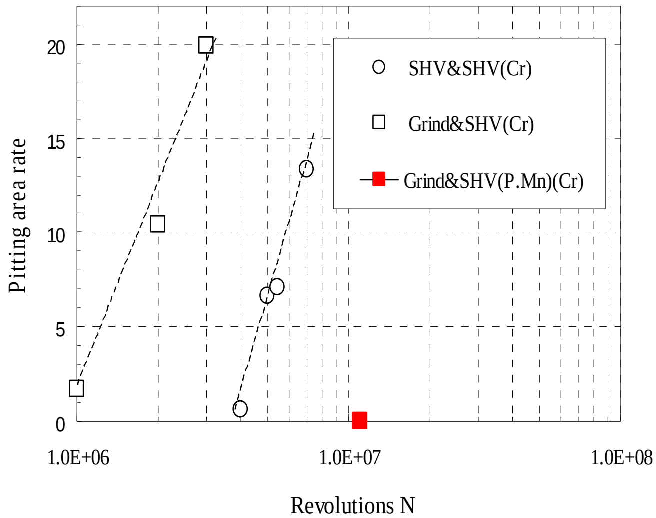


Fig. 6   Change in pitting area rate

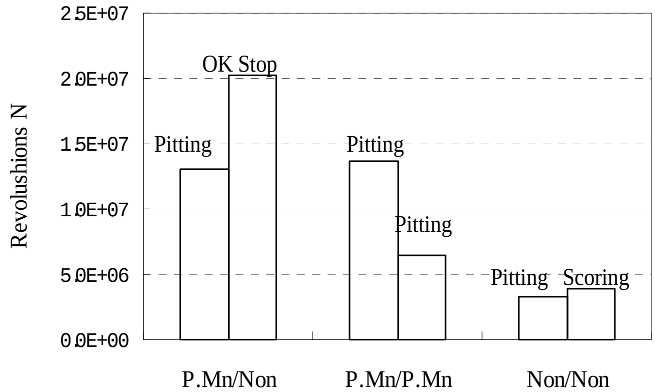


Fig. 7 Gear damage situation of AT system examination

to the condition before test), after the test. These results were measured by x-ray diffraction analysis near the pitch circle at the center of the face width. Because the residual stress of the unmeshed tooth surface was higher than that of the meshed tooth surface, it is assumed that surface residual stress was more attenuated by the friction heat of the meshed tooth surface. The teeth of the gears are

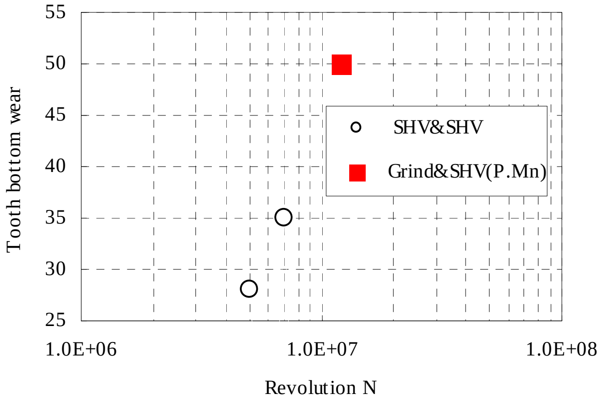


Fig.8 Tooth bottom wear after testing

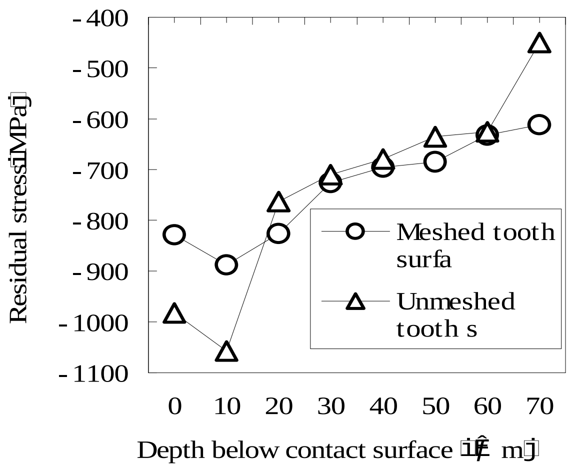


Fig. 9 Distribution of dedendum stress

engaging under high load mesh with impact shock at the mesh onset due to the gear bending deformation. And the high tooth surface stress occurs near the dedendum of the drive pinion. In this area, relative sliding speed is high and local heat generation is also high. It is assumed the fatigue crack tends to start in this area. The ATF temperature in an AT is above 80°C in the range of normal use. Also, the maximum flash temperature (Flash Temperature [4]) at the tooth surface contact point, which has been proposed by AGMA, is approximately 90 - 120°C. Therefore, it is assumed that the temperature at the tooth surface of AT gears even under proper lubrication will rise as high as the ordinary tempering temperature (150 - 200°C). The softening due to tempering is thought to be an important factor which affects the pitting fatigue life, however the effects have not been clarified [5] [6]. **Fig. 10** shows the condition of the pitting damage on the test gears with and without manganese phosphating after AT unit test. The small pitting area observed on the gear pair of which only the reduction gear was manganese phosphated and shows the longest life, is below the pitch circle at the tooth surface center. The location of the pitting is different from those on the other two test gear pairs. It is assumed that the break-in effects have caused the difference. **Fig. 11** shows the dedendum wear amount of each specification gears measured after the test. The conditions of the tooth surface wear on each specification gears are almost the same.

IV. Discussion

IV.1 The effect of manganese phosphating coating

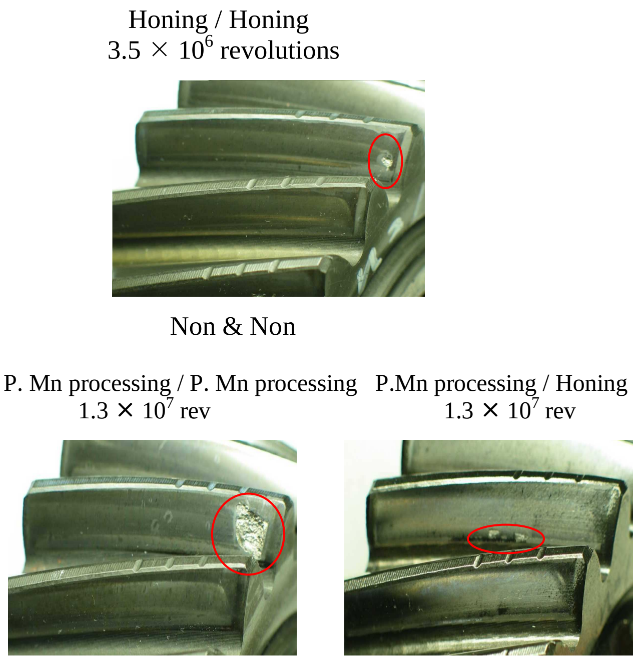


Fig. 10 Pitting condition after testing

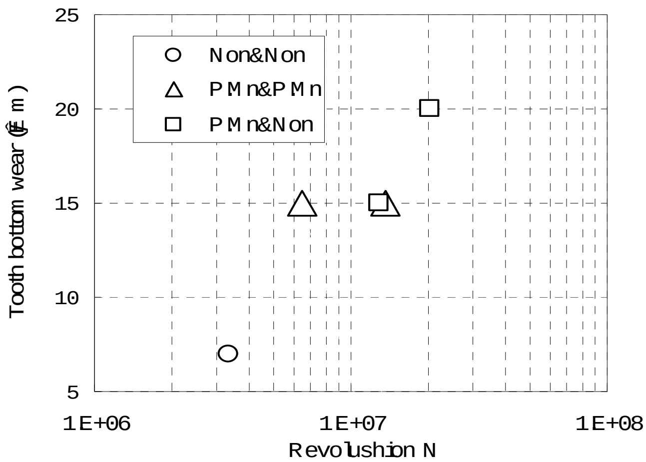
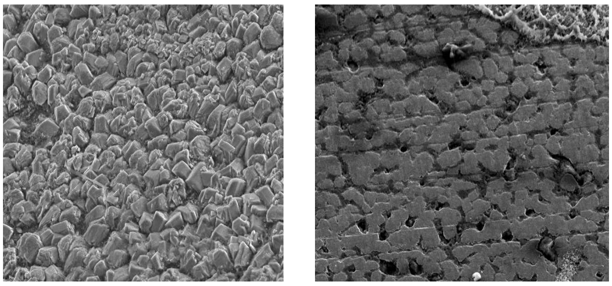


Fig. 11 Tooth bottom wear after testing

Fig. 12 shows the scanning electron microscope observations of the tooth surface pitch circle area on the manganese phosphating gears before and after operating with load in the simple substance gear pair test. The thickness of manganese phosphate coating is approximately 10 – 15 μm. Since the coating has a porous crystal structure, the lubricating oil is maintained well and it can be assumed that this prevents the oil film from being cut out.The tooth surface is black in color with a non-glossy appearance.The grinding marks are coated and the surface morphology is smooth. Therefore, direct metal contact is prevented and even smoother sliding surface can be created (initial break-in effect). This presumably has the effect of reducing friction and can



P. Mn coating before testing　　P. Mn coating after testing

Fig. 12　Manganese phosphate coating

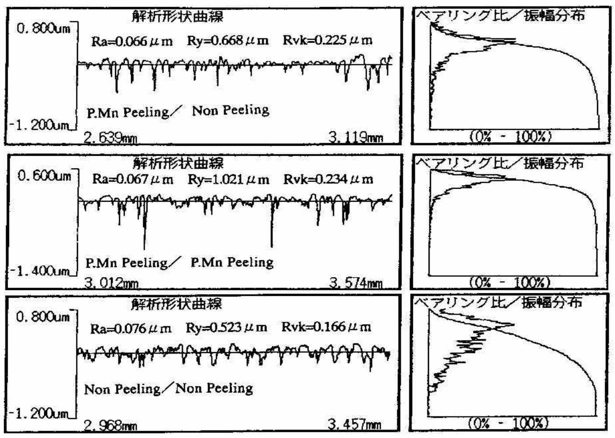


Fig. 13　Surface roughness of gear tooth

prevent the generation of friction heat compared with non-coated test gears [7]. The coating is produced as etching the steel surface, and the remained etching bit will prevent the lubricating oil film from being cut out even after the coating surface is machined out [8]. Therefore, it is thought that the manganese phosphating has the function to prevent the damage from pitting fatigue.

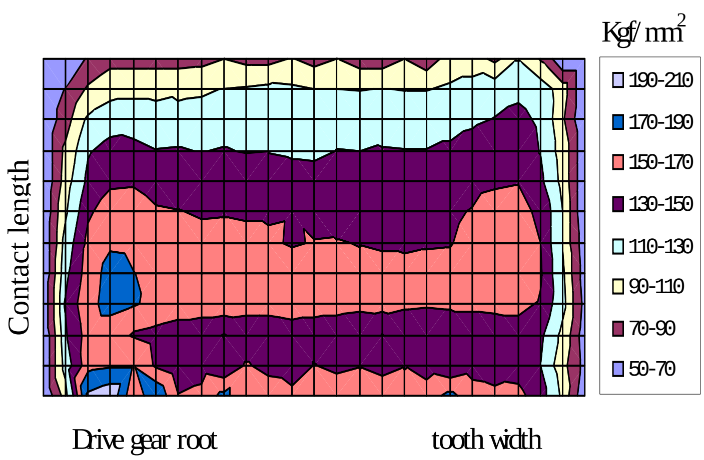
IV.2 Comparison of tooth surface roughness

Fig. 13 shows the results of the gear surface roughness measured along the tooth profile after the AT unit test for comparison of with and without manganese phosphating. The oil reservoir depth (Rvk) which is the parameter to affect the sliding and lubrication is larger for manganese phosphating, and smaller for the plateu ratio (the bearing ratio in the figure). It is assumed the asperities on the tooth surface which are the starting point of pitting, have been shaved. According to the roughness measurement results, the roughness sum for the gear pair with only one gear processed is smaller when compared to the gear pair with both gears processed. (Difference is 1.34 μm on Ry.) The reason is assumed to be the coating of both gears which scratches each other, resulting in more wear when compared to the gear pair with only one manganese phosphated gear. Therefore, it is assumed the pitting fatigue life for the gear pair with only one gear manganese phosphated was the best specification.

IV.3 Tooth surface contact pressure and temperature

Fig. 14 shows the tooth surface contact pressure contour curves on an action plane, for the AT unit test gear with manganese phosphate after the unit test. The contact pressure was calculated using the relative error curves of the tooth profile/tooth trace on the tooth surface and input load at arbitrarily chosen meshing points. The contact pressure at the dedendum of the drive pinion shows local high pressure point. Due to the tooth bending deformation of the gears which are already meshed, the stress at the dedendum of the drive pinion becomes high by meshing with impact shock at the mesh onset. **Fig. 15** shows the contour curves for the distribution of the flash temperature rise at overall gear action plane. It is seen that the maximum tooth surface flash temperature rose

Fig. 14　Distribution of Hertzian plane pressure in a test pinion after testing



approximately 90°C at the tip and dedendum surfaces having a large sliding speed and contact pressure. It is inferred that softening resulting from the temperature rise which occurs when gear pairs mesh, must be taken into account.

□. Conclusion

The followings are the conclusion based on the study comparing the pitting fatigue strength of the carburized/quenched or carbonitrided/quenched gears with and without manganese phosphate.

The gear with manganese phosphating has initial break-in effects and improves its pitting durability as the coating covers the grinding marks of tooth finishing.

The gear with manganese phosphate coating shows bigger Rvk (oil reservoir depth) which affects the tooth surface lubrication, and better lubricating oil holdout which prevents the oil film from being cut out. The coating remains as etching bit and has lubricating oil holdout even after the coating surface is machined out.

Among the several test specifications in this study, the gear pair with only one gear manganese phosphated was observed as the best specification for the pitting fatigue life. It is assumed that gears with manganese phosphating lowers friction due to smoothing of the asperities of the mating gear surface and keeps the tooth surface shape.

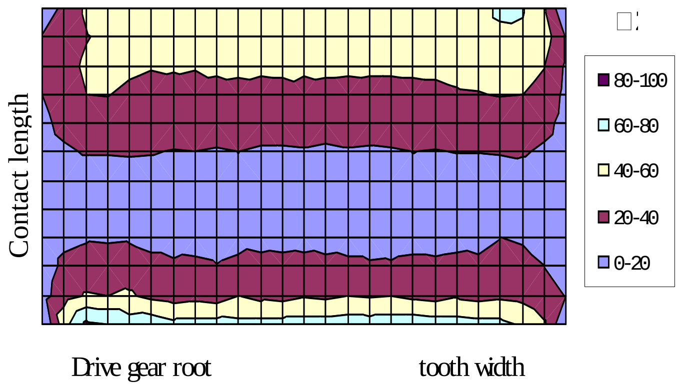


Fig. 15 Distribution of flash temperature rise in a test pinion before testing

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