Lapping and Superfinishing Effects on Surface Finish of Hypoid Gears and Transmission Errors

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Management Summary

This presentation is an expansion of a previous study (Ref.1) by the authors on lapping effects on surface finish and transmission errors. It documents the effects of the superfinishing process on hypoid gears, surface finish and transmission errors. There are several geometric and process parameters, besides offset, that affect hypoid gears' efficiency—spiral angle, pressure angle, lubricant type, temperature and surface finish serve as good examples. In this paper, a study on measurement of surface finish of both ring gear and pinion will be presented. Moreover, the effects of lapping and superfinishing on surface finish will be addressed. Surface finish measurements were done on several experimentally produced hypoid gear pairs. Results are shown of measurements taken before and after superfinishing.

Introduction

Hypoid gears are widely used in the automotive industry to transfer rotation between non-intersecting axes in rear-wheel drive and 4WD vehicles. Compared to other gear types (such as straight and spiral bevel gears) that are geometrically capable of transferring power between perpendicular axes, hypoid gears have more advantages that allow this type of bevel gear to dominate in automotive axle applications. In general, two basic, yet different, cutting processes are used to generate hypoid gears—face milling (FM, or single indexing) and face hobbing (FH, or continuous indexing)—which have their own advantages and disadvantages over each other. However, face hobbing is dominant in automotive industry applications, mostly because it requires shorter cutting time compared to face milling (Refs. 2–4). With hypoid gears' non-intersecting axes, a higher sliding velocity between contact surfaces exists; as a result, sliding friction is one of the main power loss sources, in addition to rolling friction. Therefore, hypoid gears lose considerably more mechanical power during gear mesh than intersecting types of bevel gears and are, as a result, less efficient. In a study on gear surface finish effects on friction (Ref. 5), by comparing frictional losses of conventionally ground (Ra = 0.4 μm) teeth with superfinished (Ra = 0.05 μm) teeth, it was shown that with the same load and speed, this surface finish improvement will decrease friction by around 30%, in addition to decreasing tooth surface temperature. Moreover, based on Xu's proposed model for hypoid gear efficiency prediction (Refs. 6–7), which uses an EHL model with contact data provided by an FEA-based modeling software (Ref. 9), and depending on lubricant temperature at inlet, a change in surface finish from Ra = 0.2 μm to Ra = 0.6 μm may decrease hypoid gear efficiency around 0.5%. As a result, improving surface finish can be one way to increase efficiency. In this study a set of measurements was done to see how superfinishing and lapping will change the surface finish of hypoid gear sets. The aim of this study is to investigate the effects of superfinishing and lapping on the surface finish of hypoid gears to gain insight into the effects of these processes on surface finish. Moreover, it will be experimentally shown how superfinishing and lapping may change transmission errors (up to the first two harmonics for lapping and the first harmonic for superfinishing).

First, the surface finish measurement procedure will be explained, followed by sample results of measurements using this procedure. In this study, superfinishing effects on surface finish and transmission errors will be explained as a complement to a previous study by the authors. This study will not cover theoretical issues related to this phenomenon (effects of superfinishing and lapping on surface finish and transmission errors) at this step. Rather, the goal here is to discuss the issue experimentally, with the hope that future experiments and theoretical studies will help in investigating the superfinishing and lapping effects in more detail.

Surface Finish Measurement Procedure/Hypoid Gears

The surface finish measurements were performed on nine hypoid gear sets before and after lapping. All gear sets were the same and had 11.5" outer diameter; their geometric parameters are as mentioned in Table 1. To measure surface finish, a CNC form-measuring machine (Fig. 1) equipped with *FormTracePack* software was used to analyze measured data to extract surface finish. Table 2 shows an example data sheet of surface finish measurement with several surface finish parameters—Ra, Ry, R_{zDIN}, etc.) and settings.

There are several measuring parameters which need to be set before beginning measurement that are mentioned in Table 2. The machine is equipped with both pinion and gear fixtures in order to keep parts securely in place while measurements are performed. The software is capable of removing surface curvature from data and calculating pure surface finish for curved surfaces. (It should be mentioned here that all measurements were done with 0.8 mm sample length [length of taking data cut-off]). Measuring the surface finish quality in different locations on gear and pinion shows

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Table 1. Hypoid Gear Set Geometric Parameters

Geometric parameters	Pinion	Gear
Number of teeth	11	41
Diametral Pitch	---	3.57"
Face width	2.13"	1.78"
Pinion offset	2.00"	
Shaft Angle	90°	
Outer cone distance	5.36"	6.46"
Pitch diameter	---	11.50"
Pitch angle	25D 23M	62D 50M
Mean spiral angle	49D 59M	27D 38M
Hand of spiral	LH	RH
Generation type	Generated	Non-Generated
Depthwise tooth taper	FH	

Figure 1—Form measuring machine setup.

Table 2. A Sample of Measurement Parameters

Parameter	Results	Parameter	Results
Ra	1.24255 μm	Rp	3.49220 μm
Ry	6.54780 μm	R_{zDIN}	6.54780 μm

Evaluate Condition List<<Profile=R – Section=[1]>>		Measurement Condition	
Standard	OLDMIX	Measurement Length	1.6mm
Kind of Profile	R	Column Escape	5.0mm
Smplg Length (lc)	0.8 mm	Auto-Leveling	Off
No of Smplg(nle)	1	Speed	0.0mm/s
Lc	0.8mm	Over Range	Abort
Kind of Filter	Gaussian	Pitch	0.5 μm
Evltn Length(lm(	0.8 mm	Machine	
Pre-Travel	0.4 mm	Detector	
Post-Travel	0.4 mm	Polar Reversal	Off
Smooth Connection	Off	Arm Compensation	Off
Mean Line Compensation	Off	Auto-Notch(+)	Off
		Compensation Method	Off

Table 3. Pinion surface finish (at center) before and after lapping for drive and coast sides

	Drive side				Coast side			
	Before Lapping		After Lapping		Before Lapping		After Lapping	
No.	Ra	R_{zDIN}	Ra	R_{zDIN}	Ra	R_{zDIN}	Ra	R_{zDIN}
1	0.53	3.78	1.88	15.0	2.75	12.92	1.79	12.24
2	1.52	10.4	1.47	11.8	2.30	18.24	2.37	15.71
3	1.35	5.23	1.59	9.54	2.18	16.69	1.93	11.58
4	1.26	9.35	1.31	10.1	1.86	9.07	1.63	10.13
5	1.88	8.54	1.21	7.61	2.11	13.98	1.78	12.39
6	1.92	7.10	1.03	8.09	2.34	14.50	1.66	12.29
7	0.56	3.13	1.00	9.49	1.48	10.47	1.72	12.23
8	1.40	7.87	0.97	9.46	2.42	13.27	1.93	16.04
9	1.48	10.2	1.44	11.6	1.84	15.02	1.77	11.30
Ave.	1.32	7.29	1.32	10.3	2.14	13.8	1.84	12.66
Var.	0.24	7.27	0.09	5.02	0.14	8.07	0.05	3.84

Table 4. Gear surface finish (at center) before and after lapping for drive and coast sides

	Drive side				Coast side			
	Before Lapping		After Lapping		Before Lapping		After Lapping	
No.	Ra	R_{zDIN}	Ra	R_{zDIN}	Ra	R_{zDIN}	Ra	R_{zDIN}
1	0.93	9.92	1.45	11.6	0.78	6.07	1.54	10.86
2	1.21	7.83	1.75	13.9	1.22	8.79	1.71	10.90
3	0.83	6.61	1.78	12.3	1.16	6.32	1.27	8.04
4	0.53	3.70	1.84	13.9	1.14	8.54	1.71	13.78
5	0.77	7.27	1.53	11.0	0.87	7.09	1.70	13.17
6	0.26	2.69	1.14	8.00	0.96	6.79	1.26	8.77
7	0.71	5.32	1.77	13.0	0.90	8.38	1.80	10.91
8	2.01	13.14	1.85	18.3	1.46	7.02	1.27	9.30
9	0.91	7.54	1.55	9.81	1.03	8.39	1.65	11.07
Ave.	0.907	7.113	1.629	12.4	1.06	7.49	1.55	10.76
Var.	0.93	9.92	1.45	11.6	0.04	1.08	0.05	3.57

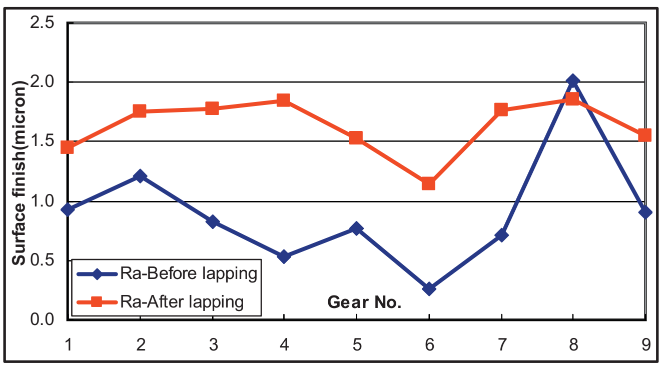

Figure 2—Gears drive side surface finish: before and after lapping (Ra).

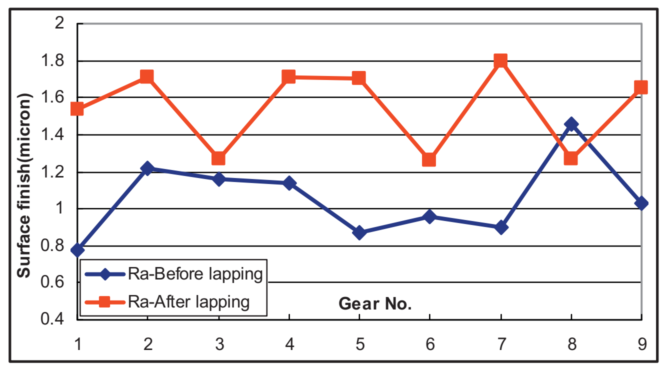

Figure 3—Gears coast side surface finish: before and after lapping (Ra).

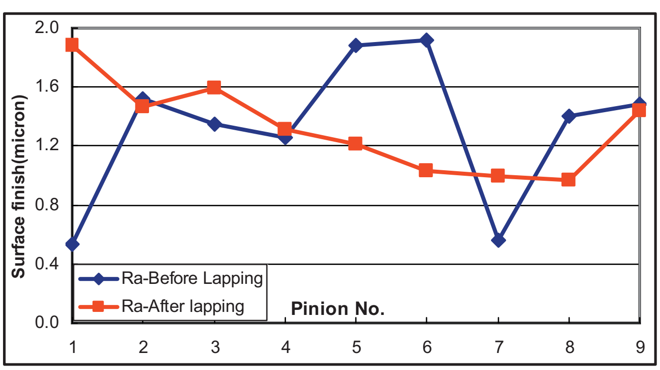

Figure 4—Pinions drive side surface finish: before and after lapping (Ra).

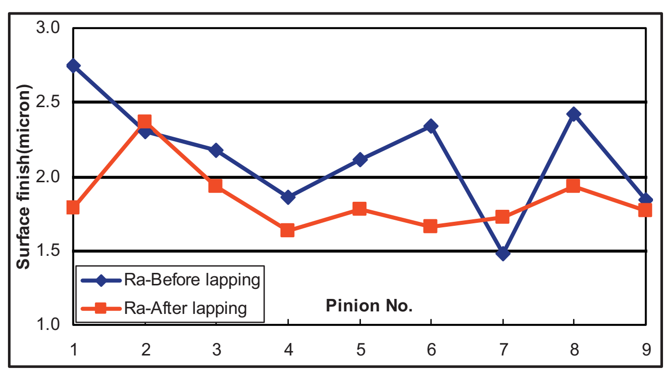

Figure 5—Pinions coast side surface finish: before and after lapping (Ra).

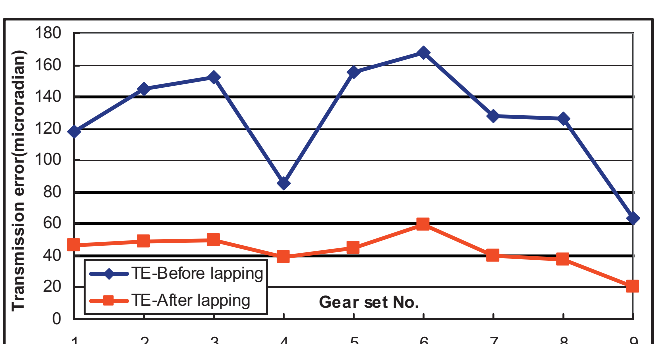

Figure 6—First-harmonic (drive side) transmission error.

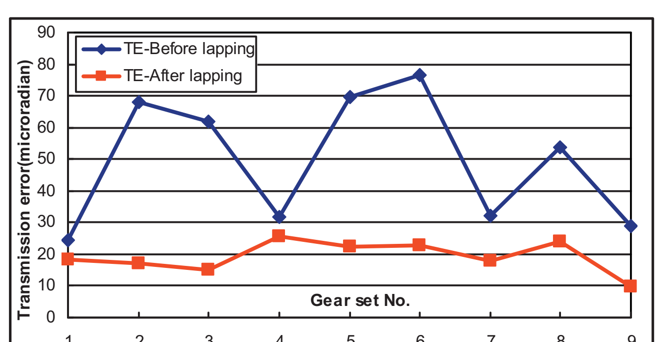

Figure 7—First-harmonic (coast side) transmission error.

that it varies considerably in both lengthwise and profile directions. To have consistent surface finish data to compare results before and after the lapping process, data should be taken from the same location on the flank, i.e., lengthwise (from toe to heel) and profile (from top to root) location of measuring spot should be consistent for all measurements.

In order to check the surface finish variation on pinion flank, a pinion surface was divided into nine regions—three divisions from toe to heel and three divisions from top to root—and surface finish was measured in the middle of each region. The results show that surface finish improves from top to middle and then worsens, continuing further to the root in the profile direction. In addition, the surface finish will improve from toe and heel toward the center (in lengthwise direction). Although it may not be a general rule, it is a consistent result for most of the measured pinions.

Lapping Effects on Surface Finish and Transmission Errors

Lapping is one of the processes used for gear finishing. While for many types of gears grinding may at times be economical—for bevel and hypoid gears, lapping is the most applicable and economical process (except for some aerospace applications). Lapping also smoothes the surface through increasing mesh between pinion and gear, which in turn serves to reduce noise levels (Refs. 3–4). As for hypoid gears in automotive applications, their large production volumes preclude grinding with currently available machine technology, thus making lapping the best choice.

The main advantage of lapping over grinding in large-volume production is that lapping requires less time and employs price-friendly machinery (Ref. 8). Depending on the hypoid gear geometry (especially the amount of offset), the sliding velocity and contact pressure will be changed during mesh cycle. As a result, sliding distance caused by the combination of sliding velocity and contact pressure on every contact point (or spot) results in surface wear. Therefore, the complex physical quantity of sliding distance on each surface point forms a surface wear distribution over the gear flank. To experimentally measure how much lapping will affect surface finish, some sets of experiments have been performed.

In order to check lapping effects on surface finish, a set of measurements was performed to evaluate surface finish (namely Ra and R_{zDIN}) on both gears and pinions. All measurements were done on the same area in all gears and pinions (at the center of lengthwise and profile directions). For all gear sets, the same lapping settings were used, and all were lapped with the same abrasive (silicon carbide) lapping compound. The lapping procedure was conducted under a light brake load, with about 10 Nm torque on the gear shaft, and pinion speed was kept at 2,300 rpm.

For all gears and pinions, measurements were performed on both drive and coast sides before and after lapping. The results in each of these four sets—Pinion/Drive, Pinion/Coast, Gear/Drive and Gear/Coast sides—are shown in Tables 3 and 4 (all measurements were performed on the same tooth).

Moreover, the average and variation of each column of data are shown at the end of Tables 3 and 4. To have a graphical view of the surface finish changes by lapping, the measurement results for the gear drive and coast sides before and after lapping are seen in Figures 2 and 3. As is shown, the surface finish of all gears is higher (rougher) after lapping, when compared to before lapping. In addition, surface finish changes for the drive and coast sides of the pinion before and after lapping are shown in Figures 4 and 5. In these graphs, Ra was used; however, R_{zDIN} also was measured (see Tables 3 and 4) and the same trend was observed. As for the

continued

Table 5.Transmission Errors: (first, second and third harmonics) for drive side before and after lapping

	Transmission Errors							
	Drive side				Coast side			
	Before Lapping		After Lapping		Before Lapping		After Lapping	
No.	DM01	DM02	DM01	DM02	DM01	DM02	DM01	DM02
1	118	14.7	46.83	9.51	24.4	8.44	18.35	3.71
2	145	13.7	48.94	8.63	68	16.9	17.29	6.34
3	153	11.5	49.4	7.72	62	12.1	15.21	4.14
4	85.9	10.1	38.97	7.22	31.8	12.1	25.68	6.14
5	155	15.3	44.93	8.74	69.8	10.5	22.21	2.5
6	167	10.7	59.8	11	76.8	9.63	22.7	3.2
7	128	15.1	40.05	8.47	32.3	26.8	17.88	7.14
8	126	17.7	37.82	7.38	53.6	9.57	24.2	4.07
9	63.6	15.4	20.04	3.09	29	11.4	9.61	1.54
Ave	126.9	13.78	42.98	7.97	49.74	13.04	19.24	4.31

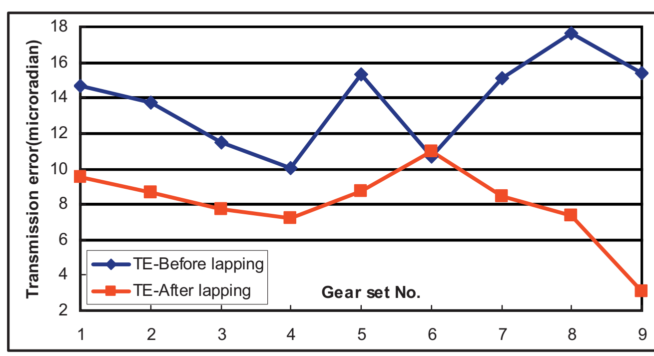

Figure 8—Second-harmonic (drive side) transmission error.

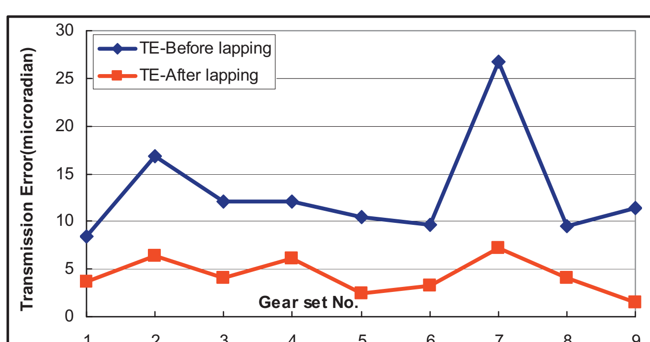

Figure 9—Second-harmonic (coast side) transmission error.

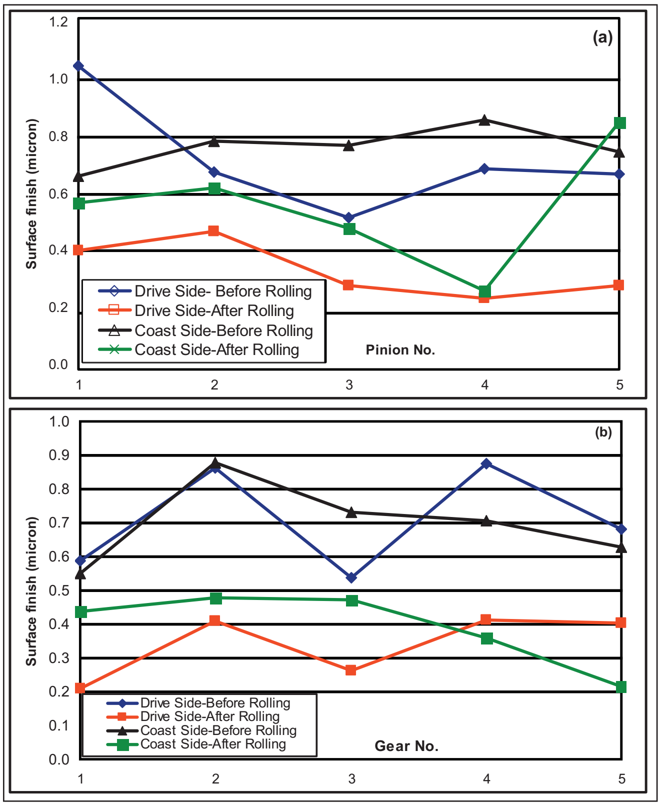

Figure 10—Surface finish changes after rolling for: a) pinion; b) gear.


Figure 11—Gear set photo before superfinishing process.


Figure 12—Gear set photo after superfinishing process.

pinion, there are no consistent changes, and lapping effects on surface finish vary from part to part. In addition, to see how other hypoid gear characteristics may be affected by lapping, transmission errors of the gear sets were measured (by Gleason SFT machine) and the measurement results are shown in Table 5 for both drive and coast sides, respectively. The results of Table 5 are graphically shown in Figures 6–9 for the first two harmonics, for both drive and coast sides. As can be seen in the graphs, lapping decreased both harmonics for both drive and coast sides.

Also, to see the effects of rolling of lapped pinions and gears on surface finish, the roughness of five gear sets—before and after rolling—was measured. The results for Ra on both drive and coast sides of pinions and gears are as shown in Figures 10a and 10b.

Rolling was performed by an SFT machine under 17 Nm brake load on a gear shaft at 100 rpm for pinion speed, and lightweight oil (SAE 30W) was used for lubrication for the entire hunting tooth cycle time. As can be seen, rolling gear sets together after lapping will improve surface finish slightly. Although these figures (Fig.10a and 10b) are for Ra, surface finish improvement with the same results was observed for R_{zDIN} as well.

Superfinishing Effects on Surface Finish and Transmission Errors

Isotropic superfinishing (ISF) is an abrasive type of finishing process. It is a chemically accelerated vibratory finishing that has the capability to finish surfaces with (Ra) < 3 μ-inch. A smooth work surface is produced by simultaneously loading an abrasive stone against a rotating workpiece surface and oscillating (reciprocating) the stone (Ref. 12).

To see how superfinishing will affect the surface finish of hypoid gears, a set of hypoid gears after lapping was superfinished, and both pinion and gears were measured, as in the previous example. Figures 11 and 12 show the gear sets before and after superfinishing. The results of the surface finish measurements for the pinion and gear are in Table 6. In this table, row 1 shows the surface finish before superfinishing; row 2, after superfinishing; and row 3, after rolling.

This Table 1 sample result is for one gear set. However, measurements were also done on eight additional gear sets, and surface finish changes were completely consistent among all parts.

As such, superfinishing significantly improved the surface finishing quality, the surfaces now appearing much smoother. However, after rolling (with the same rolling condition mentioned for rolling after lapping), the smoothness of this gear set has decreased. The measurement results after rolling the gear set together are in the third row (marked by 3) of Table 6 for pinion and gear (all measurements were performed on the same tooth).

Moreover, to graphically see the surface finish changes before superfinishing, after superfinishing, and after rolling, the results are shown in Figures 13 and 14 (for both Ra and R_{zDIN}) for the pinion and gear for both drive and coast sides.

Also, to see the effects of the superfinishing process on transmission errors, single flank tests were done on those original eight gear sets, and the results for both drive and coast sides are shown in Figures 15a and 15b.

It is shown that, although superfinishing improves surface finish drastically, it doesn't affect first-harmonic transmission error. Moreover, the results for SFT show that superfinishing does not have any considerable or consistent effect on 2nd- or 3rd-harmonics.

For an example of surface quality before and after superfinishing, and after rolling, Figure 16 shows all of the steps in the same graph for both the pinion and drive side.

Conclusions

In this paper, a study on measuring the surface finish of both ring gear and pinion was presented. Moreover, the effects of superfinishing and lapping on surface finish and transmission errors were discussed. Surface finish measurements were done on several experimentally produced hypoid gear pairs that are manufactured at the GearLab of American Axle and Manufacturing Inc., using an accurate form-measuring machine. Despite the fact that lapping was expected to improve surface finish, measurement results show that gear surface finish becomes worse after lapping, while no consistent or definitive results for pinion surface finish were observed. In addition, it can be seen that lapping decreases surface finish variation among gear sets. However, it was shown that lapping decreased the first three harmonics of transmission errors for both drive and coast sides. Also, further studies need to be done to check the effects of lapping on higher harmonics. And last, this paper presented the effects of the superfinishing process on hypoid gear set surface finish and transmission errors.

continued

Table 6. Surface finish data for pinion; 1) After lapping, 2) After superfinishing, 3) After rolling

	Pinion				Gear			
	Drive		Coast		Drive		Coast	
	Ra	R_{zDIN}	Ra	R_{zDIN}	Ra	R_{zDIN}	Ra	R_{zDIN}
1	2.03	12.34	1.72	10.90	2.00	15.29	2.12	14.70
2	0.14	1.492	0.31	0.86	0.29	2.00	0.31	3.34
3	0.30	1.563	0.43	3.08	0.33	4.38	0.36	3.69

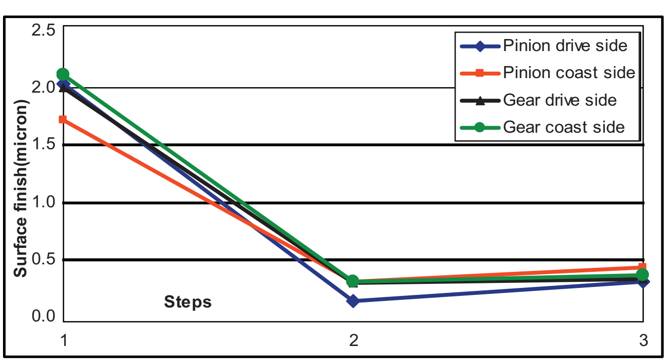

Figure 13—Ra for pinion and gear: 1) after lapping; 2) after superfinishing; 3) after rolling.

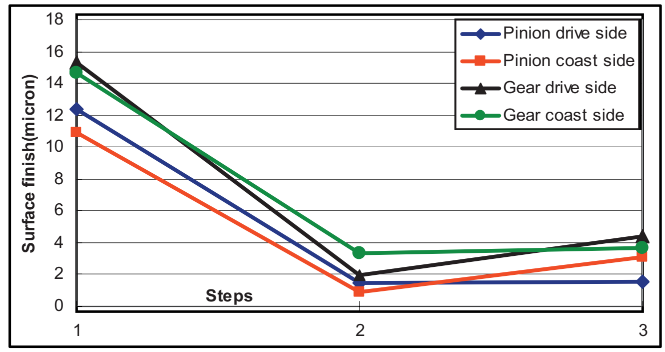

Figure 14—R_{zDIN} for pinion and gear: 1) after lapping; 2) after superfinishing; 3) after rolling.

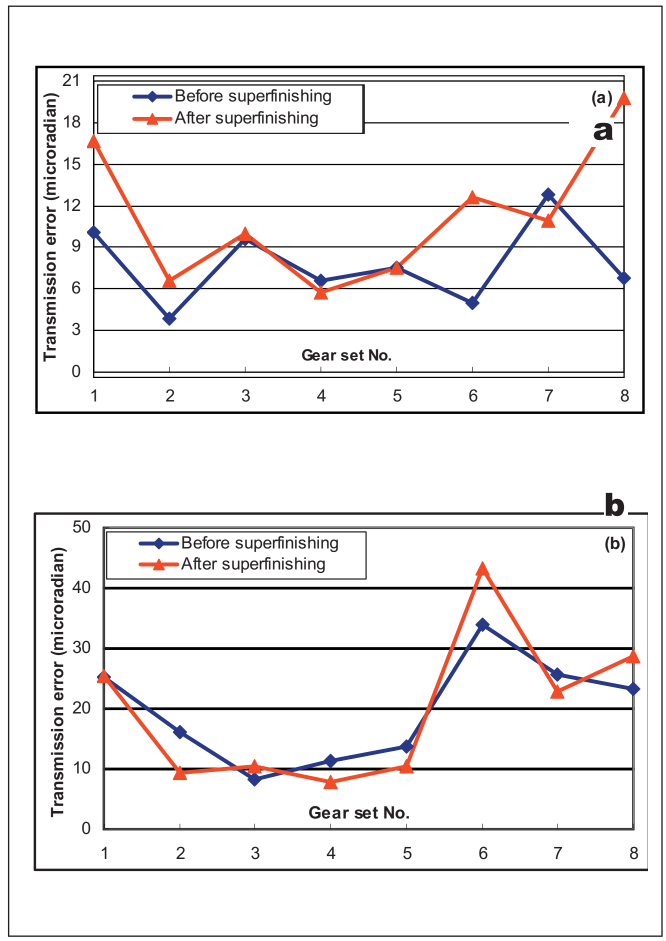

Figure 15—First-harmonic transmission error of gear sets before and after superfinishing: a) drive side; b) coast side.

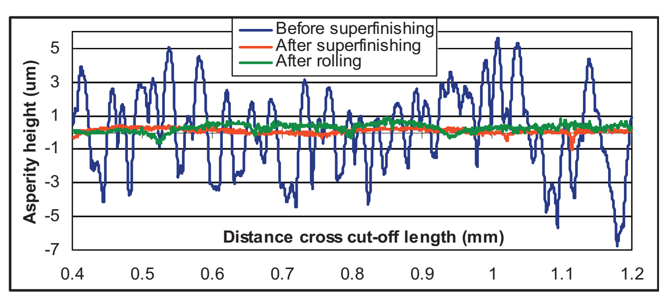

Figure 16—The effect of a different surface finish process on surface finish quality for pinion: drive side.

This study shows the results of measurements taken before and after superfinishing. Although superfinishing dramatically improves surface finish, it was also shown that the surface finish quality achieved by superfinishing decreased markedly when gear sets were rolled together. Moreover, the results for single flank testing showed that superfinishing does not have any considerable or consistent effect on transmission errors.

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