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LAPPING AND SUPERFINISHING EFFECTS ON HYPOID GEARS SURFACE FINISH AND TRANSMISSION ERRORS

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ABSTRACT
There are several geometric and working parameters, besides offset, that have minor effects on hypoid gears efficiency (i.e. spiral angle, pressure angle, lubricant type & temperature, surface finish, etc.). Some theoretical analyses of mechanical efficiency of hypoid gears show that surface finish has considerable effect on hypoid gear efficiency. This is due to a high sliding to rolling ratio in these types of gears. In this paper, a study on measuring of surface finish of both ring gear and pinion will be presented. Moreover, the effects of lapping and superfinishing on surface finish will be discussed. Using an accurate form-measuring machine, surface finish measurements were done on several experimentally produced hypoid gear pairs. Despite the fact that lapping is expected to improve the surface finish, measurement results show that ring gear's surface finish becomes worse (roughness increased) after lapping while no consistent results for pinion surface finish were observed. However, it will be shown that lapping decreases transmission errors for both sides (drive and coast). Utilizing a Gleason single flank tester (SFT) 600HTT it will be shown experimentally that transmission errors up to the second harmonics for both sides will be decreased. In addition, it can be seen that lapping decreases surface finish variation among gear sets. As an expansion of the previous study [1] by the authors on lapping effects on surface finish and transmission errors, this paper will also present the effects of the superfinishing process on hypoid gears surface finish and transmission errors. This study shows the result of measurements taken before and after superfinishing, although superfinishing improves surface finish drastically it will be shown that surface finish quality will be decreased when gear sets are rolled together.

1 INTRODUCTION
Hypoid gears are widely used in automotive industries to transfer rotation between non-intersecting axes in rear wheel drive and 4WD vehicles. Compared to other options for gear types (such as straight and spiral bevel gears), that geometrically are capable of transferring power between perpendicular axes, hypoid gears have more advantages which allows this type of bevel gear to dominate in automotive axle applications. In general two basic different cutting processes are used to generate hypoid gears namely face-milling (FM, also called single indexing) and face-hobbing (FH, also called continuous indexing), which have their own advantages and disadvantages over each other. However, face-hobbing method is dominated in automotive industry applications mostly because they need shorter cutting time compared to face-milling method [2-4]. In hypoid gears due to having 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 have considerably more mechanical power loss during gear mesh than intersecting types of bevel gears and as a result are less efficient than other types of bevel gears. In a study on gears surface finish effects on friction [5] by comparing frictional losses of conventionally ground (Ra =0.4 um) with superfinished (Ra=0.05 um) teeth, it was shown that with the same load and speed this surface finish improvement will decrease friction around 30 percent in addition to decreasing tooth surface temperature. Moreover, based on Xu's proposed model for hypoid gear efficiency prediction [6, 7] which uses an EHL model with contact data provided by a FEA based modeling software (9), (depending on lubricant temperature at inlet) a change in surface finish from Ra=0.2 um to Ra=0.6 um may decrease hypoid gear efficiency around 0.5 percent. As a result, improving surface finish can be one way to increase efficiency.

In this study a set of measurements were done to see how superfinishing and lapping will change surface finish of hypoid gear sets. The aim of this study is to investigate the effects of superfinishing and lapping on surface finish of hypoid gears for to have an insight of effects of these processes on surface finish. Moreover, it will be experimentally shown how superfinishing and lapping may change transmission errors (up to first two harmonics for lapping and first harmonic for superfinishing).

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First, surface finish measurement procedure will be explained and then the results of measurements with more details of measuring procedure will be provided. In this study, superfinishing effects on surface finish and transmission errors will be explained as a complement of previous study by the authors of this paper. 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; the goal here is to discuss the issue experimentally and more experiments and theoretical studies in future will help investigating the superfinishing and lapping effects in more details.

2 SURFACE FINISH MEASUREMENT PROCEDURE

To experimentally see the effects of lapping or superfinishing on surface finish of hypoid gears; surface finish measurements were performed on nine hypoid gear sets before and after lapping. All gear sets were the same and had 11.5 in outer diameter and their geometric parameters are as mentioned in table1. To measure surface finish a CNC form-measuring machine[1] (figure 1), equipped with software called FormTracePack was used to analyze measured data to extract surface finish. Table 2 shows an example of data sheet of surface finish measurement with several surface finish parameters (i.e. 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. Machine is equipped with both pinion and gear fixtures (holders) in order to keep parts securely in place while measurements is being performed. The software on the machine is capable to remove surface curvature from data and calculate 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 surface finish quality in different location on gear and pinion shows that surface finish considerably varies in both lengthwise and profile directions. Therefore in order to have consistent surface finish data to compare results before and after lapping process; data should be taken from same location on flank meaning that lengthwise (from toe to heel) and profile (from top to root) location of measuring spot should be consistent for all measurements.

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	

[1] - Mitutoyo SV3000

Figure 1. Form measuring machine setup

Table 2. A sample of measurement parameters

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

Evaluate Condition List<<Profile=R – Section=[1]>>		Measurement Condition	
Standard	OLDMIX	Measurement Length	1.6 mm
Kind of Profile	R	Column Escape	5.0 mm
Smplg Length (lc)	0.8 mm	Auto-Leveling	Off
No of Smplg(nle)	1	Speed	0.0 mm/s
Lc	0.8 mm	Over Range	Abort
Kind of Filter	Gaussian	Pitch	0.5 um
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

In order to check surface finish variation on pinion flank a pinion surface was divided into 9 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 shows that surface finish improves from top to middle and then get worse continuing further to root in profile direction. In addition, surface finish will improve from toe and heel toward center (in lengthwise direction). Although it may not be a general rule, it is consistent result for most of measured pinions.

3 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 also be (sometimes) economical, for bevel and hypoid gears still lapping is the most applicable process and is used as an economically applicable procedure (except for some case in aerospace applications). It is also the aim of lapping to make surface smoother through increasing conjugacy between pinion and gear and hence reduction in level of noise [3, 4].

As for hypoid gears in automotive industries, due to large production volume, grinding with currently available technology of machines and procedures is hard to be used instead of lapping. The main advantage of lapping over grinding in large volume production lines is that lapping needs cheaper machines and shorter processing time [8].

Depending on hypoid gear geometry (specially 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 effect on surface finish, some sets of experiments have been performed.

In order to check lapping effects on surface finish, a set of measurements were performed to evaluate surface finish (namely Ra and R_{zDIN}) on both gears and pinions. All measurements were done on same location in all gears and pinions (at the center of lengthwise and profile directions). For all gear sets the same lapping settings for lapping machine were used and all were lapped with a same abrasive (silicon carbide) lapping compound. Also lapping procedure was conducted under light brake load with about 10 N.m torque on gear shaft and pinion speed was kept at 2300 RPM.

For all gears and pinions, measurements were performed on both drive and coast sides before and after lapping. The measurements results in each of these four sets i.e. Pinion-Drive, Pinion-Coast, Gear-Drive and Gear-Coast sides are shown in tables 3 and 4 respectively (all measurements were performed on the same tooth). Moreover, average and variation of each column of data is shown at the end of table 3 and 4. To have a graphical view of surface finish changes by lapping, the measurement results for gear drive and coast sides before and after lapping is drawn in figures 2 and 3 respectively. As it can be seen surface finish of all gears is higher (rougher) after lapping; compared to what they were before lapping. In addition, surface finish changes for drive and coast sides of pinion before and after lapping are showed in figures 4 and 5. In this graphs Ra was used however R_{zDIN} also was measured (as they are mentioned in tables 3 and 4) and same trend has been observed. As for pinion, there are no consistent changes and lapping effects on surface finish varies 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 as table 5 for both drive and coast sides respectively.

The results of table 5 graphically are shown in figures 6 to 9 for the first two harmonics for both drive and coast sides. As it can be seen in graphs, lapping decreased both harmonics for both drive and coast sides.

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

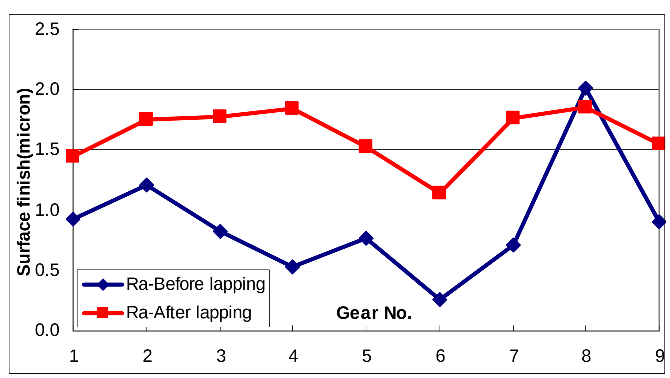

Figure 2. Gears drive side surface finish before and after lapping (Ra)

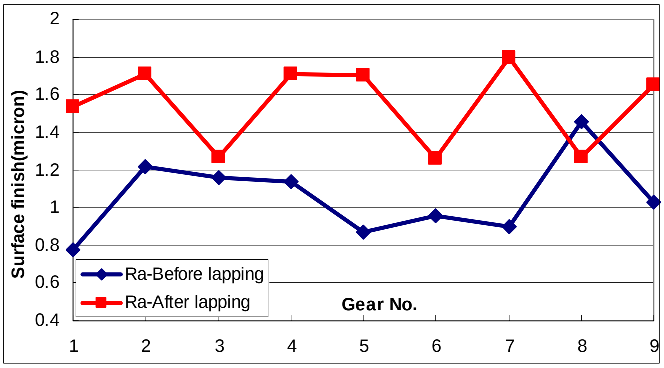

Figure 3. Gears coast side surface finish before and after lapping (Ra)

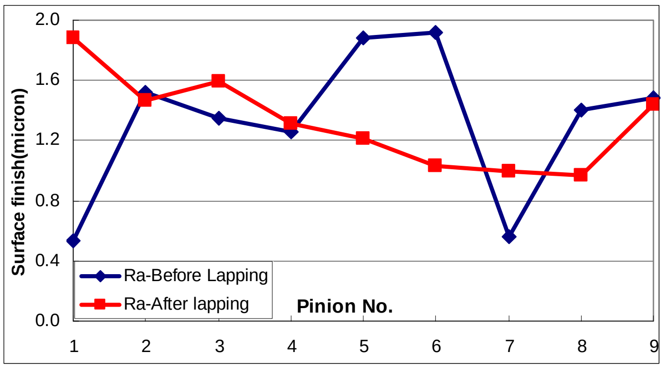

Figure 4. Pinions drive side surface finish before and after lapping (Ra)

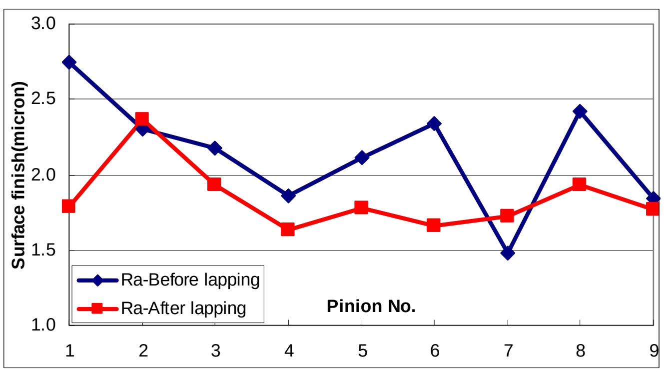

Figure 5. Pinions coast side surface finish before and after lapping (Ra)

Also, to see the effects of rolling[2] of lapped pinions and gears on surface finish the roughness of five gear sets before and after rolling were measured and the results for Ra on both drive and coast sides of pinions and gears are as figure 10 part a and b respectively. Rolling was performed by SFT machine under 17 N.m brake load on gear shaft with 100 RPM for pinion speed and light weight oil (SAE 30 W) was used for lubrication for full hunting tooth cycle time. As it can be seen rolling gear sets together after lapping will improve surface finish slightly. Although these figures (10 (a) and (b)) are for Ra, surface finish improvement with the same trend were observed for R_{zDIN} as well.

[2] - This rolling here is due to single flank test.

Table 5. Transmission errors (first, second and third harmonics) for drive side before and after lapping[3]

	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

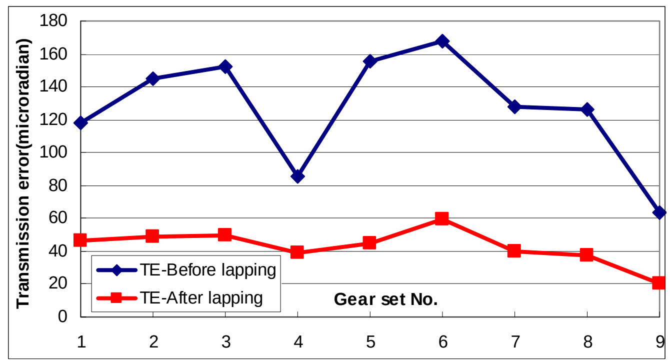

Figure 6. First harmonic drive side transmission error

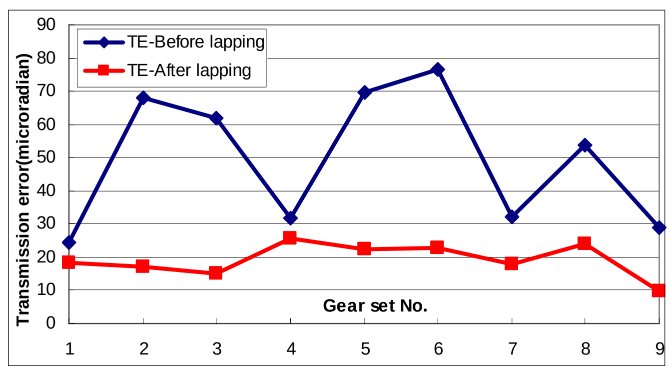

Figure 7. First harmonic coast side transmission error

[3] - All units for transmission errors are micro radians

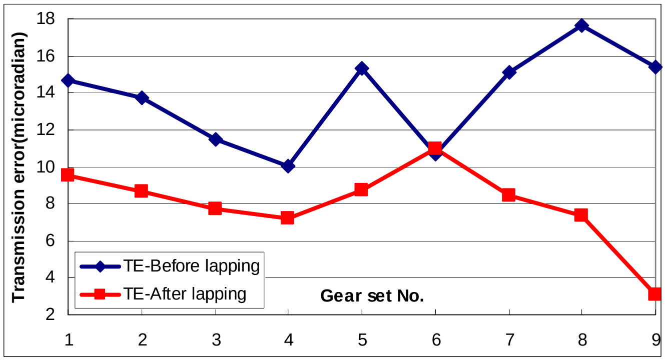

Figure 8. Second harmonic drive side transmission error

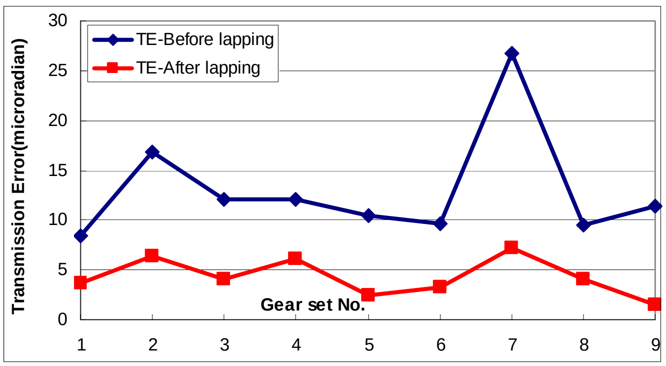

Figure 9. Second harmonic coast side transmission error

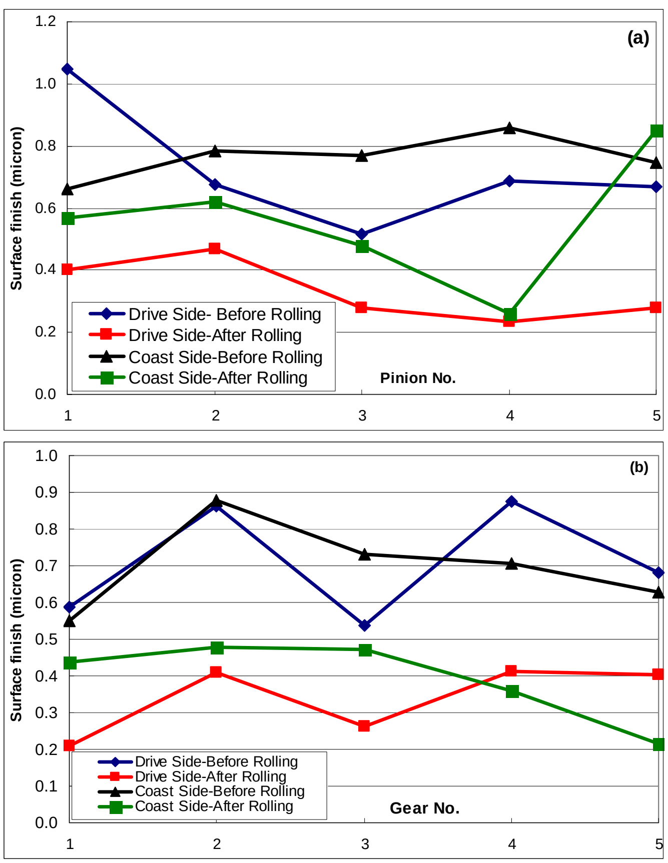

Figure 10. Surface finish changes after rolling for a) Pinion b) Gear

4 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 capability to smoothen surfaces with (Ra) < 3 u-inch. A smooth work surface is produced by simultaneously loading an abrasive stone against a rotating workpiece surface and oscillating (reciprocating) the stone [12].

To see how superfinishing will effect on surface finish of hypoid gears a set of hypoid gears after lapping was superfinished and the same surface finish measurements as it was explained in previous sections was performed on both pinion and gears. Figures 11 and 12 show the gear sets before and after superfinishing respectively. The results of surface finish measurements for the pinion and gear are as mentioned in table 6. In this table first row (marked by 1) shows surface finish before superfinishing, second row (marked by 2) is surface finish after superfinishing and third column (marked by 3) shows surface finish after rolling.

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

This table one sample result for one gear set while these measurements were done on 8 gear sets and surface finish changes were completely consistent among all parts.

As it can be seen, superfinishing significantly improved surface finishing quality and the surfaces after superfinishing is much smoother. However, after rolling (with the same rolling condition mentioned for rolling after lapping) smoothness of this superfinished gear set has been decreased.

The measurement results after rolling the gear set together are in third row (marked by 3) of table 6 for pinion and gear (all measurements were performed on the same tooth).

Moreover to graphically see 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 pinion and gear for both drive and coast sides.

Also, to see the effects of superfinishing process on transmission errors, single flank tests were done on those 8 gear sets and the results for drive and coast sides are as figure 15 part a and b respectively.

As it can be seen, although superfinishing improves surface finish drastically it doesn't have effect on 1st harmonic transmission error. Moreover the results for SFT shows that superfinishing also do not have any considerable and consistent effect on 2nd and 3rd harmonics as well.

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

Figure 11. Gear set photo before superfinishing process

Figure 12. Gear set photo after superfinishing process

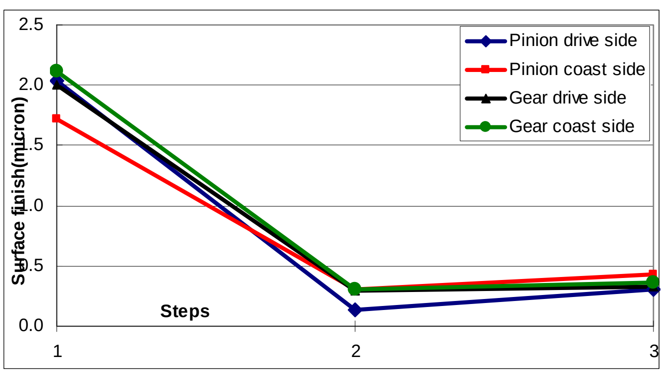

Figure 13. Ra for pinion and gear; 1) After lapping, 2) After superfinishing, 3) After rolling

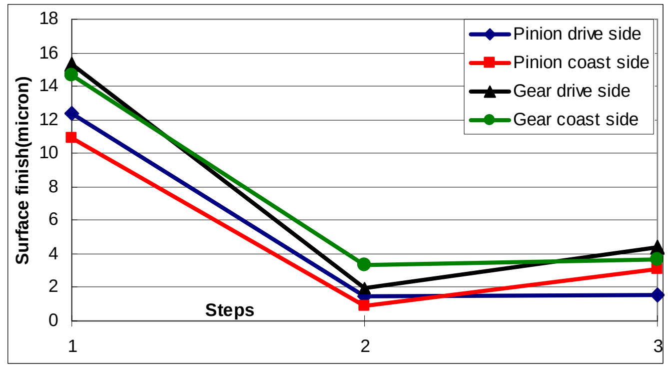

Figure 14. R_{zDIN} for pinion and gear; 1) After lapping, 2) After superfinishing, 3) After rolling

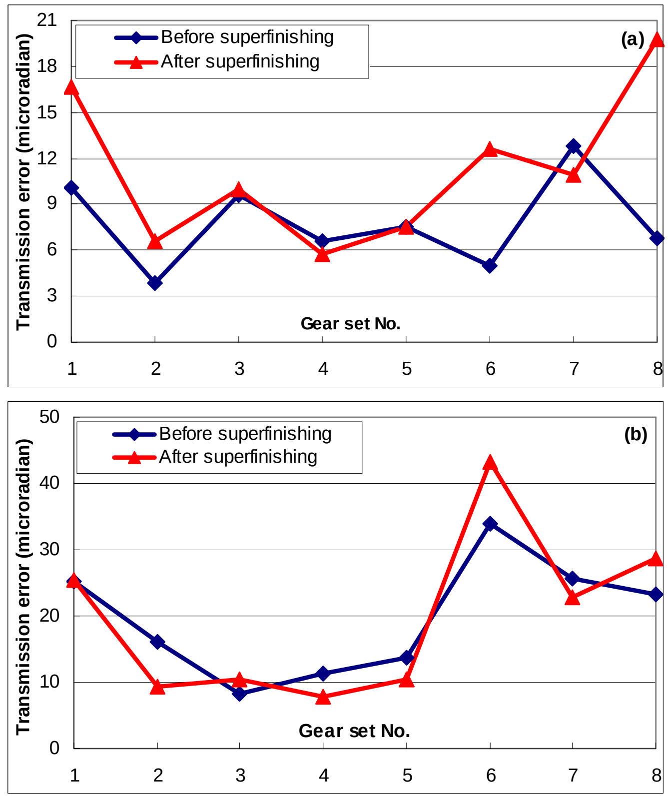

Figure 15. First harmonic transmission error of gear sets before and after superfinishing a) Drive and b) Coast side

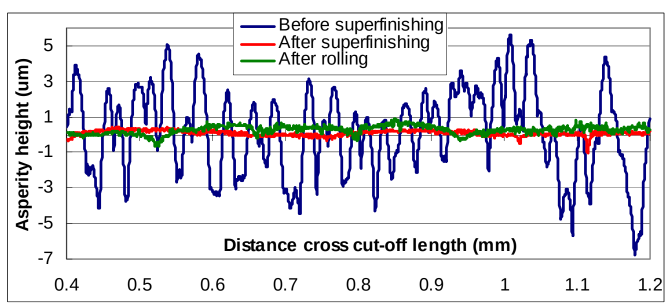

Figure 16. The effect of different surface finish process on surface finish quality for pinion drive side

5 CONCLUSION

In this paper a study on measuring of 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 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 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. Moreover, this paper presented the effects of the superfinishing process on hypoid gears set surface finish and transmission errors.

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

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