The Hunting Tooth and its Effect on Break-In

QUESTION

Has there ever been any experimental verification of the benefits of designing a gear pair to have a "hunting tooth" or is it just theoretical?

Expert response provided by Dr. Hermann J. Stadtfeld

Introduction

When referencing the literature, it will be noticed that there is no comprehensive explanation with visualizing graphics about the hunting tooth and its relationship to the performance of a gearset. This is the reason why this article turned out larger than expected for the answer to the question, "Is the hunting tooth a more academic phenomenon, or is there a practical application?" The expression "hunting tooth" is a descriptive term created in the practical world. It describes that each tooth of one member chases and then touches each tooth (or slot) of the mating member after a certain number of revolutions.

In the case of an integer ratio for example 10×30, there will be three pinion revolutions and one ring gear revolution until the cycle repeats (Ref. 1). This scenario is graphically shown in the matrix in Figure 1. One gear revolution is shown in the top row in blue, labeled "A." The pinion revolutions are shown in row "B" and "C." The first pinion revolution is shown in green, the second revolution in maroon and the third in yellow. After this sequence, the colors repeat. For example, pinion tooth 1 will mesh strictly with the slots 1, 11 and 21 of the gear. The second sequence of pinion revolutions in row "C" is merely a repetition of the first three pinion revolutions in row "B." The pinion rotation blocks do not shift because of the integer ratio.

In the case of a ratio 12×30, which has a common denominator of 2 but is not an integer ratio, pinion tooth 1 rolls with the gear slots 1, 13, 25, 7 and 19. It takes two pinion revolutions until the cycle repeats (see Figure 2). It could be speculated if the scenario shown in Figure 2 has advantages to the scenario in Figure 1. Nevertheless, in both cases, the pinion teeth mesh in groups of gear slots. In Figure 1 these are three groups and in Figure 2 these are five groups. Only meshing between the groups is possible for the defined ratios.

A hunting tooth relationship in gear pairs means that there is no common denominator between the number of pinion and gear teeth. As a result, every tooth of the pinion will mesh with every slot of the gear. After all teeth and slots have been rolling with each other, the cycle repeats. The cycle repetition happens after the gear performs a number of revolutions, equal to the number of pinion teeth. This is of course also true if the pinion preforms a number of revolutions equal to the number of gear teeth. The number of revolutions to achieve "one tooth hunting sequence" is independent from the fact if the number of teeth are prime numbers or if simply one number is even and the other number is odd.

In Figure 3 it is graphically demonstrated how revolution by revolution of the pinion the green, maroon and yellow blocks shift from row to row. It requires the pinion revolutions in rows "B" to "L" until one hunting tooth sequence is finished. Row "M" has the identical phase relationship as row "B" and therefore presents the first repetition

The shifting of the pinion revolution blocks from row to row in Figure 3 allows, in each pinion revolution, each pinion tooth to mesh with a different gear slot. However, in one revolution each pinion tooth can only mesh with one gear slot. In order to cover all gear slots, the pinion has to rotate for each gear slot once which is then called the hunting tooth number of rotations.

Ratio 10 x 30

A = Gear Revolution

A	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
B	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
C	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10

B = Pinion Revolutions

C = Repetition of Pinion Revolutions

Figure 1 Integer ratio 10×30.

Ratio 12 x 30

A = Gear Revolution

A	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
B	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6
C	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
D	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6

B = Pinion Revolutions

C = Repetition of Pinion Revolutions

Figure 2 Common denominator ratio 12×30.

Is the Influence of the Hunting Tooth Theoretical or Reality?

It is stated in older literature that a hunting tooth ratio is helpful in the case of lapped gears. However, in the case of not heat treated or ground gearsets, the older literature points out that integer ratios are preferred. As a reason it is mentioned that gearsets with integer ratios are easier to inspect, test and assemble accurately (Ref. 2). This rule is still applied today for precision actuation with moderate to low load. The following sections will reveal that for power transmissions the effect of break-in is an extremely important factor which has a key influence to the operating performance of the transmission during its lifetime. However, if the break-in improves or worsens the performance of a power transmission depends on the optimal interaction between all teeth, which is only given with a hunting tooth ratio.

A typical single flank variation of a ground gearset is shown in Figure 4. The graphic shows a harmonic deviation over one gear revolution and three harmonic waves from the three pinion revolutions. The high frequency content is created by the tooth mesh which repeats in the graphic 30 times.

The influence of the hunting tooth is not an academic effect, which in theory would improve the performance of a gear pair. To the contrary, there is a very simple and very easy detectable, practical difference between a gearset with a hunting tooth and a gearset with a common tooth count denominator; this difference becomes tangible during the gearset's break-in.

Independent from the fact if a gearset is ground, honed, lapped or not hard-finished at all, there are certain flank form deviations from tooth to tooth and there is an indexing error; the break-in will go a quite different path in case of integer ratios. In the case of a 10×30 ratio, the three sections of the larger gear will mesh with the 10 slots of the pinion. Tooth 1, 11 and 21 will therefore only contact slot one of the pinion. During the break-in period, teeth 1, 11 and 21 will become similar or even equal to each other. The pinion teeth 1 to 10 will become more and more different to one another. Figure 5 shows a single flank variation of the 10×30 gearset, after it is broken in. The graphic shows lesser harmonic content, but larger runout amplitudes during one gear revolution. The break-in did not improve the gearset's single flank quality. The three sections of the pinion revolutions manifested a

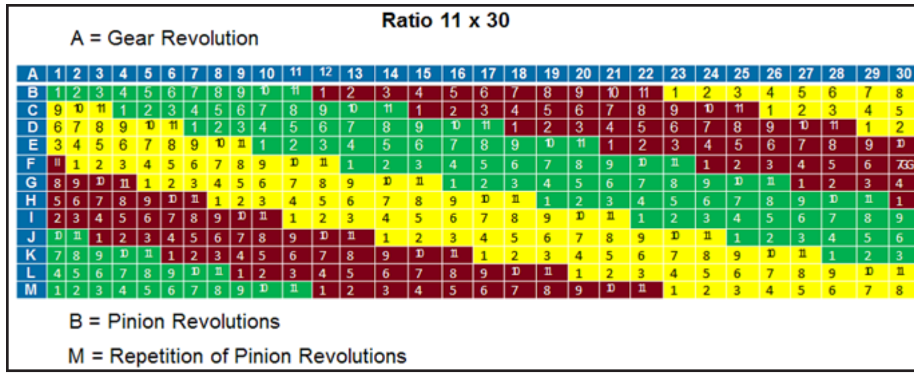

Figure 3 Hunting tooth ratio 11×30.

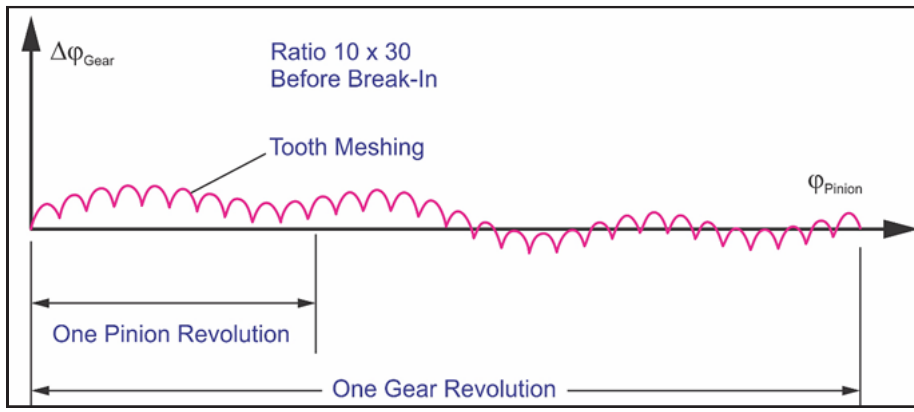

Figure 4 Single flank graphic after grinding.

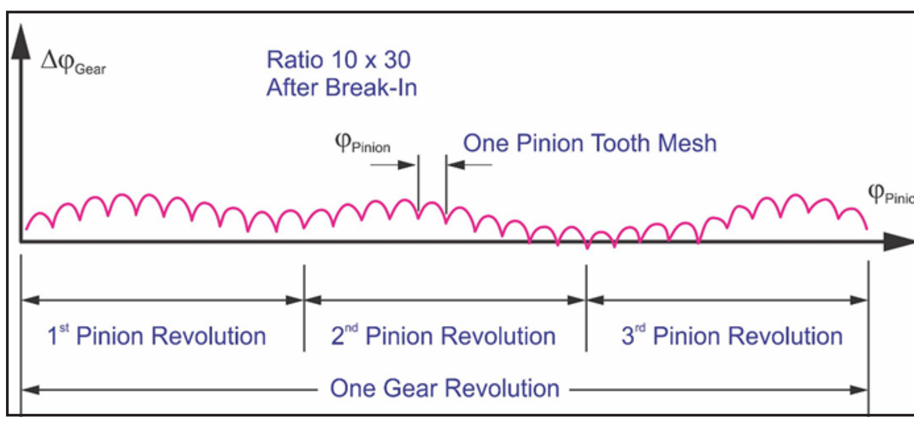

Figure 5 Single flank graphic of gearset with integer ratio after break-in.

distinct single flank pattern, which is less favorable than the initial single flank variation after grinding. Superimposed to the pinion runout are the single tooth ripples from the tooth meshes. The graphic in Figure 5 represents the discussed integer ratio of 10×30 after break in. It appears that certain errors are created as the break-in progresses.

There is no influence from one section to the other two sections. Due to the integer ratio, the three sections develop independent from each other and stay after break-in basically in a permanent condition.

Because the break-in degraded the quality of the gearset performance, it is recommended to super-finish ground gearsets with integer ratios. The super-finishing will prevent a further break-in, which in this case is an advantage because it will preserve the initial motion transmission quality after grinding (Fig. 4).

Servicing a Transmission with Integer Ratio

If one of the two gears is removed during servicing the transmission, then it is important to mark a tooth of the gear and the pinion slot it rolls with. If that is not done, and the gears are assembled in a random orientation, then a much bigger problem occurs. At the time of servicing, the tooth surfaces had already been broken in and a second attempted break-in with different tooth and slot combinations will fail because the surfaces are too smooth and the hydrodynamic oil film separates the flank surfaces. However, the larger motion error in higher load conditions can cause the flank surfaces to break through the oil film and damage the flank surfaces. In many known cases, the noise level of a randomly assembled, already broken-in gearset with integer ratio increased. This would often lead to the false concern that pre-loads had been wrongly adjusted or that the bearings were contaminated during the service call.

The Break-In Procedure

Break-In is an abrasive action which changes the micro-geometry on the flank surfaces. A controlled break-in begins with light load and moderate RPM. Reversing the hand of rotation is recommended after only 20 minutes of operation.

Figure 6 shows the recommended break-in cycle for Super Reduction Hypoids. The surface in areas which cause a momentary acceleration impulse will be abrasively altered more than areas without acceleration. Areas which cause a momentary deceleration will show little or no surface alteration.

The surface action is a combination of removing sharp peaks and then super-finish them with a mix of abrasive removal and a plastic deformation. This explains that broken-in gearsets have a polished appearance on the active areas of the flank surfaces.

First the load is increased in the cycles 1 through 4 while the speed is 50% of the nominal speed or below. During this low-speed load increase, the superfinishing action is also increased. The flank form modifications during the low-speed and light-load break-in period improve the noise vibration and harshness (NVH) properties of the gearset (cycles 1 & 2) — especially in low-load operating condition — when transmission noise is most critical. The following two cycles 3 and 4 with low speed and high load cause larger tooth and flank surface deflections without having a sustainable surface separation due to hydrodynamics. This condition activates the removal of roughness peaks in the remaining areas of potential tooth contact and also polishes these areas. This section of the break-in prepares the gearset for high-load operation regarding effective contact ratio and optimal surface finish for optimal elasto-hydrodynamics.

Cycles 5 through 8 operate with the maximal RPM for which the gearset is rated. Cycles 5 and 6, where the load is lower, are dominated by a polishing effect accompanied by very small abrasive action; there is no abrasive action expected in cycles 7 and 8. The high speed and high load will initiate a final surface polishing. The duration of the entire break-in is 16 hours, which is realistic for a higher reduction gearset with a module at or below 3mm.

SRH Break-In	Direction	% of max. RPM	% of max. Load	Duration minutes	Repetitions
Cycle 1	Drive	50	25	20	3
	Coast	50	25	20	
Cycle 2	Drive	50	50	20	3
	Coast	50	50	20	
Cycle 3	Drive	50	75	20	3
	Coast	50	75	20	
Cycle 4	Drive	50	100	20	3
	Coast	50	100	20	
Cycle 5	Drive	100	25	20	3
	Coast	100	25	20	
Cycle 6	Drive	100	50	20	3
	Coast	100	50	20	
Cycle 7	Drive	100	75	20	3
	Coast	100	75	20	
Cycle 8	Drive	100	100	20	3
	Coast	100	100	20	

Figure 6 Break-in cycle for super reduction hypoids (SRH).

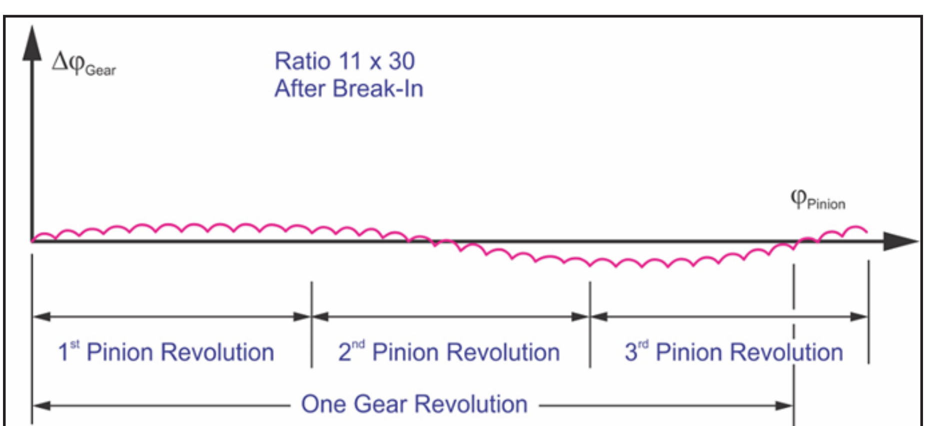

Figure 7 Single flank graphic of hunting tooth ratio 11×30 after break-in.

Surface Optimization during Break-In of a Hunting Tooth Ratio

In order to achieve the break-in results described in the last paragraph, it is imperative to design gearsets with hunting tooth ratios. A hunting tooth condition can be established if the number of pinion or gear teeth of an integer ratio or a common denominator ratio are increased by just one tooth. Now, during the break-in every pinion tooth will mesh with every gear tooth. The influence of this kinematic difference allows the teeth to become more equal as opposed to developing their individual shapes in groups of 10 (in the above mentioned example). Figure 7 shows a single flank graphic of an 11×30 gearset after break-in. The starting condition after grinding is the same as shown in Figure 4. The single flank pattern in Figure 4 shows next to the high-frequency tooth mesh, the sine-shaped gear runout per gear revolution which is superimposed with the sinusoidally shaped pinion runout of each pinion revolution. After the break-in it can be observed in Figure 7 that the pinion runout as well as the tooth mesh ripple has reduced noticeably. Overall it can be stated that the break-in improved the transmission quality of the gearset and most likely also the gearset's quality class.

In order to visualize the different effects of a break-in and of polishing, it was possible to allocate a ground hypoid gearset which was driven in a vehicle for 300 miles. The ring gear of this set was then compared to the same size hypoid gearset, which was freshly ground and with a second one which had been super finished after grinding. These three ring gears were used for a measurement of the surface roughness in the mean tooth surface area, where the contact pattern is located. The results of this surface roughness comparison is shown in Figure 8. The top graphic in the figure shows the roughness measurement results of the ground ring gear. The center graphic in Figure 8 shows the alteration which occurred after a 300 mile break-in. The surface roughness value Ra dropped to about 50% of the original roughness. Also the value Rz dropped below 70% of the value after grinding.

The bottom graphic in Figure 8 shows the surface finish after super finishing the freshly ground ring gear. The roughness value Ra dropped to 12% of the ground pinion surface. Also the value Rz reduced significantly to only 15% of the original number.

The roughness characteristic as it is created by the break-in process has advantages for the buildup of a stable oil film with a high-load carrying properties versus the super finished gearset. It can be noticed, comparing the center and the bottom graphic in Figure 8 that the oil pockets provided by the roughness valleys have completely disappeared during the super finishing treatment. Single flank tests with slow RPM and high RPM microphone recordings also

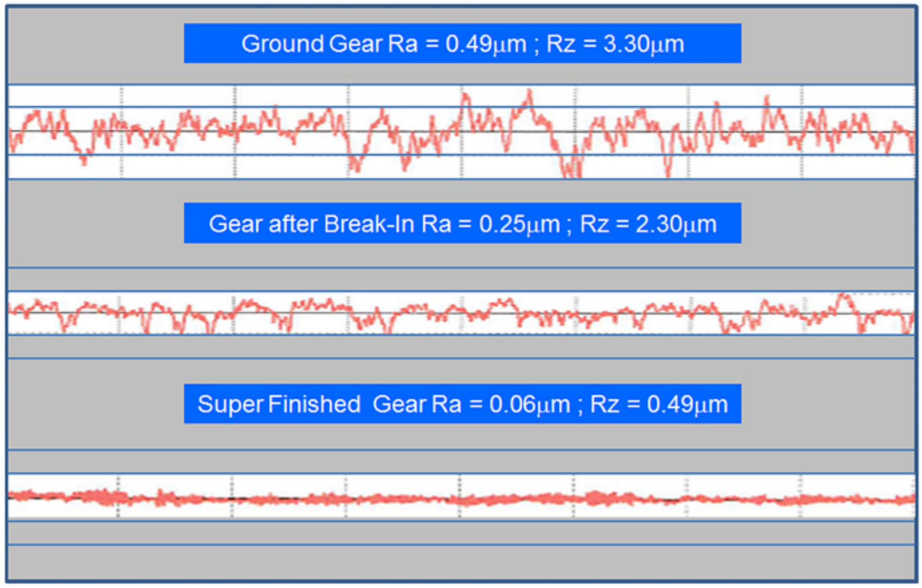

Figure 8 **Surface roughness of a ground, broken-in and super-finished flank.**

proved that the operating noise at the most critical low load conditions is lower for conventionally broken-in gearsets compared to the super finished version.

During the servicing of a gearset with a hunting tooth ratio, it is not of any use to mark a tooth and the slot it meshes with because the "tooth hunting" will put the gears back for an equally optimal performance as before removal — independent from the orientation of the gears.

For more information.

Questions or comments regarding this paper? Contact Dr. Stadtfeld at *hstadtfeld@gleason.com.*

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For 35 years, Dr. Stadtfeld has had a remarkable career within the field of bevel gear technology. Having received his Ph.D. with summa cum laude in 1987 at the Technical University in Aachen, Germany, he became the Head of Development & Engineering at Oerlikon-Bührle in Switzerland. He held a professor position at the Rochester Institute of Technology in Rochester, New York From 1992 to 1994. In 2000 as Vice President R&D he received in the name of The Gleason Works two Automotive Pace Awards — one for his high-speed dry cutting development and one for the successful development and implementation of the Universal Motion Concept (UMC). The UMC brought the conventional bevel gear geometry and its physical properties to a new level. In 2015, the Rochester Intellectual property Law Association elected Dr. Stadtfeld the "Distinguished Inventor of the Year." Between 2015–2016 CNN featured him as "Tech Hero" on a Website dedicated to technical innovators for his accomplishments regarding environmentally friendly gear manufacturing and technical advancements in gear efficiency.

Stadtfeld continues, along with his senior management position at Gleason Corporation, to mentor and advise graduate level Gleason employees, and he supervises Gleason-sponsored Master Thesis programs as professor of the Technical University of Ilmenau — thus helping to shape and ensure the future of gear technology.