Gear manufacturing simulation for high quality/low cost

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1 Abstract

SMT has developed a toolkit of advanced cylindrical gear manufacturing simulation software. This technology includes: gear hobbing / shaping cutter tip optimization to gain at least 12% improvement in bending strength over the current best practice (gear produced by full fillet tip hobbing / shaping cutter); shaving dynamics simulation to avoid shaving process issues and therefore high manufacturing cost; hobbing / shaping process simulation to allow trouble shooting of poor hobbing / shaping quality problems at little cost. These technologies have been well validated against ISO and real life application to gear manufacturing problems. They are proven to be effective cost saving technologies which are generating a high level of interest.

2 Introduction

Striving for high quality and low cost products is a permanent goal for mass production. Due to the pressure for low noise, low cost transmissions, the demand for higher quality and lower cost gears becomes increasingly more important.

Many organizations have accumulated tremendous experience in improving gear manufacturing quality by minimum investment such as well proven process of gear shot-peening. Nevertheless it is still widely accepted that there are some areas worthy of further investigation:

- Hobbing / shaping cutter tip fillet full optimization to maximize gear bending strength

- How to audit at the gear design stage for potential shaving problems to avoid expensive solutions to correct quality at the manufacturing stage.

- Simulate the hobbing / shaping process to predict the probable gear quality and to help identify potential root causes to hobbing / shaping quality problems. The quality problems may be caused by compatibility between the gear design and hobbing / shaping cutter, or combination of gear blank quality, hobbing / shaping cutter manufacturing quality, hobbing / shaping machine set up including rigidity.

SMT has investigated these areas and developed a toolkit of relevant technology to reduce cost significantly. Based on these technologies a set of software modules have been developed and integrated to a transmission software system called MASTA produced by SMT. It has been confirmed by SMT customers that there is a significant benefit gained by using this technology.

This paper will describe the relevant technology and demonstrate the benefit of using this toolkit of technology and software modules.

3 Gear root optimization for maximum bending strength by optimizing hob / shaper tip fillet

3.1 Principle

Target of the optimization: to minimize the product of Form factor (Y_F) & Stress Correction Factor (Y_S)

Variables: shape of the cutter tip fillet, locations of the root diameter and form diameter

Please note that current existing approaches all predefine the shapes of the hobbing / shaping cutter tip fillet normally some specific simple shapes, such as single circular curves. In this case they will only allow limited parameters, such as the joint location between hob flank and fillet, to be decided by optimization. The approach used by SMT considers the shape of the hobbing / shaping cutter tip fillets as part of the variables to be optimized, and assumes the fillet is an arbitrary curve not just a simple circular curve.

Optimization method: Multiple linear searches are used to obtain the best possible shape of the fillet so that the resulting critical section produces the best possible bending strength. Critical section calculation is based on ISO 6336.

3.2 Benefits of using this optimization

Here is an example to demonstrate how much further potential could be explored by the optimization. One pair of gears was provided (detailed data see Appendix) and their original hobbing cutter design for both pinion and wheel were full fillet tips which are normally considered the best practice.

After optimizing the hobbing cutter tip fillet shape and parameters, the pinion bending stress at the critical section is reduced by 11.66% and the wheel bending stress at the critical section is reduced by 28.22%. This is a significant result.

The hobbing cutters before and after optimization and the wheel/pinion root after optimization are shown in Figure 1 to Figure 6.

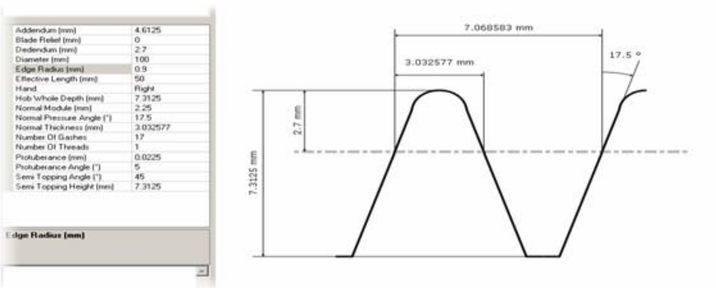

Figure 1 - Original Hobbing Cutter for Pinion – full fillet

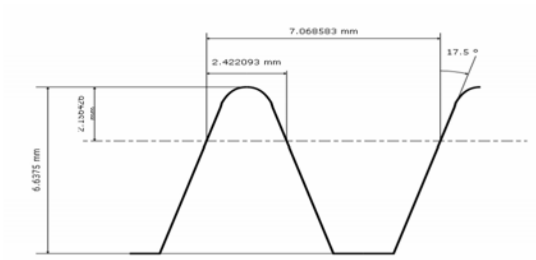

Figure 2 - Optimized Hobbing Cutter for Pinion

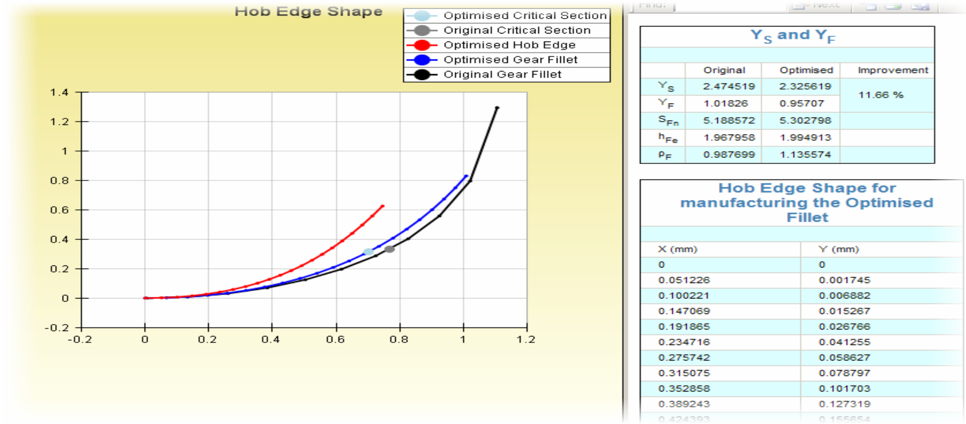

Figure 3 - Optimized hob tip fillet and the resulting pinion fillet

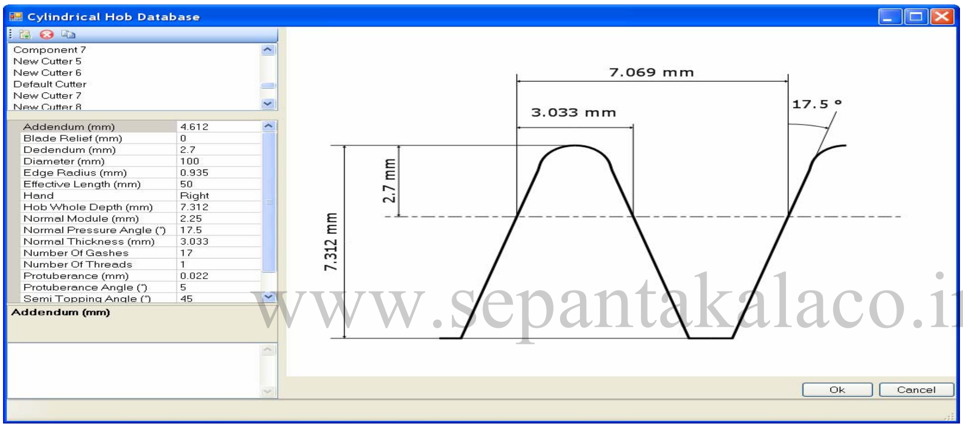

Figure 4 - Original hobbing cutter for the wheel – full fillet tip

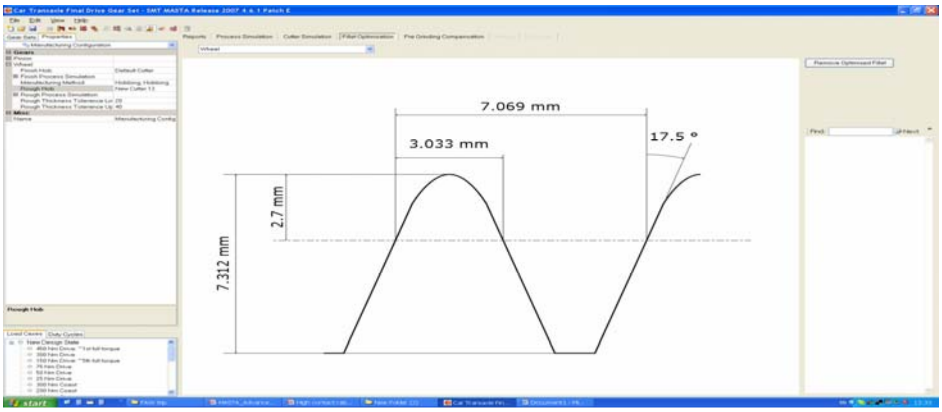

Figure 5 - Optimized hobbing cutter for the wheel

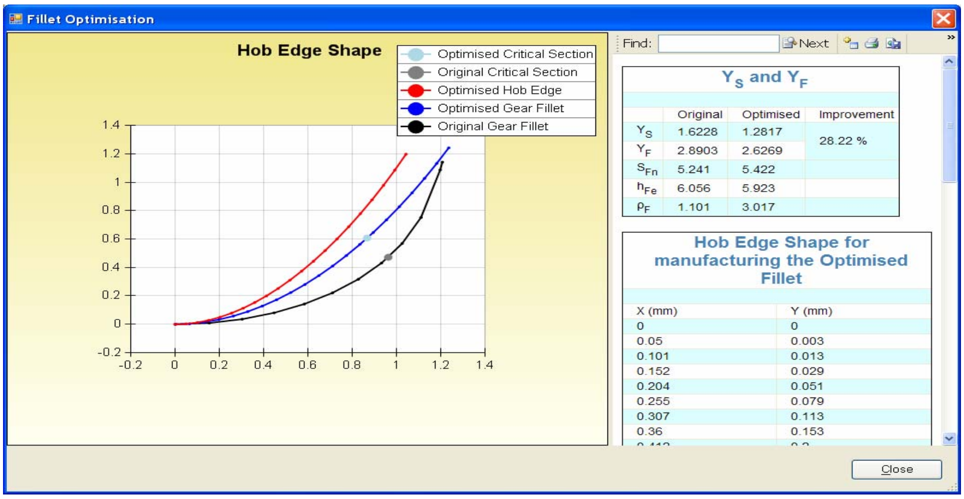

Figure 6 – Optimized hob tip fillet and the resulting wheel fillet

Normally the bending strength for the pinion is more critical than for wheel. However from the example quoted above, the improvement of the bending strength for the wheel is much more significant than for the pinion and this results in excessive safety margin in the wheel's bending strength. This creates an opportunity to increase the bending strength of the pinion further. This can be achieved by a re-design process by slightly modifying the macro geometry. Specifically the distribution of the addendum modification coefficient of the gear pair to reduce the wheel bending strength and increase the pinion bending strength so as to balance the bending strength between the pinion and wheel. After the re-design process, re-optimizing the hobbing cutter tip fillets will be required. This iteration helps improve the pinion bending strength further. For the example above, the total final improvement of the bending strength of the pinion shall be more than 12% over the bending strength produced by a hobbing cutter with a full fillet tip which is considered as the current best practice.

4 Technology for auditing potential gear shaving problems at gear design stage

4.1 Principle

Controlling shaving quality is one of the most difficult tasks in gear manufacturing due to the unsynchronized transmitting relationship between gear blank and shaver. Hence understandably it is very difficult to predict accurately whether or not there will be shaving quality problem before shaving process is carried out.

It is also probable that about 10% - 20% of gears within a single transmission will have more serious shaving quality problems than others due to the gear macro geometry design. In this case, changing hobbing/shaping cutter and shaving cutter design does not make an effective improvement and the best solution is to find the problem at the early design stage and modify the gear design to avoid the problem. Otherwise any solution applicable during the manufacturing stage only, will be much more costly.

SMT has established such technology that can audit whether or not a given gear macro geometry will result in shaving problems.

The key of the technology is to understand the fundamentals of the shaving dynamics and to build mathematical models to represent the complex interaction between the gear blank and shaving cutter. The dynamic interaction between the gear flank and the shaving cutter results in uneven shaving force distribution across the gear flank and hence the gear material is not evenly taken away by the shaving cutter as required.

The mathematical models will calculate the distribution and variation of the shaving forces across the gear tooth flank according to given gear macro geometry and shaving / hobbing / shaping cutter or assumed possible best shaving / hobbing / shaping cutter design for given machine sizes.

SMT has also developed the technology further as a software tool which is easy to use.

4.2 Example & benefits

SMT received a gear for a prototype truck transmission from a customer and was requested to identify the root causes of poor shaving quality as shown in Figure 7.

This customer had tried different hobbing cutters and shaving cutters, including over 60 different shaving cutter profile modifications. The customer was not successful in fixing the poor shaving quality and a request was made to SMT for assistance. By this time the manufacturing was significantly delayed resulting in a high cost penalty.

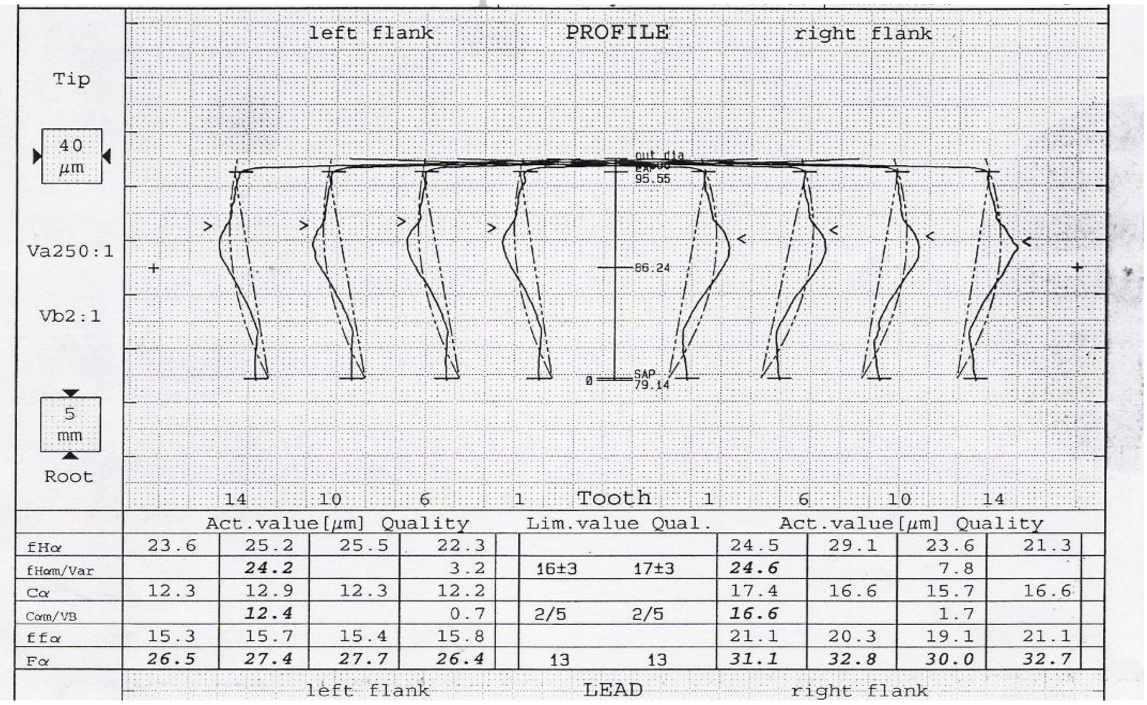

Figure 7 - Poor shaving quality – measured profile chart

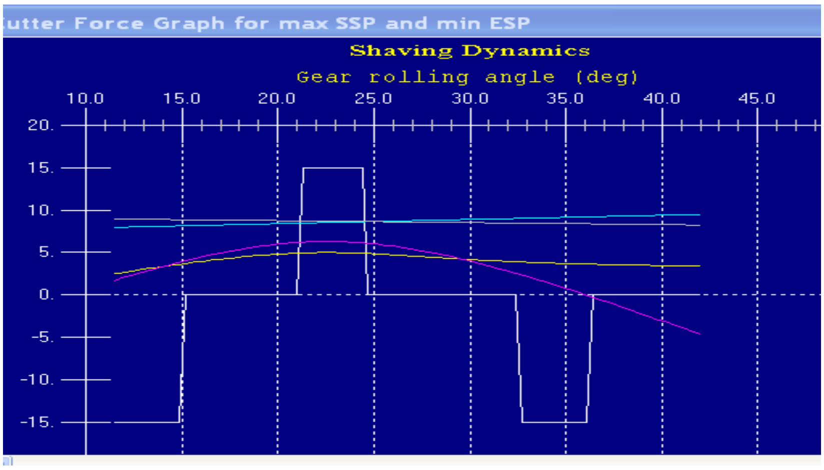

Figure 8 - Simulation result – Shaving forces distribution across gear profile

Using shaving dynamics simulation, it was found the shaving forces across the gear flank were distributed in an undesirable way as shown in Figure 8.

According to Figure 8 there is large resultant shaving force between roll angles at 20–25 degrees, and low resultant shaving force between roll angles at 32–36 degrees. This produces excessive negative material between roll angles at 20–25 degrees and excessive positive material between roll angles at 32–36 degrees. This correlates very closely with the measured chart as indicated in Figure 9.

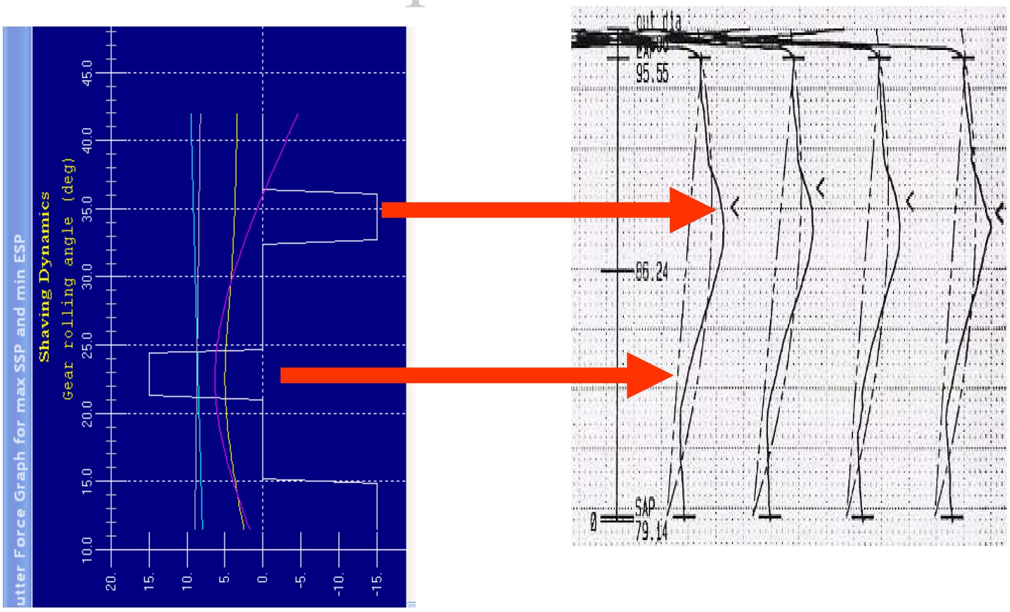

Figure 9 - Correlation between simulation result and actual measurement

There were 2 proposed solutions. The best solution was to modify the gear design to avoid additional cost at both prototype level and full production. Otherwise a compromised solution could be considered at higher cost which requires an additional process to target a good shaving force distribution across the gear flank during shaving process.

This problem should have been identified before the design was released for prototype by simulating the shaving forces distribution and much extra cost and time delay in development would have been saved for this customer. This direct and indirect saving is significant and should not be underestimated.

With the help of this technology, in theory, all gear shaving issues can be completely avoided at gear design stage. In practical terms, occasionally there is no way to avoid gear shaving issues due to some special design constraints. In this case the problem gear will have to be made. However, this technology can also effectively assist in finding a solution to fix the shaving quality with minimum extra cost as good quality shaved gears can only be produced within a controlled shaving dynamics condition.

5 Technology for quick trouble shooting in gear hobbing / shaping process

5.1 Principle

Accurate mathematical models between all key factors affecting the hobbing/shaping quality and the hobbed / shaped quality have been established. Based on these models, two software modules have been created and integrated to SMT's MASTA software package. For any given gear blank, hobbing / shaping cutter design, manufacturing quality and machine set up tolerances, one can use these simulation modules to test exactly how each key parameter affects hobbing / shaping quality within a few seconds. This is an extremely powerful tool in assisting and identifying the root causes of poor hobbing / shaping quality.

The key parameters considered for hobbing process include
- Hob dimensions including manufacturing tolerance
- Hob redressing tolerance, including slot lead, slot indexing and rank angle.
- Gear macro geometry.
- Tolerances of the hobbing machine set up, including hob and gear blank mounting tolerance.
- Process data such as feeds and speeds.

The key parameters considered for shaping process include
- Shaper parameters.
- Shaper manufacturing tolerances including those for pitch and profile.
- Shaper redressing tolerances.
- Gear macro geometry.
- Shaping machine set up tolerances, including shaper and gear blank mounting tolerances.
- Process data such as feeds and strike.

As usual profile, lead and pitch error are the criteria of evaluating hobbing/shaping quality. The simulation modules output the three results in both chart and number format as shown in Figure 10 – Figure 12 and Table 1.

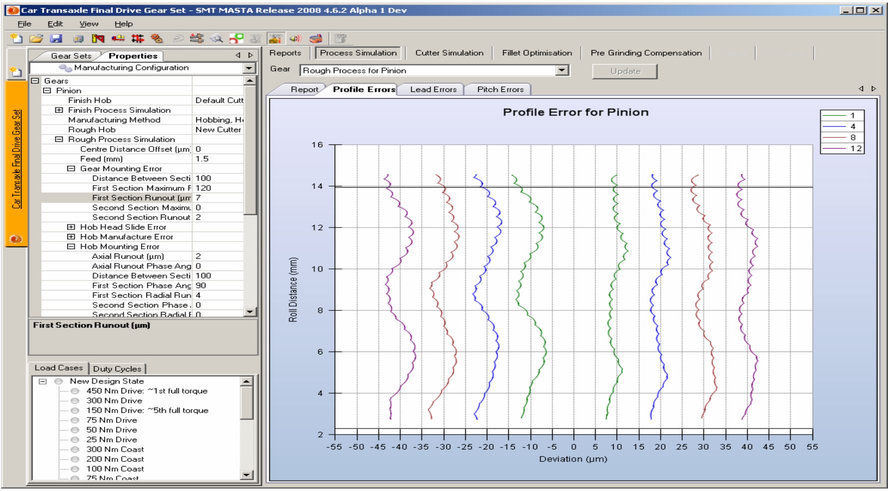

Figure 10 - The profile error for pinion in the simulation

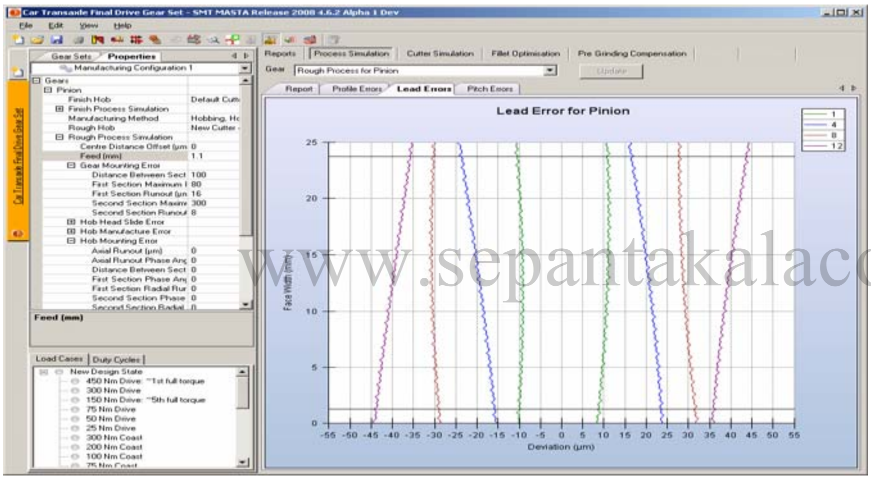

Figure 11 - The lead error for pinion in process simulation

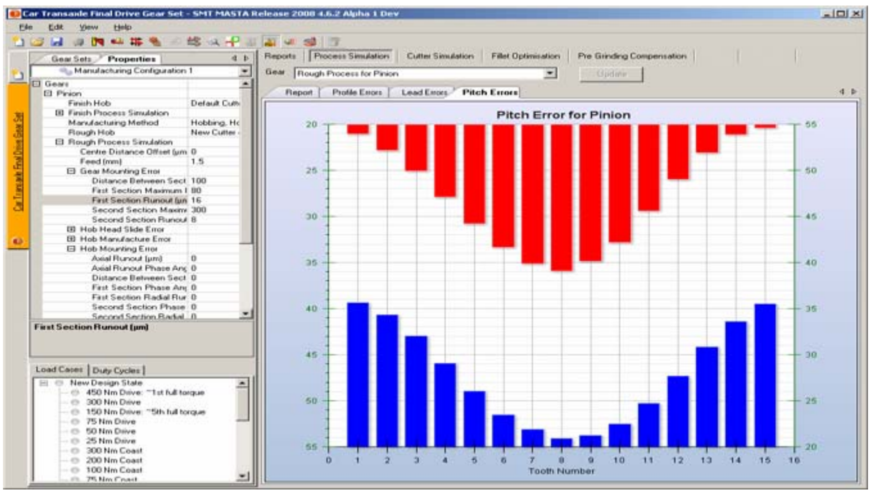

Figure 12 - The pitch error for pinion in the process simulation

Profile Deviation - Left Flank (0 mm from middle of face width)			
Tooth	Total Error F_α (µm)	Slope Error $f_{H\alpha}$ (µm)	Form Error $f_{f\alpha}$ (µm)
1	24.1	-16.5	10.2
3	14	-5.2	13
6	18.2	10.1	19.5
9	19.9	-6.3	17.7
Average	19.1	-4.5	15.1
ISO Tolerance	19	12	14
ISO Quality Grade (Designed)	7	7	7
Quality Grade (Obtained)	8	8	8

Lead Deviation - Left Flank			
Tooth	Total Error F_β (µm)	Slope Error $f_{H\beta}$ (µm)	Form Error $f_{f\beta}$ (µm)
1	18.5	9.1	11.6
3	18.1	-8.7	11.8
6	22	-12.6	11.6
9	21.8	12.3	11.6
Average	20.1	0	11.6
ISO Tolerance	23	16	16
ISO Quality Grade (Designed)	7	7	7
Quality Grade (Obtained)	7	7	7

Profile Deviation - Right Flank (0 mm from middle of face width)			
Tooth	Total Error F_α (µm)	Slope Error $f_{H\alpha}$ (µm)	Form Error $f_{f\alpha}$ (µm)
1	30.4	24.7	29.9
3	29.7	21.1	32.7
6	24.5	0.9	24.8
9	21.2	7.3	18.1
Average	26.4	13.5	26.4
ISO Tolerance	19	12	14
ISO Quality Grade (Designed)	7	7	7
Quality Grade (Obtained)	9	10	10

Lead Deviation - Right Flank			
Tooth	Total Error F_β (µm)	Slope Error $f_{H\beta}$ (µm)	Form Error $f_{f\beta}$ (µm)
1	23.7	14.7	11
3	12.5	-0.6	12.2
6	25.5	-16.2	10.3
9	15.3	5.2	12
Average	19.2	0.8	11.4
ISO Tolerance	23	16	16
ISO Quality Grade (Designed)	7	7	7
Quality Grade (Obtained)	8	7	7

Table 1 - The quality grade reports for lead and profile deviations

5.2 Benefits of using this technology

These simulation modules have been used by a number of manufacturers successfully. Users of the software tools have reported the following benefits:

- Useful and reliable for checking the compatibility of the gear design and hobbing /shaping cutter dimension before hobbing cutter / shaping cutter is ordered to avoid ordering a hobbing / shaping cutter which is too small.
- Assisting in hobbing /shaping process plan to ensure the process specification matches with the quality target.
- Assisting in identifying the potential root causes of poor hobbing / shaping quality very quickly at both prototype and production stages.

6 Conclusion

- The gear manufacturing technologies introduced in this paper do not involve any new equipment investment but result in significant gear performance / quality improvement, and cost reduction.

- These technologies have been developed into easy use simulation tools (within SMT's MASTA software) already and are currently being used by gear manufacturers to solve production problems.

7 References

1 Manual of MASTA Release 4.6.1, Smart Manufacturing Technology, 2007
2 Cylindrical Gear Standard ISO 6336
3 Charles H Logue, American Machinist Gear Books: Simplified Tables and Formulas for Designing, and Gear Practical Points in Cutting All Commercial Types of Gears, published by International Law & Taxation, 2002, ISBN 9780898756869
4 Darle W. Dudley, Handbook of Practical Gear Design, published by CRC Press, 1994, ISBN 1566762189

Appendix: Gear data for hobbing cutter tip fillet optimization

Parameter Name		Pinion	Wheel
Number Of Teeth	z	15	64
Normal Module (mm)	m_n	2.25	
Normal Pressure Angle (°)	α_n	17.5	
Helix Angle (°)	β	30	
Transverse Pressure Angle (°)	α_t	20.0053	20.0053
Material Name	Q	20MnCr5	20MnCr5
Reference Diameter (mm)	d	38.971	166.277
Addendum Modification Factor	x	0.7416	0.4
Addendum Modification Factor (From Sn)		0.7331	0.3029
Tip Diameter (mm)	d_a	46.808	174.377
Effective Tip Diameter (mm)	d_{ae}	46.808	174.377
Root Diameter (mm)	d_f	34.658	160.877
Rim Diameter (mm)		20.078	144.677
Base Diameter (mm)	d_b	36.62	156.244
Base Normal Pitch (mm)	p_{bn}	6.741	6.741
Normal Thickness (mm)	s_n	4.574	3.964
Normal Thickness Modification Factor		0	0
Thickness At d_{ae} (mm)	$s_{n\ ae}$	1.082	1.053
Tip Thickness (mm)		1.082	1.053
Face Width (mm)	b	25	25
Form Diameter (mm)	d_{form}	36.77	162.239
Cutter Type		BasicRack	BasicRack
Addendum Factor		1	1.4
Dedendum Factor		1.7	1.6
Cutter Protuberance		0	0
Normal Thickness Upper Limit (mm)	$s_{n\ max}$	4.586	3.976
Normal Thickness Lower Limit (mm)	$s_{n\ min}$	4.562	3.952

Tooth Thickness Tolerance (mm)		0.024	0.024
Over Balls Upper Limit (mm)		48.435	175.475
Over Balls Lower Limit (mm)		48.388	175.411
Ball Diameter (mm)		4.5	4.5
Chordal Span Upper Limit (mm)		18.337	66.513
Chordal Span Lower Limit (mm)		18.314	66.491
Number Of Teeth for Chordal Span Test		3	10
Profile Quality Grade (ISO)		7	7
Helix Quality Grade (ISO)		7	7
Pitch Quality Grade (ISO)		7	7
Radial Quality Grade (ISO)		7	7