Optimization of a Process Chain for Gear Shaft Manufacturing

Fritz Klocke, Markus Brumm, Bastian Nau and Arne Stuckenberg

The research presented here is part on an ongoing (six years to date) project of the Cluster of Excellence (CoE). CoE is a faculty-wide group of researchers from RWTH Aachen University in Aachen (North Rhine-Westphalia). This presentation is a result of the group's examination of "integrative production technology for high-wage countries," in which a shaft for a dual-clutch gearbox is developed.

Introduction, Goal and Approach

Industrial production in high-wage countries like Germany remains at risk. Nevertheless, there exist examples of thriving manufacturing companies who are dominating their competitors by utilizing advanced cost-, time- and materials-saving systems to enhance their production capabilities and profit margins. The RWTH Aachen University Cluster of Excellence program (CoE) is contributing to exploring and realizing fundamental developments in the theory of production science—in both its organizational and technical aspects (Ref. 1).

To succeed in this endeavor, top-down research of entire enterprises is required—beginning with management, proceeding on to the process chains, and ending at single-process technology efforts. To validate the need for this work, newly gained, "real" knowledge is used to make "real" parts. Indeed, in this paper the manufacture of a modern, dual-clutch gearbox gear shaft is investigated; the main intent being to assess existing and new process chain and manufacturing technologies.

Today's complex production systems produce components and products of high complexity, requiring sophisticated yet cost-efficient process and supply chains. The production system of the mentioned gear shaft was documented—beginning with analysis of the turned green body. This documentation includes: manufacturing technologies; completed actions; input and output conditions; and process parameters at every step of the operation. The example observed was compared to existing practices and the state-of-the-art manufacturing of gear shafts. To gain additional value the methods and results of the CoE were adapted to the optimization of the gear shaft. In practice, the CoE is divided into several parts; for this study individualized, virtual and hybrid production systems of the CoE are validated.

- "Individualized" production is the ability of production systems to be flexible for either small or large batch sizes.
- "Virtual" production means using smart software solutions to shorten, for example, construction and design processes.
- "Hybrid"production presents opportunities for employing different manufacturing technologies simultaneously. The optimization is achieved with both technological and economic realities in mind. This includes consulting with the customer, examining market research data and drawing upon the collective knowledge and expertise of groups like the CoE.

After assessing the in-place process chain with the customer, alternative chains are developed. The proposed new process chain is analyzed concerning its potential for flexible and economic production of small-batch sizes. This is crucial in this particular scenario because, to be profitable, a production line for gear shafts must be able to produce many types of shafts over a year's time—even if it is a high-volume product.

The results are then assessed using factors and protocols that are valid and practical for a company and its entire operation. These general factors are: process reliability; manufacturing costs; floor-to-floor time; required staff; investment costs; flexibility; and logistic effort. These factors help define a company's new process chain and processes. As well,

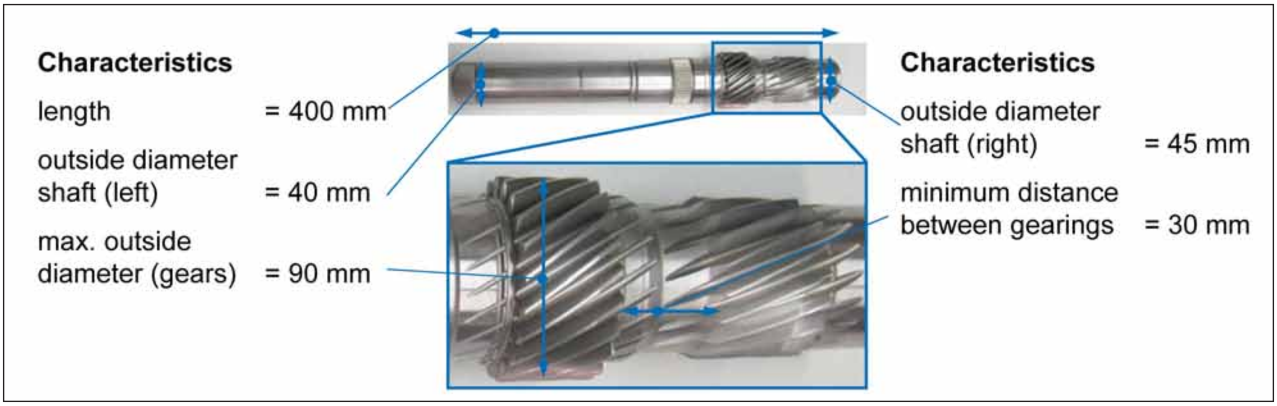


Figure 1 Example of dual-clutch gear shaft.

Y ↓ / X →	Process reliability	Manufacturing costs	Floor to floor rime	Staff requirements	Investment costs	Flexibility	Logistic effort	Sum	Weighting
Process reliability	-	2	2	2	2	2	2	12	5
Manufacturing costs	0	-	1	2	2	2	2	9	4
Floor to floor time	0	1	-	1	2	2	2	8	4
Staff requirements	0	0	1	-	1	2	1	5	2
Investment costs	0	0	0	1	-	2	2	5	2
Flexibility	0	0	0	0	0	-	2	2	1
Logistic effort	0	0	0	1	0	0	-	1	1

	Process reliability	Manufacturing costs	Floor to floor rime	Staff requirements	Investment costs	Flexibility	Logistic effort	Result
Weighting	5	4	4	2	2	1	1	
Hobbing	5	5	5	4	5	3	5	91
Shaping	5	3	3	4	4	5	5	75
Skiving	2	3	4	4	3	4	5	61
Broaching	4	5	5	4	4	1	5	82
Rolling	1	5	5	5	5	5	5	75

Standings	
1	Hobbing
2	Broaching
3	Shaping
3	Rolling
5	Skiving

Figure 2 **Process chain result.**

these factors are impacted—for good or bad—by weighting factors; the weighting factors are generated by a method-paired comparison. (*Authors' Note: the general structure in the investigation addressed by this article is in two parts: i.e.—1) An investigation on gearing; and 2) Secondary machine elements—bearings, sealing surface. Validation of the "gained knowledge" is the end-product: a high-art, dual-clutch gearbox shaft*—Fig. 1*)*.

The main challenges presented by this particular gear shaft are its close proximity between gear sets and the diverse bearings locations. In addition, the shaft is of a tube design—specified for lightweight needs and realization of the dual-clutch concept. Through this tube a second shaft—with a connection to the second clutch—is inserted. Length is about 400 mm; maximum outside diameter for the gears in the case about 90 mm; the maximum outside diameter for the gears of the shown example part is less. The outside diameter of the shaft is increasing from 40 mm on one side to 45 mm on the other; minimum distance between the gearings is about 30 mm.

Analysis of the Gear Manufacturing

An example for the assessment of manufacturing technology can be seen in Figure 2. Each realistic and possible manufacturing technology for the green-machining of gears is assessed against the main factor. The result is multiplied by the weighting factors and assessed—leading to the given order. The ranking of broaching is superfluous here because the second power gear with smaller tip diameter cannot be broached. This approach is also used for the other manufacturing steps.

The analysis method above shows that hobbing is best for green-machining, while the conclusion drawn for hard-finishing of the gears is that honing works best. Generating gear grinding is not an option because both gears on the shaft are too close together, i.e.—insufficient space for the recess of the grinding worm. In this instance a new or alternative manufacturing process for power gears does not yet exist, due, perhaps, to the relatively long gaps between technological "breakthroughs" specific to a mature industry such as gear manufacturing. Indeed, gear manufacturing innovation requires significant investment; e.g.—machine tools. The latest innovation in machining gears may be the ability to hone manufacturing parts with a near-grinding quality via "power honing."

Upon complete evaluation of the in-place process chain, one more optimization potential can be found in the single manufacturing process. This can be achieved by using virtual production methods such as manufacturing simulation. Therefore for the design of gear hobbing processes a manufacturing simulation is developed. Its necessity and the benefit of simulation software are acknowledged, especially for complex machining operations with a high number of variants for the tool and process design. After the calculations the results are compared with momentary process design for both gears. However, no software exists at this time capable of providing universal simulation of the entire production process due to missing interfaces and inconsistent data formats. It is a gap that must be closed in the future.

The approach for process optimization of gear hobbing begins with starting parameters—just like the process parameters and limitations of the actual process design. Potential limitations may be machine tool parameters such as maximum-revolutions-per-minute for the tool or workpiece spindle, or gear design restrictions like maximum-feed-mark deviations. Yet despite these default values and given restrictions, the software calculates every possible tool design capable of achieving these requirements.

The design of the gear shaft shows two power gears arranged close together, directly on the shaft; one gear is an interfering element for the manufacture of the other. The tool design is started with the general geometric boundary conditions for the tool. The results are no restrictions concerning the tool outside diameter for Gear No. 2 and a maximum tool outside diameter for Gear No. 1. A geometric calculation leads to a maximum outside diameter for Gear No. 1 of 45 mm. The outside diameter for Gear No. 2 can be chosen freely. The calculation is started with momentary process design (Fig. 2—red signs).

For example, Gear No. 1:

It has a hob outside diameter of $d_a = 45$ mm; number of threads $z_0 = 1$; and number of gashes $n_i = 9$. In the chart the limits for variation are shown. The number of threads were varied from one to three; the hob diameter from 40 to 45 for Gear No. 1, and from 60 to 100 mm for Gear No. 2. The number of gashes is varied from 7 to 19, and 11 to 21.

The result revealed by the simulation is that the single-threaded variant is always the most productive. The reason—especially for Gear No. 1—is the lower helix angle for the thread at a lower number of threads. A higher helix angle results in a longer way of entry for the tool. Also, the larger the outside diameter process, the more productive the process. The larger, outside diameter of the single tooth is thicker and therefore more reconditioning cycles can be realized. In general, with the investment for one tool, more workpieces can be produced. As mentioned, the tool outside diameter for Gear No. 1 is limited by Gear No. 2. The maximum-outside-diameter is also limited by the machine tool, as both gears have to be produced in one step, on one machine tool.

The number of gashes should be as high as possible from the technological side. A higher number of gashes leads to lower-generated cut deviations. From the productivity aspect a certain number of reconditioning cycles becomes possible, so the single teeth should not be too thin. Especially for Gear No. 1, this tool design—with number of gashes at $n_i = 11$—is quite a low number when compared with Gear No. 2, with its number of gashes almost doubled at $n_i = 21$. The remaining teeth will be quite thin, with the small outside diameter of $d_{a0} = 45$ mm.

The simulation for Gear No. 1 leads to a tool design similar to the real-time process, so the use and functionality of the actual process design could be proven. In general, the simulation enables a very fast design of the tool by avoiding long-lasting iteration cycles. In contrast to only experience-based tool design, the calculation has a robust basis.

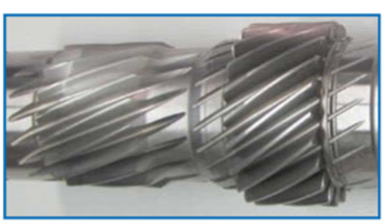
Analysis of Secondary Machine Elements

Within analysis of secondary machine elements the bearing seats of the gear shaft were investigated. Alternative manufacturing technologies for the finish process of the bearing seats were also evaluated. The technologies had to meet a number of requirements and conditions, including:

- Material: case-hardened steel 20MnCrS5
- Surface hardness: HRA 81-83
- Surface roughness: $Rz = 2$ µm
- Concentricity: 0.02 mm
- Circularity: 0.004 mm
- Parallelism: 0.06 mm
- Retain fitting tolerance
- Retain accuracy grade of cylindrical shaft
- Right angularity tolerance of contact surfaces
- Free of damage and pores
- Economic manufacturing

During rough analysis, five manufacturing technologies were identified that are able to manufacture the bearing seats with the necessary requirements (Fig. 4).

Because the project's focus was on innovative manufacturing technologies *and* conventional processes (grinding, hard-turning), a hybrid manufacturing process known as "ultrasonic-assisted-



Gear 1	Gear 2
z = 17	z = 29
α = 21.5°	α = 18.5°
m_n = 2.37 mm	m_n = 2.5 mm
β = 19.9°	β = 27.9°
d_a = 50.7 mm	d_a = 90.96 mm
d_f = 37 mm	d_f = 74.6 mm

threads	1, **2**, 3	1, **2**, 3
hob diameter	40, **45**	60..**80**..100
gashes	7..**9**..19	11..**19**..21

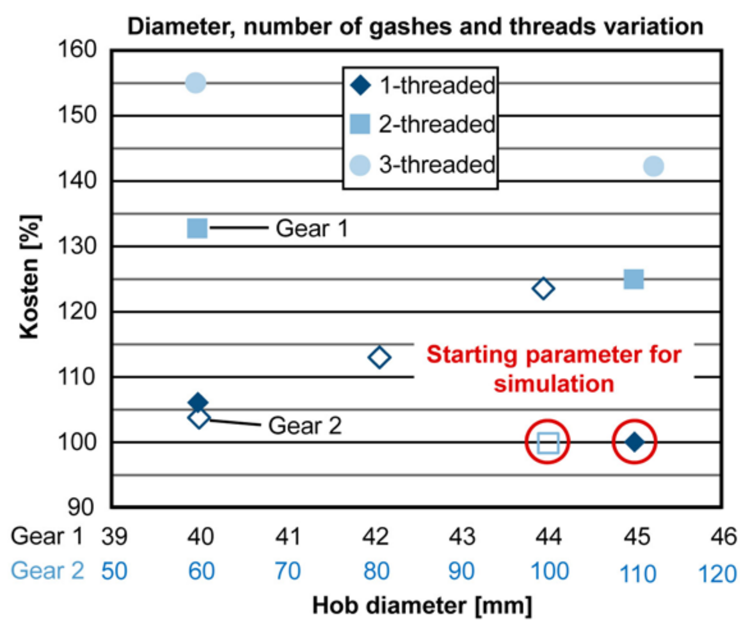


Figure 3 Calculation result.

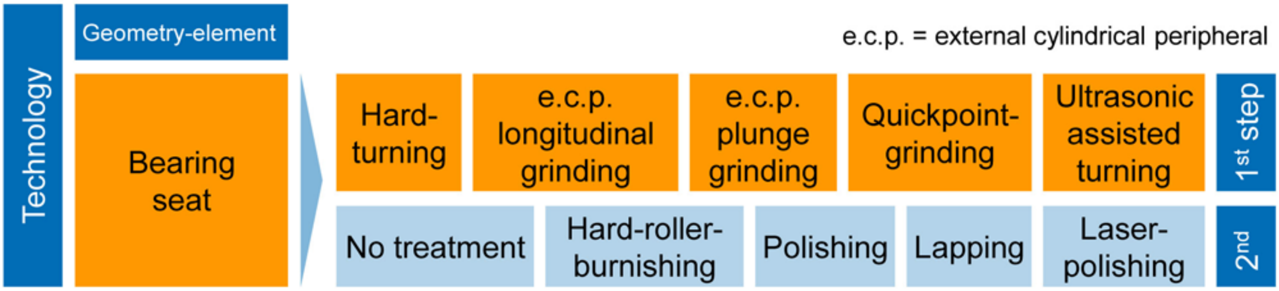


Figure 4 **Alternative manufacturing technologies for bearing seats.**

	Process reliability	Manufacturing costs	Floor to floor time	Staff requirements	Investment costs	Flexibility	Logistic effort	Result
Weighting	5	4	4	2	2	1	1	
Hard-turning	4	5	4	5	5	5	5	86
E.c.p. longitudinal grinding	4	4	3	3	3	4	5	69
E.c.p. plunge grinding	5	4	5	5	3	3	5	81
Quickpoint-grinding	3	4	5	4	3	4	5	74
Ultrasonic aided turning	3	3	3	4	3	4	5	62

	Process reliability	Manufacturing costs	Floor to floor time	Staff requirements	Investment costs	Flexibility	Logistic effort	Result
Weighting	5	4	4	2	2	1	1	
Hard-roller-burnishing	5	5	5	5	5	4	5	94
Polishing	4	4	2	4	3	3	3	64
Lapping	4	4	3	4	3	3	3	68
Laser-polishing	4	3	2	3	1	5	4	57

E.c.p. = external cylindrical peripheral

Figure 5 **Results of rough analysis.**

	Requirement	Hard-turning	E.c.p. longitudinal grinding	E.c.p. plunge grinding	Quickpoint-grinding	Ultrasonic assissted turning
Rz [µm]	2	< 1	≈1	≈1	≈1	< 0,1

E.c.p. = external cylindrical peripheral

Figure 6 **Results of surface roughness tests.**

turning" was considered. In addition, a second process step was considered for manufacture of the surface properties should the first process step prove incapable of meeting all requirements. For this step, hard-roller burnishing—a process not yet common to this field—was employed. Within rough analysis the manufacturing technologies were assessed considering the impact factors shown in Figure 2. This assessment was conducted by experts from the industry and research institute. The results show that hard-turning and plunge-grinding are the preferred manufacturing processes. As a possible second step, hard-roller burnishing should be used (Fig. 5).

To assess the surface quality that can be achieved with the manufacturing technologies discussed here, a Fourier analysis was performed, enabling assessment of the possible surface roughness of the bearing seats. The advantages and disadvantages of these alternative manufacturing technologies are listed below; results of the surface roughness tests are shown in Figure 6.

- Hard-turning without ultrasonic support
  - Low ripple
- Grinding-procedure
  - Higher amplitudes during lower wave numbers
  - Ripple is influenced by self-excited (regeneration effect) and separately excited (imbalances, SLS-radial deviation) oscillations
- Quickpoint grinding
  - Higher amplitudes than e.c.p. longitudinal grinding are machine-based
  - Higher machine stiffness
  - Lower oscillations than e.c.p. longitudinal grinding
- Ultrasonic-assissted turning
  - Low fundamental oscillation
  - Very good concentricity

Via rough analysis of manufacturing technologies, two manufacturing chains were chosen for a detailed observation.

1. ***Plunge-grinding followed by hard-roller burnishing***: This alternative was chosen because plunge-grinding is a common process that can achieve good results; roller burnishing is an innovative process that can manufacture the required surface properties. Also, these technologies can be combined well.
2. ***Ultrasonic-assisted turning***: To date, this manufacturing technology is rarely used in this field. The surface properties can be achieved without a second step, so it was investigated to determine whether significant time savings can be obtained and if this technology can operate cost-effectively.

Within the detailed observation time, costs and the quality of the manufacturing technologies were analyzed by experts that in fact provide these processes. It can therefore be said that in both cases, only one machine tool is needed, as the roller-burnishing tool can be integrated into the grinding machine. There is a lot to be said for both plunge- grinding and roller-burnishing, but their set-up and process-parameter optimization must be done individually. Another advantage of roller-burnishing is the low tool wear and savings in cooling lubricant. The actual process of finishing with abrasive blocks can be substituted. But the main advantage of ultrasonic-assisted turning is that the second finishing step is eliminated. This translates to lower machine investment as the cost for an ultrasonic unit for machine integration is low. But this is a limited experience with this technology and it will require much more effort in process-parameter optimization to lower the process time and attain high production output. It is also unknown at this time which workpiece materials can be manufactured using ultrasonic-assisted turning. Silicon and carbides prevent the use of diamond tools typically required for this process because of their risk of fracture. It is yet to be determined whether a surface roughness far beyond the required properties is needed and justifies the effort in establishing this innovative technology.

Conclusion

- In partnering with the Cluster of Excellence, "Integrative Production Technology for High-Wage Countries" methods were developed to anticipate future requirements of tomorrow's markets. Beyond the theoretical research technology conducted, examples were chosen that in fact demonstrated the acquired knowledge. This article examined and presented the results of the technology used in producing the prototype gear shaft.
- In general, it was possible to create alternative manufacturing chains to manufacture a gear shaft in a more effective and efficient way than is typically done. By using these new manufacturing chains it is possible to manufacture more individual products and reduce planning efforts via simulation methods and the integration of other planning alternatives over defined interfaces. However, a general planning approach was not implemented or tested at this time.
- Within the investigation, a general look at the process chain—as well as a more detailed technological look at a single process—was taken. The investigations were done on an actual gear shaft
- In summation, the traditional process chain was approved as good. Likewise, the same process design of single-technology-hobbing was approved. The advantages demonstrated by the new methods are the faster and more economical ways to generate a process chain and single-process designs.
- For the next testing phase, evaluation of three manufacturing chains—including logistics and factory planning—would be useful. In this way the exact time and cost potential of a specific manufacturing chain could be determined and an integrated planning approach implemented.

References

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Prof. Dr.-Ing. Dr.-Ing. E.h. Dr. h.c. Fritz Klocke is head of the chair of manufacturing technology at the Laboratory for Machine Tools and Production Engineering (WZL), a part of RWTH Aachen University, Germany. He is also director of the Fraunhofer Institute for Production Technology in Aachen.

Dr.-Ing. Markus Brumm is chief engineer for gear technology at the Laboratory for Machine Tools and Production Engineering (WZL). He began his career as a research assistant in 2006 at the chair of machine tools, investigating gear noise behavior with a special emphasis on bevel gears. Since 2011 Brumm has led the gear technology department at RWTH; he was awarded his doctorate in 2011.

Dr.-Ing Bastian Nau was a research associate and doctoral candidate under Prof. Klocke in production engineering at the technology planning group at RWTH Aachen University. His principal research activities are technology planning and investigations on process chain design; he was awarded his doctorate in 2012.

Dipl.-Ing. Arne Stuckenberg is a research associate and doctoral candidate under Prof. Klocke in production engineering at the gear technology department at RWTH Aachen University. Since 2010 he has led the group for gear manufacturing. His principal research activities are in gear hobbing and general investigations in process chains for gears.