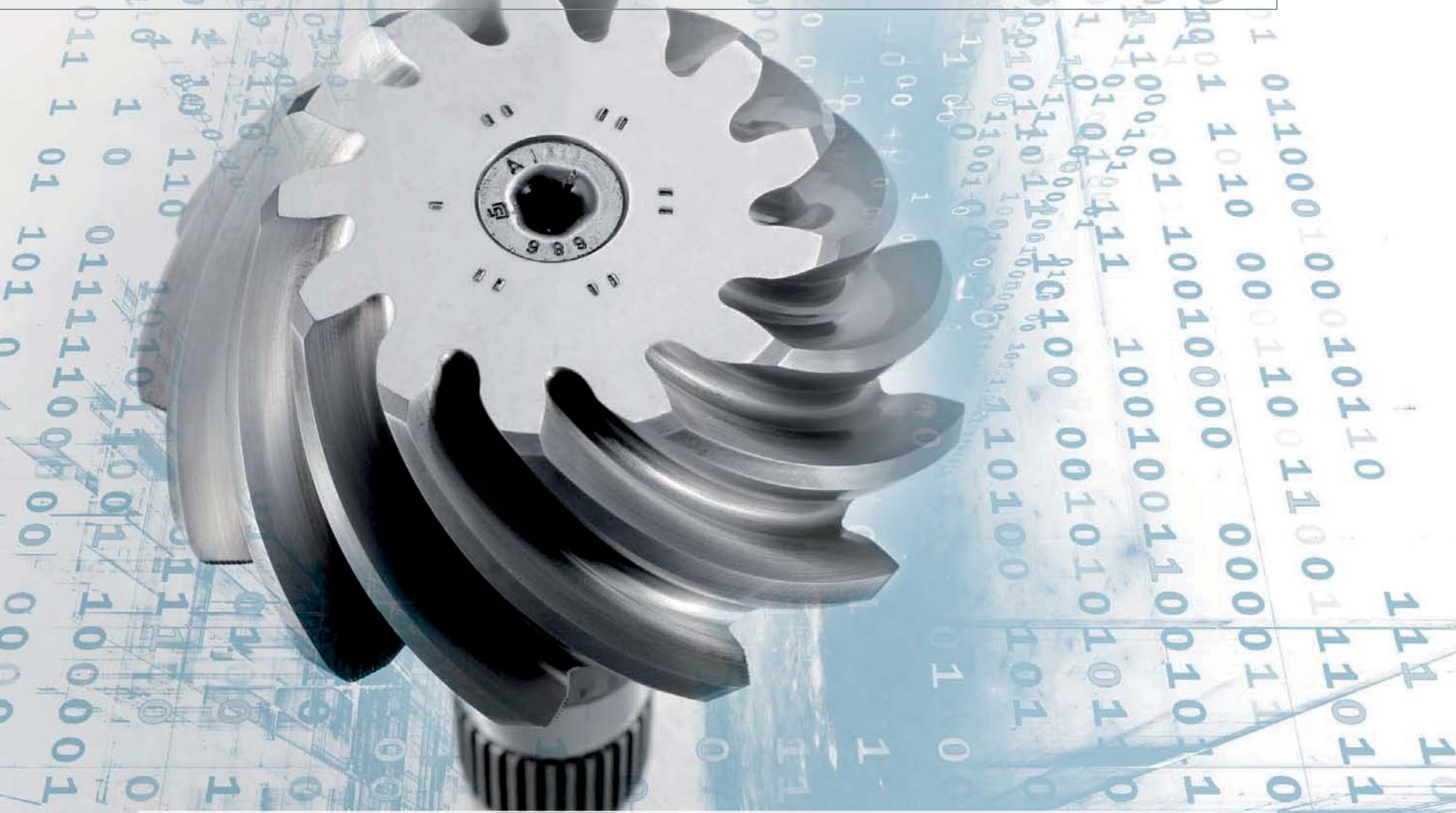
LAPPING OR GRINDING? – WHICH TECHNOLOGY IS THE RIGHT CHOICE IN THE AGE OF INDUSTRY 4.0?



Bevel gear transmissions for the automotive industry are subject to extremely stringent requirements. They must be able to transmit ever greater outputs at lower weights, in less space. Noise quality and, increasingly, efficiency, must measure up to high standards. During bevel gear teeth dimensioning, a decision must already be made as to whether the gearing will be lapped or ground. The existing machinery is frequently what determines which technology will be used. Yet the question "Lapping or grinding?" should not just be asked for new investments, because both methods have their advantages and disadvantages.

Production technology is currently undergoing a transformation, known in industry and science as Industry 4.0. Production processes must meet ever-growing requirements for flexibility and self-optimization. This calls for information to be gleaned from the processes and directly manipulated by the production systems. Against the background of this discussion on the benefits of Industry 4.0, it is worthwhile to re-examine an old question in bevel gear production: "Should bevel gears be lapped or ground?"

> The final quality of a lapped bevel gear depends to a far greater degree on the preceding process steps than is the case for ground gearing.

At first glance, the process chains for ground and lapped bevel gear teeth differ only in hard finishing. The geometry changes that can be achieved with generation-lapping are significantly smaller than with gear grinding. Consequently, the final quality of a lapped bevel gear depends to a far greater degree on the result of the preceding process steps. For production, this means that significantly more effort is required to optimize the component quality during gear cutting. This includes an allowance for geometry changes brought about by heat treatment, usually case hardening. The so-called hardening distortion compensation is required because these distortions can only be corrected to a limited extent by lapping. As regards ground gearing, by contrast, due to a significantly greater material removal compared with lapping, much greater amounts of hardening distortions can be eliminated.

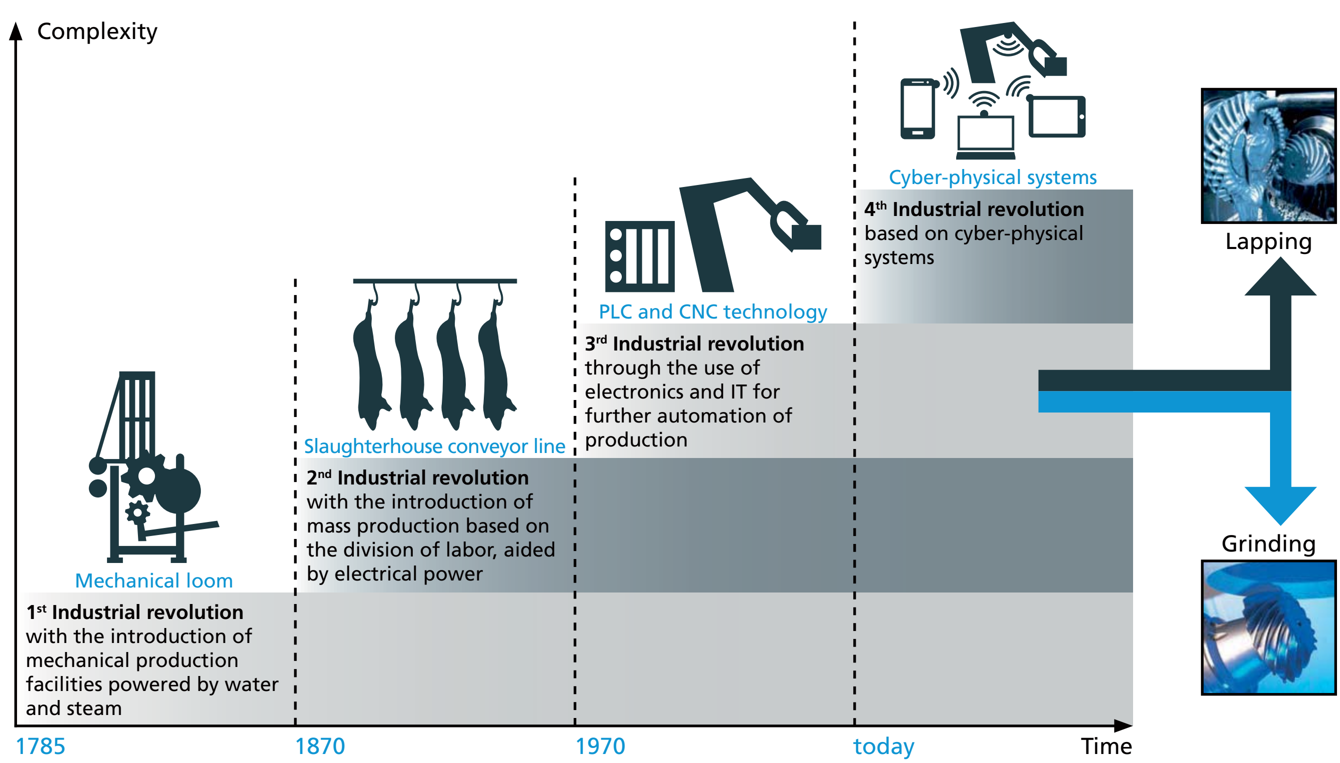


Fig. 1: Grinding or lapping? A question for the digital age of Industry 4.0

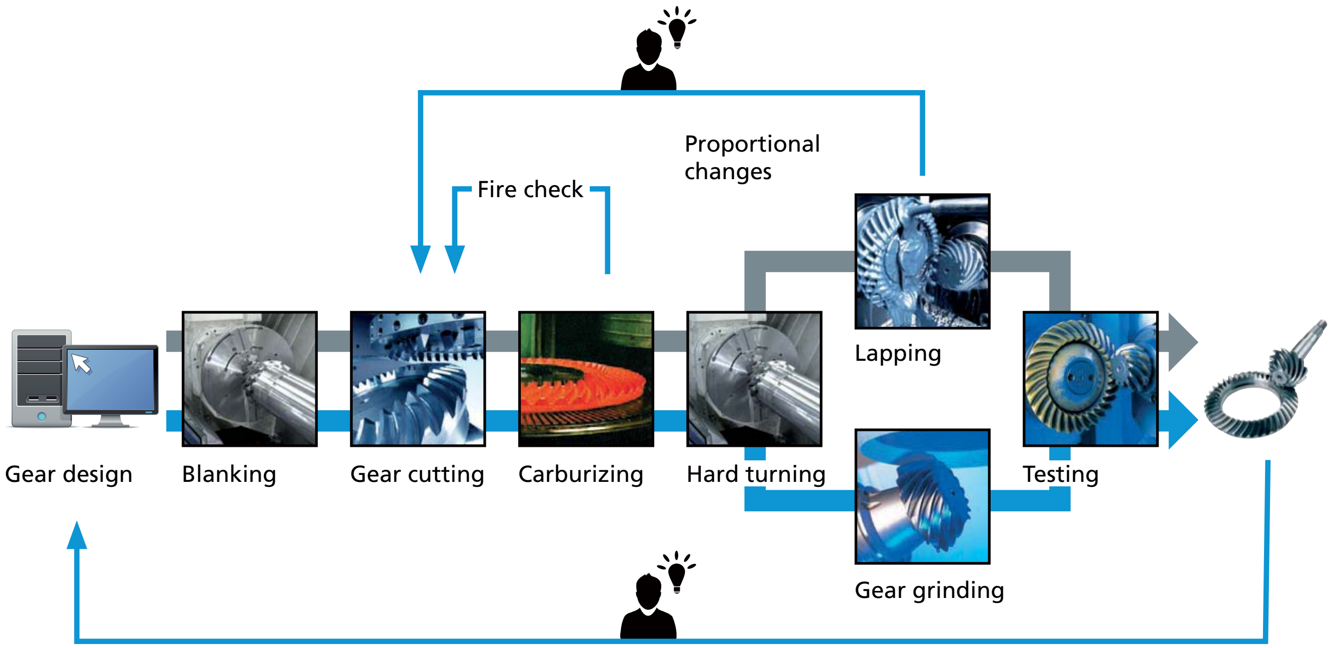


Fig. 2: Quality backward chain bevel gear production

Features of lapped bevel gear teeth

Due to the shorter gearing times, lapped gearings in mass production are mostly manufactured in a continuous process (face hobbing). These gearings are characterized by a constant tooth depth from the toe to the heel and an epicycloid-shaped lengthwise tooth curve. This results in a decreasing spacewidth from the heel to the toe.

During bevel gear lapping, the pinion undergoes a greater geometric change than the gear, since the pinion experiences more meshing per tooth due to the smaller number of teeth. Material removal during lapping results in a reduction of lengthwise and profile crowning – primarily on the pinion – and to an associated reduction of the rotational error. As a result, lapped gearings have a smoother tooth mesh. The frequency spectrum of the single flank test is characterized by comparatively low amplitudes in the harmonic of the tooth mesh frequency, accompanied by relatively high amplitudes in the sidebands (noise). Indexing errors in lapping are reduced only slightly, and the roughness of the tooth flanks is greater than that of ground gearings. One characteristic of lapped gearings is that each tooth has a different geometry, owing to the individual hardening distortions of each tooth.

Features of ground bevel gear teeth

In the automotive industry, ground bevel gears are designed as duplex gearings. A constant spacewidth and an increasing tooth depth from the toe to the heel are geometric features of this gearing. The tooth root radius is constant from the toe to the heel and can be maximized due to the constant bottom land width. Combined with the duplex taper, this results in an comparable higher tooth root strength capability. The uniquely identifiable harmonics in the tooth mesh frequency, accompanied by barely visible sidebands, are significant attributes. For gear cutting in the single indexing method (face milling), TwinBlades are available. The resulting high number of active cutting edges increases the productivity of the method to an extremely high level, comparable to that of continuously cut bevel gears. Geometrically, bevel gear grinding is an exactly described process, which allows the design engineer to precisely define the final geometry. To design the EaseOff, geometric and kinematic degrees of freedom are available to optimize the running behavior and load capacity of the gearing. Data generated in this way are the basis for the use of the quality closed loop, which in turn is the prerequisite for producing the precise nominal geometry.

The geometric precision of ground gearings leads to a small variance between the tooth geometry of individual tooth flanks. The indexing quality of the gearing can be significantly improved by bevel gear grinding.

Influence of hard finishing on gear set development

The geometry of lapped gearings is the result of an iterative development. The design engineer ultimately specifies the final geometry of the gear set on a conditional basis, since the final quality variance in lapped bevel gear teeth is greater than for ground gearings. As a result, the influence of production on running performance is also greater than is the case for ground bevel gear teeth. This leads to a greater uncertainty in the gear set development, since the design engineer must continually evaluate the production influence and quality of the design.

The high geometric accuracy of ground bevel gear teeth allows for clear feedback during the gear set development of gearing performance with respect to geometric design. The design engineer receives clear feedback as to which geometric variations result in poor running behavior or insufficient load capacity of the gearing – and gleans information from this for optimized gear geometry.

Klingelnberg closed loop

An important part of the process chain for bevel gear grinding is the quality closed loop. During gearing design, the design engineer uniquely defines the nominal geometry of the ground gearing. A virtual master and virtual machine model form the basis for the Klingelnberg quality closed loop: on the precision measuring center, deviations in the ground gearing are measured against a virtual master. Based on the model of the virtual cutting machine, correction data are calculated from the real deviations, and the grinding process is tuned. Thus the closed loop describes a self-optimizing system and is a good example of Industry 4.0.

In the process chain for lapped gearings, the closed loop is also used for quality optimization of the soft cutting process. Compared with the ground gearing process chain, however, a virtual description of the lapping process does not exist. For this reason, self-optimization of the bevel gear lapping process with a virtual master is not possible. With lapping, the operator is still an elementary component of the quality closed loop.

In the process chain for ground bevel gear teeth, all Klingelnberg cutting machines are networked with the production database. The closed loop for bevel gear cutting comprises three process steps: blade grinding, cutter head setup and bevel gear cutting. The bevel gear cutting process can be supplemented with an optimization loop to

LAPPING VERSUS GRINDING

Lapped bevel gear teeth

- Constant tooth depth from toe to heel
- Reduced spacewidth from heel to toe
- Mostly epicycloid-shaped lengthwise tooth curve
- Smoother tooth mesh
- Low amplitude of tooth mesh frequency harmonic
- High amplitude in sidebands
- Every tooth has a different geometry

Ground bevel gear teeth

- Increasing tooth depth from toe to heel
- Constant spacewidth
- Tooth root radius is constant from toe to heel and can be maximized. This increases the tooth root strength
- Uniquely identifiable tooth mesh frequency harmonic
- Barely visible sidebands

Ground gearings are more precise. This leads to a smaller variance between the tooth geometry of individual tooth flanks.

Industry 4.0: Klingelnberg closed loop is a self-optimizing system for bevel gear grinding.

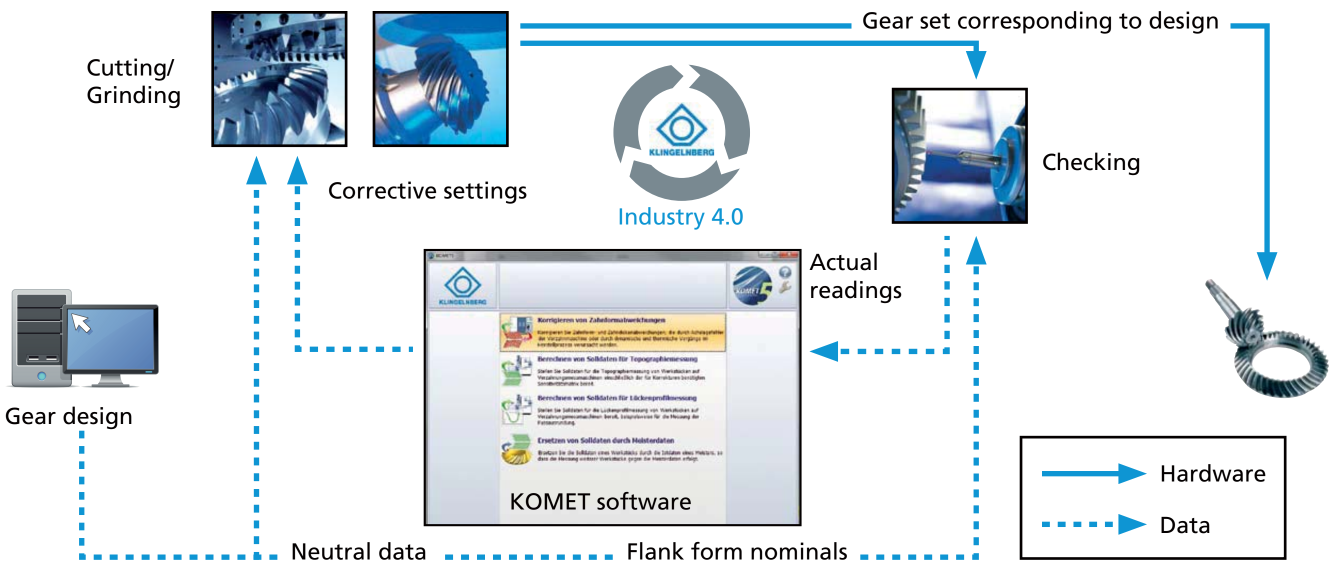


Fig. 3: Process chain for closed loop bevel gear production

allow for hardening distortions. In this case, the virtual master for the quality closed loop for gear cutting is corrected. The hardening distortion correction can be eliminated for ground gearings, since the process is insensitive to the input quality. Moreover, bevel gear grinding is optimized via a dedicated quality closed loop. If fluctuating hardening distortions in production influence the quality of the ground component, this influence is eliminated in the closed loop for bevel gear grinding. This is not possible for lapping.

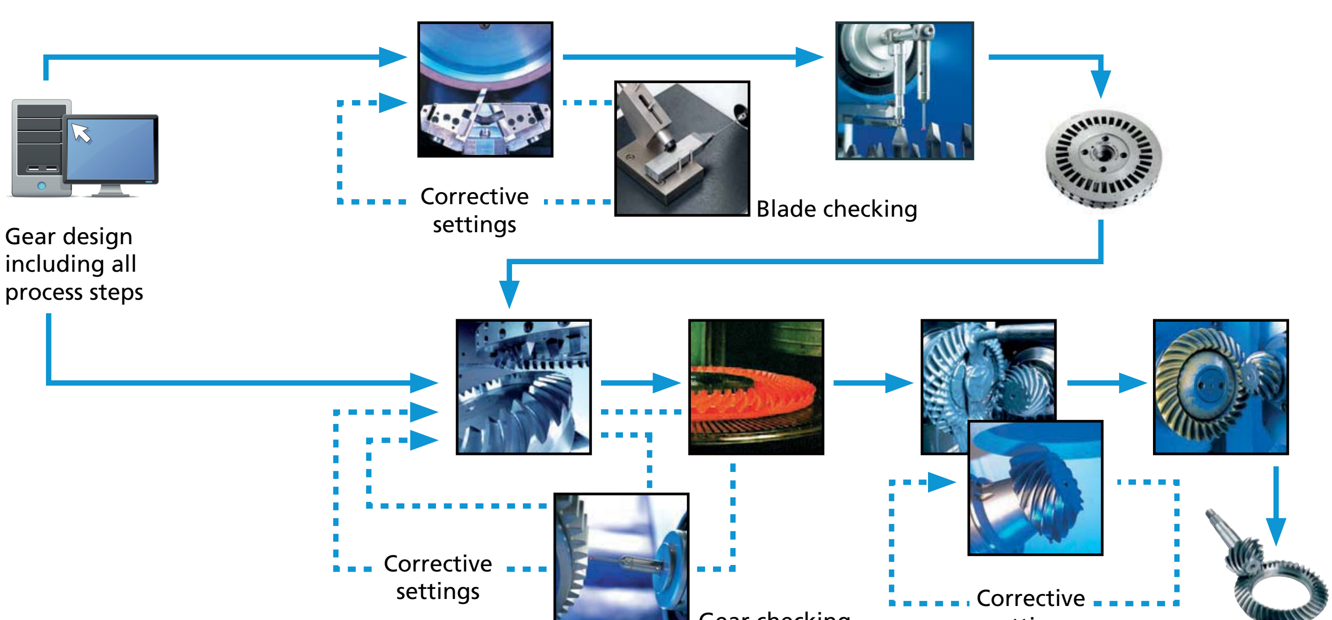


Fig. 4: Process chain for bevel gear production, detail view

	Lapping	Grinding	
⊖	Only slight improvement in quality figures possible	Constant high quality figures controlled by closed loop	⊕
⊖	Press quenching required for gear body geometry	No press quenching but reasonable gear body geometry	⊕
⊖	Good surface finish and spacing before lapping required	Surface finish and spacing not relevant	⊕
⊕	Inherent smoothening of mesh	Smooth mesh must be designed	⊖
⊖	Operator know-how for geometry control and process tuning required (fire check & contact pattern before lapping)	Operator know-how only for geometry control required	⊕
⊖	Cleaning and preservation after lapping required	No cleaning and no preservation	⊕
⊖	Recalls because of leakages and noise during life cycle	Constant running behavior over life cycle	⊕
⊕	Minimum CHD	Increased CHD	⊖
⊖	Protuberance and distortions limit load carrying capacity	Highest load carrying capacity	⊕
⊕	Machining pinion and gear in one operation	Individual machining of pinion and gear	⊖
⊖	Pairing after lapping and individual mounting distance	No pairing after grinding and constant mounting distance	⊕

Conclusion

The choice of hard finishing is primarily a question of the application, even in the age of Industry 4.0. Owing to the tooth form and the quality that can be achieved, bevel gear grinding is well-suited for transmissions subjected to very high loads and for extreme noise requirements. Likewise, in the case of strong variance in hardening distortion and flexibility requirements in production, bevel gear grinding is preferable to bevel gear lapping, to avoid disproportionately large expenditures for hardening distortion compensation.

Another key advantage: production in a self-optimized closed loop enables setup of decentralized production networks to ensure the same high production quality across all sites. In the future, networking of decentralized production facilities in a global production network will be the success factor for producing top-notch quality in a cost-effective manner, regardless of location. ◆

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