Fine Grinding on KLINGELNBERG Bevel Gear Grinding Machines

Content:

One way to implement the growing performance requirements for transmissions is by optimizing the surface finish of the gearing. In addition to increasing the flank load capacity and the transmittable torque, this also allows for improvements in efficiency. On Oerlikon Bevel Gear Grinding Machines from Klingelnberg, fine grinding can be implemented efficiently in bevel gear production, even in an industrial serial process – on one machine, without rechucking.

KLINGELNBERG

High efficiency and power density are basic requirements for a transmission. Particularly in highly dynamic applications in vehicle transmissions, the permissible dimensions, weights and inertia torques for the moving parts are strictly limited. The requirements for transmitting and converting rotation speeds and torques are increasing – not just in extreme applications such as motor racing. Yet new requirements for transmissions are only rarely implemented through a complete redesign. Instead, proven, existing components are used and adapted to the new requirements.

Parameters such as material, heat treatment, inherent stress and surface finish are considered with a view to increasing the permissible stress of a gear set. Specifically the last aspect, surface finish, is the focus of attention at Klingelnberg. In the area of aviation components, surface requirements for ground bevel gearings of Ra < 0.3 µm, Rz < 1.5 µm or finer are standard. The experience and competence the company has acquired in the area of aviation applications form the basis for implementing fine grinding of bevel gears on Klingelnberg bevel gear grinding machines – and thus also for a technology that can be applied in an industrial series setting.

Experiments conducted on an Oerlikon G 30 bevel gear grinding machine (see Figure 1) have shown that with ceramic-bonded grinding wheels used to grind typical passenger car bevel pinions, surface parameters of approximately Ra = 0.11 µm and Rz = 0.75 µm can be achieved. For comparison: Typical requirements for the tooth flank surface of ground passenger car hypoid gears today are in the range of Ra = 0.8 µm to 1.6 µm or Rz = 4 µm to 10 µm. Thus the conducted experiments show that when grinding bevel gears in serial applications on Klingelnberg machines, there is significant potential available for increasing the quality of the surface finish. According to the standard calculation, the flank load capacity of the gearing can be increased through the improved quality of the surface finish by at least 25 % to 40 % compared with the series standard (see Figure 2).

Figure 1: Oerlikon G 30 bevel gear grinding machine

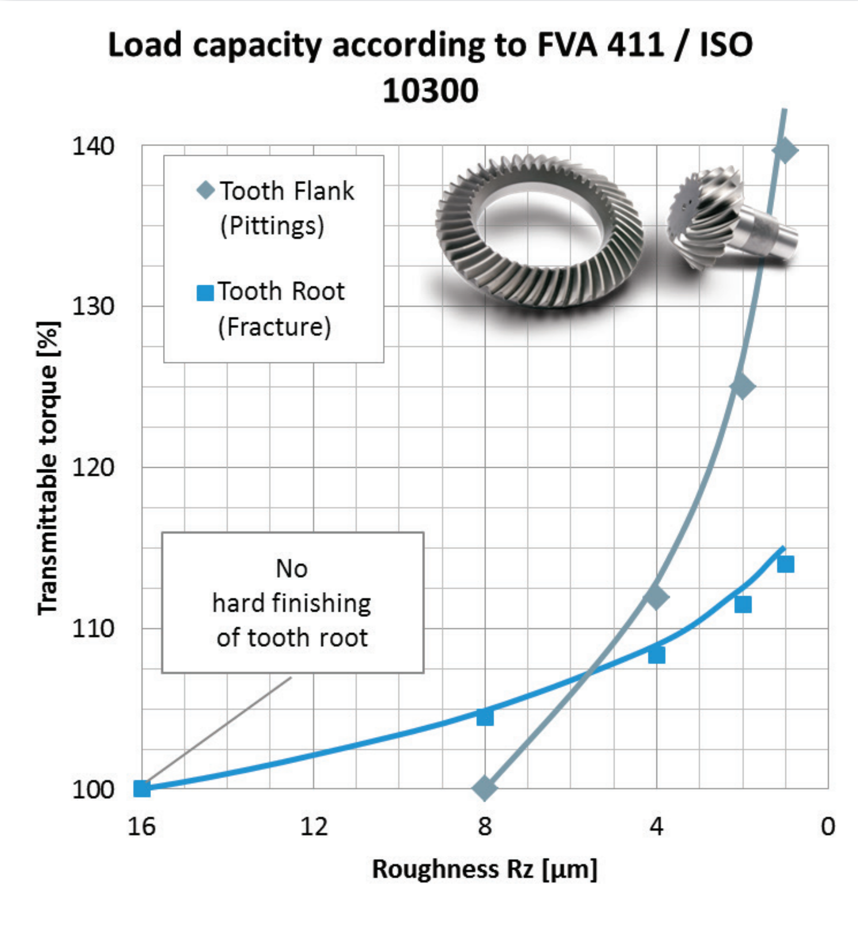


Figure 2: Influence of surface finish on standard load carrying capacity of an automotive hypoid gear set

From the Field: Increasing Performance Requirements for Gearings

Various scenarios can result in the need to adapt a bevel gear transmission:

① An existing axle drive must be used for a new combustion engine with a larger drive torque

⇨ Requirement: increased power desity

② In order to decrease fuel consumption, the viscosity of the gear oil must be reduced

⇨ Requirement: same fatigue life with reduced lubricating film thickness

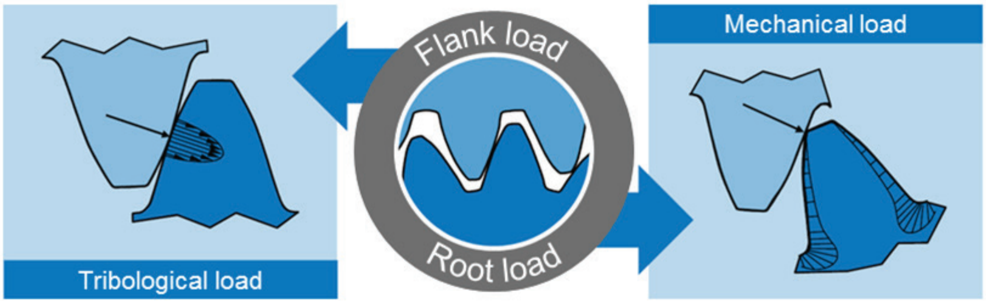
③ Increased start-up torque when using an electric motor in a hybrid powertrain results in increased wear due to an unfavorable lubrication condition for splash lubrication

⇨ Requirement: improved scuffing load

How can these requirements be met?

Stress and Permissible Stress of Gearings

When considering the fatigue life of gearings, the focus is always on the comparison of stress and permissible stress. Stress arises from the external load conditions, the gear macrogeometry, and the tribological system of the tooth contact, which is also influenced by the surface quality of the tooth flanks. The permissible stress of the gearing, in turn, is defined by the material, its heat treatment and inherent stress condition, as well as the macro- and microgeometry.



source: WZL

Figure 3: Gearing stress

The highly stress areas of a gearing are the tooth flank and the tooth root (see Figure 3). The tooth flank subjected to a complex tribological load, which can result in damage due to micro pitting, pitting, scuffing or abrasive wear. Whereas micro pitting and pitting are caused by a breakdown of the material on or beneath the surface, scuffing and abrasive wear occur due to solid body contact between the two tooth flanks and any impurities in the lubricant. The tooth root, by contrast, is primarily stressed by bending. The critical damage type in this case is breakage. Breakage must be avoided at all costs: Whereas a gearing system with tooth flank damage exhibits emergency running properties, a tooth break leads to spontaneous failure of the transmission and frequently results in subsequent damage.

In each of the three example scenarios provided here, the gearing stress is increased with respect to the status quo. If this stress exceeds the permissible stress, the required fatigue life is not achieved. If the options for adapting macrogeometric variables such as gear geometry, curvature radii and flank topography aimed at reducing stress and increasing permissible stress have been exhausted, the only remaining option is to increase the permissible stress through material or surface effects.

A common method for increasing the load capacity of the tooth root, and possibly also that of the tooth flanks, is to introduce residual compressive stress to the area peripheral to the highly stressed areas by means of shot peening. If the shot peening is performed before hard finishing of the gearing, its positive effect will be partially negated during the grinding process, since the grinding allowance of approximately 0.10 to 0.12 mm is equivalent to the penetrative effect of the shot peening. If shot peening is not performed until after the gearing has been ground, the finish of the surface generated through grinding is modified. Moreover, the form stability of the edges, particularly at the tooth tip, can be negatively impacted by peening bulges.

Increased Load Capacity through Finer Surfaces

Generally speaking, the permissible stress of mechanical components can also be improved by improving the quality of the surface finish. This is true for mechanical stress, such as bending fatigue under fluctuating load, as well as for breakdown and abrasion in tribocontact.

In tribological contact between two bodies with oil as the intermediate medium, a growing lubrication gap forms as the sliding velocity increases (see Figure 4). Starting with solid body friction with a lubrication gap of approximately h = 0 mm and very low sliding velocity, a mixture of solid body and fluid friction occurs, provided the lubrication gap does not exceed the height of the roughness peaks. This area is referred to as mixed friction. Wear occurs in the area of the solid body and mixed friction. Friction and wear decrease until the state of the fluid friction is achieved as the sliding velocity increases. Solid body contact no longer occurs here. If the sliding velocity continues to increase, however, the friction again increases due to the hydrodynamic conditions in the lubrication gap. A reduced surface roughness of the bodies causes fluid friction to be achieved even at a lower sliding velocity.

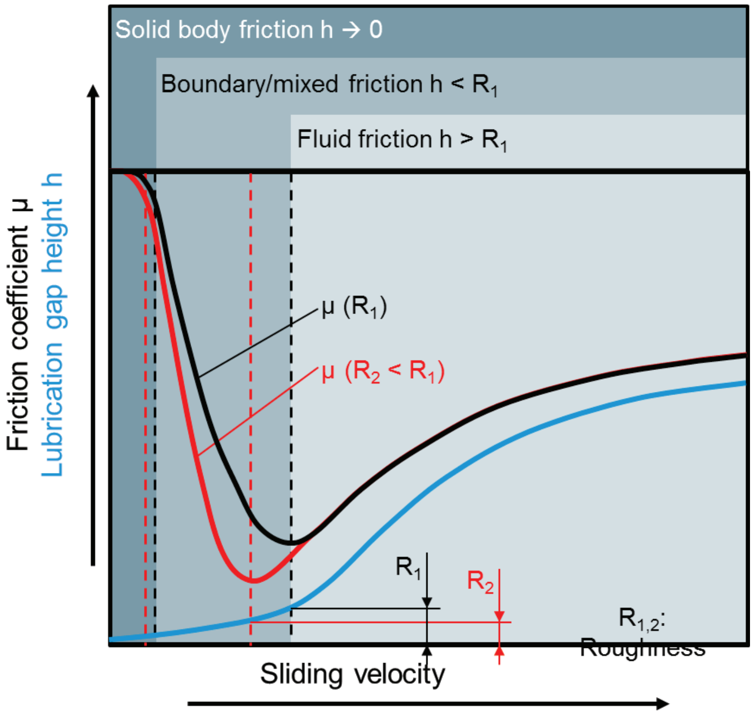


Figure 4: Influence of surface finish on tribological contact conditions

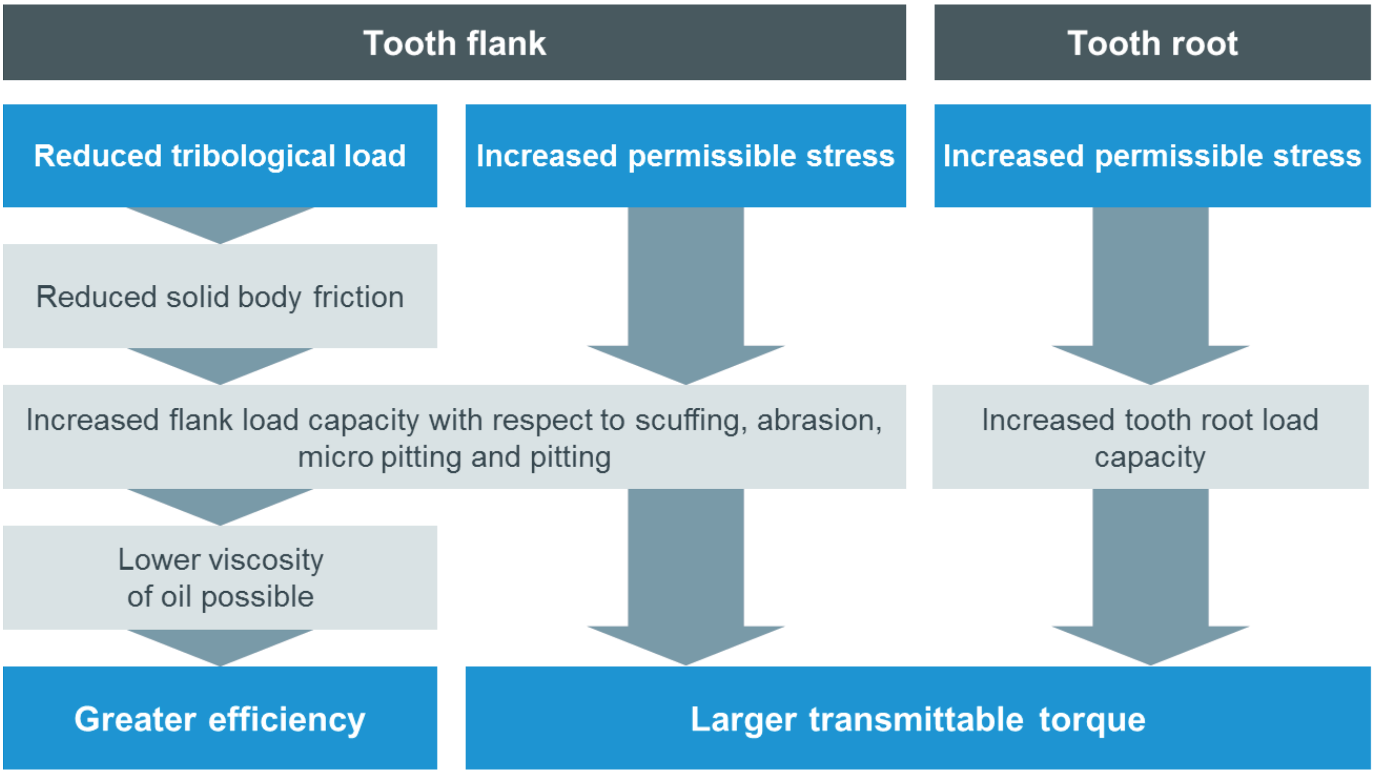


Figure 5: Advantages of higher-quality surface finish in gearings

This reduces solid body contact and thus also friction and wear.

With respect to gearings, a higher quality of the surface finish of the tooth flank means a decrease in the tribological load due to reduced friction (see Figure 5). It also means increased permissible stress due to a reduced notch effect. Moreover, an increased micropitting capacity is expected. All of this together leads to an increased load capacity of the tooth flank. A tooth root with a higher-quality surface finish also demonstrates a greater permissible stress due to the reduced notch effect. This also increases the tooth root strength. The potential gained can be used for a larger transmissible torque. If an increase in flank load capacity is not required, this can also be converted to greater efficiency through the use of a lower-viscosity lubricating oil.

Superfine Surfaces in Cylindrical Gear Transmissions

Studies of the influence of surface finish on flank load capacity have already been conducted for cylindrical gear transmissions. Ground surfaces were improved through trowalising from Ra = 0.30 µm to Ra = 0.11 µm and Ra = 0.07 µm, respectively. In this way, the continuously transmittable torque was improved by 20 % and 40 %, respectively.[1] With one variant, which underwent shot peening followed by trowalising (Ra = 0.07 µm), an increase in torque of 70 % was achieved.[2] Moreover, tests on large gearings have shown that micropitting below a roughness of Ra = 0.3 µm is avoided altogether.[3]

By trowalising cylindrical gearings, roughness values of less than Ra = 0,06 µm can be achieved.[4] With this method, considerably less than 10 µm of material is typically removed. The form stability of the gearing is therefore approximately ensured. Because the method is comparatively long and entails an additional production step that is difficult to implement in series production, efforts are being made to produce a comparable surface finish through methods using a defined tool geometry and on a gear grinding machine.

With conventional gear grinding processes, roughness values of approximately Ra = 0.3 µm are achieved. Through fine grinding processes, surfaces up to approximately Ra = 0.2 µm can be realized. To achieve finer surfaces, additional grinding wheels with an elastic bonding system can also be installed on the tool spindle of the grinding machine. Conventional gear grinding is then followed by polish-grinding with very little stock removal. Roughness values of approximately Ra = 0.1 µm are possible in this case. Polish-grinding performed as part of a research project even achieved values of up to Ra = 0.05 µm (Rz = 0.25 µm).[5, 6]

Special Case: Bevel Gear Transmissions

A characteristic feature of cylindrical gear transmissions is that at the generating circleonly rolling occurs without any sliding. In the direction towards tooth tip and root, the sliding velocity increases such that – depending on the rotation speed – mixed friction always occurs in one section of the tooth flank. By contrast, hypoid gears (bevel gear transmissions with an axis offset) show a sliding velocity at every point on the tooth flank during operation, at least in the face width direction. For this reason, the lubrication condition in tooth flank contact is more favorable, but the efficiency is lower in principle.

Figure 6: Bevel gear grinding on the Klingelnberg Oerlikon G 30

In terms of production, bevel gearings also differ fundamentally from cylindrical gearings. Ground bevel gears typically have a curved longitudinal tooth line. As a matter of principle, cup grinding wheels are used to manufacture them (see Figure 6). The possibility of using elastic-bonded tools for polish-grinding is questionable in this case. An elastic hollow cylinder has a comparatively lower form stability, which can lead to undesired dynamic effects particularly when grinding ring gears in full-surface contact, resulting in geometrical deviations. The tool would also bulge due to the centrifugal force, causing the profile to undergo a radial shift and become distorted. The use of elastic-bonded tools therefore appears to be unsuitable for bevel gear machining.

Given this background, how can the potential of superfine surfaces in series production be utilized most efficiently for the special case of the bevel gear transmission?

Fine Grinding of Bevel Gear Transmissions – A Challenge

Apparently, when a cup grinding wheel is used, a second finishing tool cannot simply be mounted on the grinding spindle in addition to a roughing tool to generate extremely fine surfaces. Accordingly, four options are available for series production: First: the use of a machine with two grinding spindles. Second: a grinding tool changeover between rough grinding and fine grinding. Neither of these variants is suitable for series production. This is because the available modern bevel gear grinding machines with the required accuracy of control for dressing and grinding movements as well as dynamic rigidity are single-spindle machines – and a changeover of the grinding tool between the rough grinding and fine grinding operation for each component cannot be realized with an acceptable changeover time for a series process. Thus ultimately only the third and fourth options remain: rough grinding and fine grinding of the component in two clampings and the use of one grinding tool that enables generation of a high-quality surface finish with an acceptable productivity level.

Due to the finite accuracy of the clamping device, the required rethreading and the gearing quality after rough grinding, when rechucking the component, a stock per flank of approximately 40 µm must be ensured for the fine grinding process in order to accommodate the deviations that will occur. This results in longer processing times for fine grinding. In addition, loading and threading must be performed twice, doubling the component-related auxiliary times. This procedure would have one positive effect, however: The component could be shot-peened between the rough grinding and the fine grinding. Because this could be done with minimal concern for the surface finish of the tooth flank and any peening bulges, the penetrative effect of the peening treatment could be increased. Klingelnberg's strategy starts with the last-mentioned option – which allows both a high-quality surface finish and a satisfactory machining performance. The particular charm of this solution is that fine grinding in this manner can be implemented in existing manufacturing sequences with minimal intervention.

Figure 7: Oerlikon G 60 bevel gear grinding machine

With the appropriate dressing tools modern grinding tools can be conditioned for a broad range of applications. In the first instance the grinding wheel is dressed in order to reach a very abrasive surface that is capable to remove the bulk of the grinding allowance effectively. Prior to the final grinding, the dressing parameters are chosen such that the desired surface finish can be reliably achieved with the appropriate process control. With the bevel gear grinding machines of the Oerlikon G 30 type designed for machining automotivegears and the G 60 type for truck applications (see Figure 7), machines meeting all these requirements are available on the market. The rigid construction of the machines in the vertical concept and the high precision provide optimal conditions for implementing the fine grinding process. The powerful cooling lubricant supply combined with the high-pressure cleaning nozzle ensure precise, adjustable process cooling and tool cleaning. The process cooling can be reproducibly positioned during tool changeovers and is entirely constant over the entire usable length of the grinding wheel due to the CNC controlled adjustment. This ensures a production process that is continuously free of grinding burn. An allowance control unit also monitors the geometry of the series components without disrupting the production process to rule out thermal joint damage due to variations in the grinding allowance. Routine automatic inspection of the stock removal ensures the desired distribution of the allowance between the two tooth flanks during the course of the series.

Klingelnberg has taken insights into the load capacity of fine ground cylindrical gears and component machining gained from the aviation industry and applied them to the production of series bevel gears in the automotive sector. Due to their design, the G 30 and G 60 bevel gear grinding machines are already quite well suited for fine grinding: The stability of the machine design, the rigidity and the high accuracy form the basis for optimized processes. The constant, reproducibly adjustable cooling lubricant supply, combined with the allowance and stock removal control, ensures constant grinding results. Both machines thus enable direct entry into the fine grinding of bevel gears in series production.

The results of the grinding tests performed on the Oerlikon G 30 demonstrate that this step is worthwhile. According to the standard calculation of load capacity, the torque in automotive gear sets that can be transmitted by the tooth flanks can be increased by approximately 40 % through the attained surface finish of less than $Rz = 1$ µm (see Figure 2) compared with the series requirement of $Rz = 8$ µm. The permissible load on the tooth root can still be increased by approximately 15 % starting from an unground surface. An improvement in the surface finish thus evidently has the potential to optimize the performance of bevel gear sets. With the Oerlikon Bevel Gear Grinding Machines from Klingelnberg, this load bearing potential for the bevel gear can be efficiently utilized in series production.

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