COST-EFFECTIVE PRODUCTION OF BEVEL GEARS IN EXTREMELY SMALL BATCHES

The production of bevel gears in a variety of sizes, can also be carried out cost-effectively with very small batches. Special tool systems and gear cutting processes as well as optimized process chains are required to achieve this. The technologies used by Drive Technology at Klingelnberg are designed to enable the most efficient production of a wide range of geometries to the highest quality standards, even with single gear sets.

Be it a ship's propulsion, a cement mill or a railway vehicle – single and occasionally double-digit batch sizes are an everyday occurrence in the Drive Technology business. In order to meet the highest quality standards in production as cost-effectively as possible, special strategies are required that guarantee the best products by means of effective, standardized processes. For example, whereas in the automotive and commercial vehicle industry set-up parts are used to establish a reliable process for mass production, in low-batch production this isn't possible and every single workpiece produced needs to be a good part.

Klingelnberg has taken technologies from series production methods such as dry cutting with coated carbide tools, and implemented them consistently for all component sizes in the universal segment. During the development of new tool systems and gear cutting processes, the primary focus has always been, and continues to be, on adapting established series production standards for use in universal processes and making use of synergies.

Modern machinery is the foundation of eco-nomical gear cutting. Numerically controlled neutral data machines are used consistently and have completely replaced the mechanical machine generation. Each of these machines is equipped with universal tool systems that are designed in accordance with a modular principle. The cutting edge geometry of the universal blades, which are classified according to the nominal module, can be used in a variety of ways. In contrast to specific design-related blade profiles in series production, this allows a wide range of geometries to be produced within a defined spectrum.

The closed-loop principle is applied throughout production. This ensures that the property profile of the manufactured gear set corresponds to the original design within tight tolerances. At the core of this system is a central production database linking all stations to each other. A data record for each gear set geometry containing precise information about the flank micro-geometry, among other things, is stored in this database.

From forged blank to bevel gear

Regardless of whether they are just a few centimeters in size or more than two meters, bevel gears are manufactured using essentially similar process sequences. In each case, a forged blank is the base material. For small dimensions forged bar stock is used, whereas custom-made, close-contour forged blanks are used for larger workpiece dimensions. An in-house material specification and a heat treatment method that has been optimally coordinated with the standard material provide, for example, a solid basis for compliance with the high quality requirements of classification societies with regard to the base material and the finished product. Using Klingelnberg's in-house calculation software KIMoS (Klingelnberg Integrated Manufacturing of Spiral Bevel Gears), the macro-geometry of the gears is defined based on customer requirements, and the micro-geometry is defined taking the gearing environment into consideration. This data forms the basis for all other stages of production. The gear body is first created using mechanical machining processes such as turning, milling, and drilling, followed by soft cutting.

Compact

Dry processes with soft cutting

Effective technologies from automotive series production were the prototype: Dry-cutting processes with coated carbide blades ensure extremely cost-effective production conditions across all component sizes, also in universal production.

High quality, short lead times and planning reliability for the customer are determining factors in the production, even with small batch sizes.

It is followed by heat treatment by means of case hardening. This is where the appropriate property profile for the gear's intended loads is defined: a hard, wear-resistant surface in combination with a ductile core material. Because heat treatment is a core competence in bevel gear manufacturing, Klingelnberg operates an in-house hardening facility specifically set up to accommodate the product range. During the next stage of the process, machining of the gearing reference surfaces on the pinion and ring gear is carried out. After that, the hard finishing and measurement of the gear takes place. The final step is the mechanical finishing of the pinion shafts and the ring gears. Finally, a quality inspection is performed as the last step in the process chain before delivery.

Whereas 10 years ago the tried-and-tested Zyklo-Palloid® method used hard skiving to conduct hard finishing on all gear sizes, there is now more differentiation in the production matrix. Depending on the component size, optimally coordinated machines, methods, and tool systems are used for gear cutting. Hard skiving using the Zyklo-Palloid® method with modified tool systems is still used today for large bevel gears. On the other hand, the final machining of small and medium-sized bevel gear sets is now carried out exclusively with a grinding process. Figure 1, "Production matrix", shows which methods are used today depending on the ring gear diameter.

Arcoflex for small bevel gears

With its latest innovation – the Arcoflex method – Klingelnberg is also making consistent use of dry-cutting technology in the production of small bevel gears with ring gear diameters up to 500 mm. This universal method for cutting and then grinding bevel gears is the best possible compromise between productivity and flexibility. Since it is a universal method, a special feature of the Arcoflex system is that it does not require any particular machine adaptation. Indeed, it can easily be implemented on the C and G series machines that are well-established in series production, such as the C 50 and G 60, without mechanical retrofitting.

During the development of Arcoflex, the main focus was on adapting the stick blade equipped cutter head concept from the automotive industry. The key difference with respect to series production lies in the standardization of blade profiles for the coated carbide blades that are used. Owing to their flexible application for a wide range

Production matrix

	Small	Medium	Large
Reference circle diameter (mm)	< 500	500–1.000	> 1.000
Mean normal module (mm)	2–9	7–18,5	12–50
Tool radii (mm)	47,625/55,5625 63,5/76,2/95,25 114,3/133,35 152,4/177,8/203,2	170 210 260	350 450 550 650
Gear cutting method	Arcoflex	Wiener 2 trace	Zyklo-Palloid®
Hard finishing process	Grinding	Grinding	Hard skiving

Fig. 1: Gear cutting method and hard finishing processes depending on gear sizes

TILT AND BLADE PROFILES

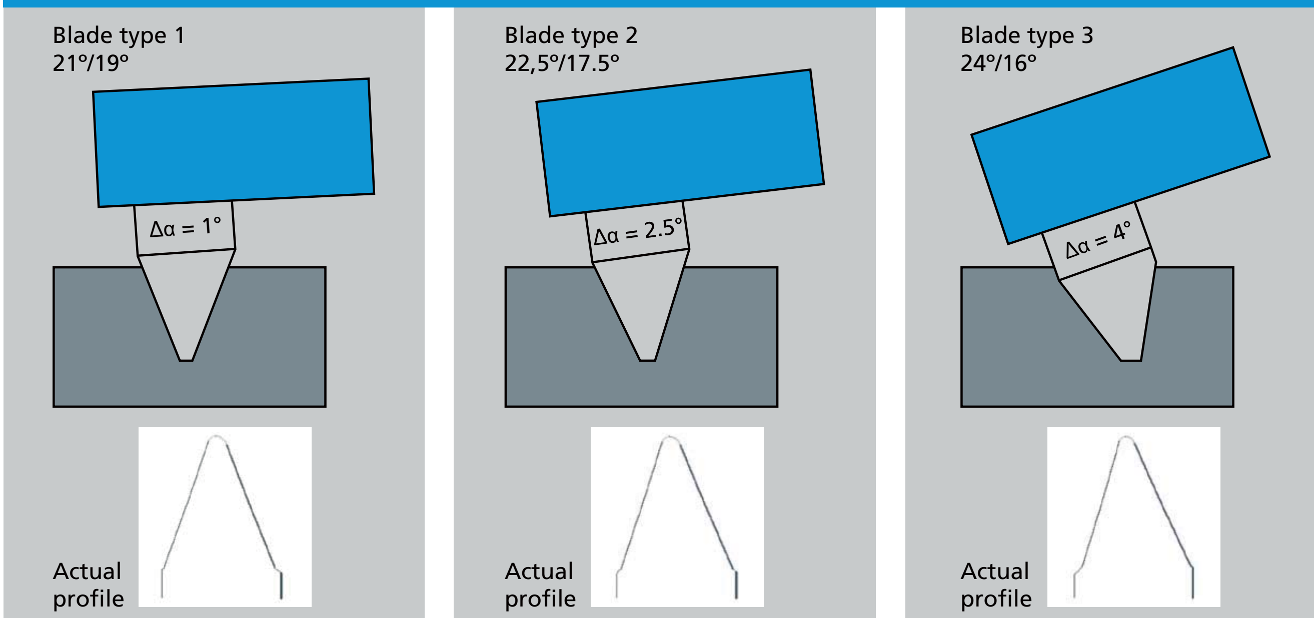

Fig. 2: Generation of lengthwise crowning with cutter head tilt and actual tool profiles

of geometries within a defined spectrum, the tools which need to be held on stock can be kept to a minimum. In conjunction with use of the UAC cutter heads (Universal ARCON® Cutter Head), which combine several cutting diameters in a single base body, the required scope of tools is further reduced. Finally, the definition of cutter heads with a uniform hand of rotation reduces tool requirements to a minimum. Furthermore, quick and easy tool adjustment is achieved by doing away with shimmings. This makes production extremely flexible and productive at the same time.

Face widths, diameters and spiral angles are different for every gear geometry – but the stick blades with a standardized profile are versatile and can be used within a specific normal module range for just about any geometry. The standardization of stick blades for gear cutting in the soft stage is similarly reflected in the profiles of the grinding wheels that are used for hard finishing. Irrespective of this, appropriate modifications of the grinding wheel profile are still possible.

The Arcoflex process corresponds to that of semi-completing. Unlike the Zyklo-Palloid® method, lengthwise crowning is achieved by tilting the cutter head rather than varying the tool radii. To compensate for the influence of pressure angles resulting from the cutter head tilt, three flank angle variations are available for each nominal blade module. The principle and the actual tool profiles are explained in Figure 2, "Tilt and blade profiles".

As well as flexibility, Klingelnberg reaches a new dimension of productivity with the Arcoflex system: In accordance with the process sequence during semi-completing, generation of the convex flanks follows plunging. With automatically modified machine settings, generation of the convex flanks takes place immediately afterward, with no intermediate tool change. The method is therefore ideal for use on single-spindle machines in the C and G series. Ideally, the pinion and ring gear can be cut using the same tool. In this case, the cutting direction is simply reversed.

Compact

Extremely versatile: Tools based on a modular principle

Bevel gear manufacturing at Klingelnberg is based on universal gear cutting processes developed specifically for small, medium, and large components in combination with tool systems built on the modular principle. This makes production extremely flexible.

FLANK COMPARISONS

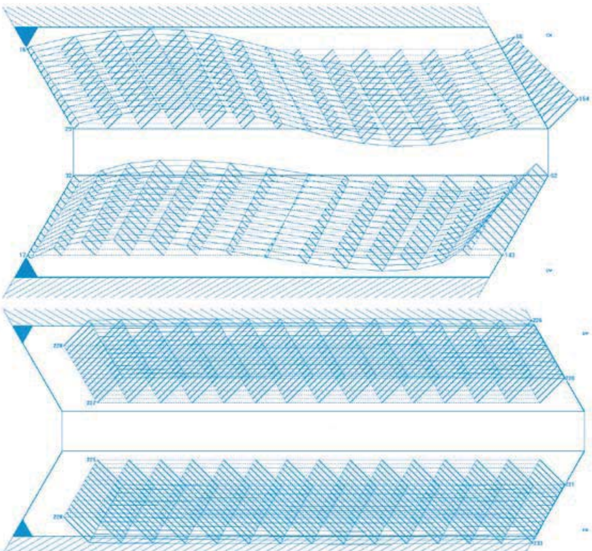

Fig. 3a: Uneven stock distribution: continuous indexing method in the soft stage vs. grinding with the single indexing method

Fig. 3b: Equidistant stock distribution: gear cutting in the soft stage and grinding, each with the single indexing method

Gear cutting in the soft stage and grinding take place in the Arcoflex process with the single indexing method. This produces a circle of an arc-shaped lengthwise tooth pattern in each case, thereby ensuring equidistant stock distribution for subsequent hard finishing by grinding. This results in improved cost-effectiveness compared to pre-cutting using the continuous Zyklo-Palloid® method with subsequent grinding. Equalization of the different lengthwise tooth curvature is dispensed with in the Arcoflex method, which speeds up the grinding process and also ensures that the remaining case hardening depth is distributed homogeneously over the flank (see also Figure 3a/b "Flank comparisons").

Converting existing Zyklo-Palloid® designs to Arcoflex also has another advantage: the constant tooth depth is retained. Consequently, changing the gear cutting process has no affect whatsoever on the geometry of the gear bodies. The contour of the workpieces and therefore the installation conditions in the gearbox housing are absolutely identical.

Wiener 2 trace for medium-sized bevel gears

The cornerstone for technology optimization in the area of medium-sized bevel gears with a ring gear diameter greater than 500 mm was laid approximately ten years ago. With the commissioning of the G 100, Klingelnberg set new standards, and extended the range of application for hard finishing by grinding to just over 1000 mm. In the medium-sized segment, this technology now represents the state of the art, and completely replaced hard skiving in Drive Technology at Klingelnberg quite some time ago. In combination with dry-process soft cutting in accordance with the single indexing method, equidistant stock distribution over the flank is ensured for subsequent hard finishing – similarly to, and as a template for, the Arcoflex method for small bevel gears. The Wiener 2 trace method is used here. Its process sequence consists of plunging followed by the generating process for the convex flanks. After a tool change, the concave flanks are generated with modified machine settings. With this method as well, the blades are mounted in a modular system and classified in accordance with the nominal module. A special form of the closed-loop concept (see information box, "Gear cutting with maximum efficiency and quality" on pg. 35) is used here during gear cutting in the soft stage and takes place continuously on the machine without taking down the workpiece.

Zyklo-Palloid® for large bevel gears

The tried-and-tested Zyklo-Palloid® method with single-piece cutter heads is used for cutting large bevel gears with ring gear diameters up to 3000 mm. In direct comparison with the previous machine and tool generation, Klingelnberg has also implemented extensive measures in this area in order to optimize efficiency. With the commissioning of the C 300, a numerically controlled neutral data machine is available for the first time for large bevel gears. This machine has a dual spindle for processing both flanks of the pinion in a single clamping. Set up and take down stations guarantee minimal workpiece change times, allowing these operations to take place parallel to the machining process. With the SPIRON® U system, a new tool concept has been developed specifically in this area as well. Gear cutting in the soft stage by the dry process is made possible through the use of inserts made from coated carbide. Each of these has four usable cutting edges. Not only does this remove the need for cooling lubricant, but also costly tool preparation. In this application area too, the universal tool system is designed in accordance with the modular principle. The cutter heads can be used flexibly for both spiral directions for gear cutting in the soft stage as well as gear cutting in the hard stage. By dispensing of the need for roughing blades within each group, which again are classified in accordance with the nominal module, a greater number of starts is possible, making the SPIRON® U tool concept extremely productive in comparison with previous systems.

Due to the contact length between the tool and the workpiece, which increases according to the size of the components, hard finishing with grinding is ruled out because sufficient coolant supply cannot be guaranteed. For hard finishing, Klingelnberg therefore continues to use the tried-and-tested concept of hard skiving with CBN cutter bars, which has also been adapted to the increased number of starts of the cutter heads. In combination with the degrees of freedom of the C 300 neutral data machine, this enables the effective generation of appropriate flank form modifications.

Conclusion

Be it a single set with a ring gear size of more than two meters or a dozen components just a few centimeters in diameter – Klingelnberg has optimized its gear cutting processes and tool systems for the cost-effective production of extremely small batch sizes. This multiple-stage process, in which new solutions are developed and implemented for different component sizes, reached its preliminary completion with the implementation of the new Arcoflex method.

Versatile, modular universal tools are the basis for production of extremely small batch sizes. They are the guarantee of a balanced ratio between tool requirements, machine preparation, and machining time. The continuous use of dry processing for gear cutting in the soft stage in combination with optimally coordinated hard finishing is a guarantee for economical production.

Maximum product quality is ensured by consistent implementation of the closed loop principle across all sizes. By combining powerful calculation software with process and application-optimized machinery, Klingelnberg meets all requirements for the production of bevel gears with any size or geometry. ◆

GEAR CUTTING WITH MAXIMUM EFFICIENCY AND QUALITY

- Closed loop also includes gear cutting in the soft stage
- Special strategy without the use of set up parts
- Cutting the first workpiece in a batch with allowance at the end-of-plunge sliding base position
- Calculation of explicit nominal data for the previously generated state
- Measurement using KOMPASS probe on the machine
- Comparison of nominal and actual measurement data using KOMET on the cutting machine
- Generation and import of correction data
- Final machining according to nominal geometry

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