Hard Gear Finishing with a Geometrically Defined Cutting Edge

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Skive hobbing, hard skiving or skive shaping can be alternatives to gear grinding for post heat treatment finishing.

Introduction

The market demand for gear manufacturers to transmit higher torques via smaller-sized gear units inevitably leads to the use of case-hardened gears with high manufacturing and surface quality. In order to generate high part quality, there is an increasing trend towards the elimination of the process-induced distortion that occurs during heat treatment by means of subsequent hard finishing.

Intensive research activity into the hard finishing of gear flanks has produced an alternative to the widely used gear grinding process. Manufacturers now have the option of choosing a process that uses a geometrically defined cutting edge. This article describes problems and trends in hard machining with a defined cutting edge, presenting the skive hobbing, hard skiving and skive shaping processes. The key feature is the elucidation of individual process kinematics, tool geometries, tool materials and coating systems. A number of fields of application are also indicated.

Hard Finishing Tooth Flanks With A Defined Cutting Edge

Nowadays, most gears are case-hardened after roughing in order to enhance their wear resistance and load-carrying capacity. With unfavorable part geometries, however, heat treatment leads to substantial hardening distortion. Because of today's standards for high quality gears, subsequent hard finishing of the tooth flanks is often needed (Fig. 1).

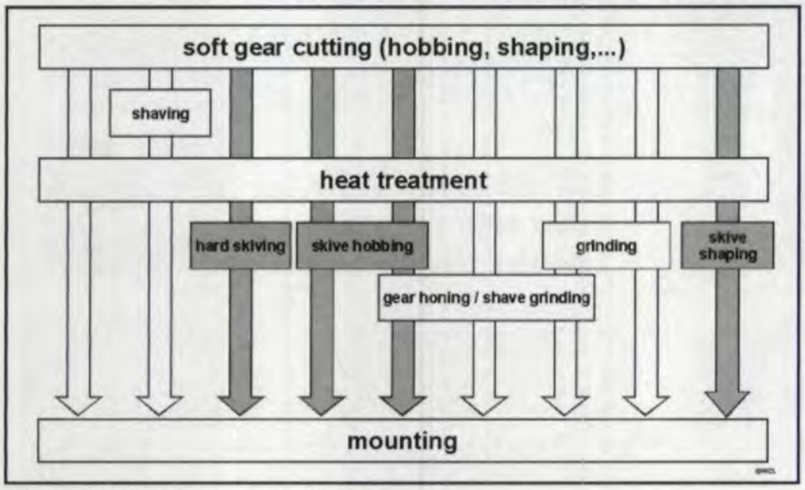

Fig. 1—Finishing external cylindrical gears.

The dominant finishing process used to compensate for hardening distortion is currently gear grinding, which can be used to machine very hard surfaces with great precision. Despite successful sophistication of grinding technology, machining with a geometrically undefined cutting edge remains a time-consuming process with correspondingly substantial machine and personnel costs. There is, therefore, a desire to substitute machining operations with a geometrically defined cutting edge for the present grinding process. Sophisticated tool materials and cuttings now permit the use of defined-edge processes like peeling, skive hobbing, hard skiving and skive shaping to finish hardened tooth flanks.

Apart from higher removal rates, defined-edge processes have the advantage of combining some soft and hard machining operations on the same machine. This enables the manufacturer to save the purchasing costs for a gear grinding machine. Another positive factor is the low energy consumption for defined-edge machining. Finally, a dry cut is often feasible, eliminating the use of cooling lubricants with their high disposal costs and environmental risks.

One drawback of hard finishing with a geometrically-defined cutting edge is lower process reliability due to the possibility of sudden tool failure resulting from breakage at the cutting edge. This is caused by the relatively low toughness of the carbide tool material. The disadvantage of "low process reliability" and the drawback of "essential minimum chip thickness" are closely linked. If the chip thickness is too small, no chip is cut; the work material is merely pushed aside, increasing friction and pressure on the cutting

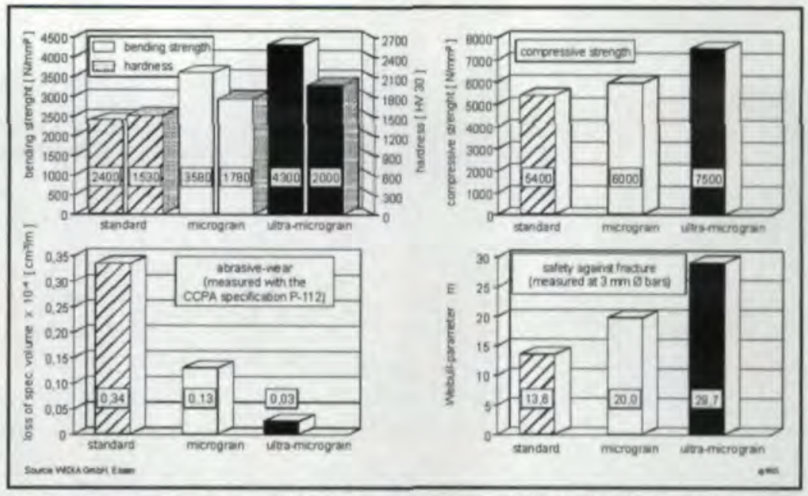

Fig. 2—Parameters of various WC-6-Co carbides (Source: WIDIA GmbH, Essen, Germany).

edge and causing early failure. The minimum chip thickness needed for a chip to form is also a drawback in terms of the accuracy-to-size that can be achieved as compared to grinding. Defined-edge hard cutting has difficulty in achieving the kind of machining accuracies possible with grinding. Especially high surface-quality requirements can only be met to a certain extent because process-specific deviations in the generating cut are mirrored on the surface of the part.

Suitable Tool Materials

Machining hardened ferrous materials demands tool materials with strength properties that match the special needs of hard cutting technologies and which possess adequate mechanical and thermal shock resistance, especially in discontinuous cutting operations. Great hardness and edge stability, low adhesion, high thermal stability, adequate toughness and a homogeneous fine-grained structure are often conflicting requirements imposed by hard finishing on a tool material. The choice of tool material is also affected by economic considerations (Ref. 6).

Micrograin Carbides

WC/Co-based micrograin carbides have recently become an important factor in gear-making technology. Carbides are sintered materials consisting of a soft metallic binder phase (cobalt), in which the carbides—in this case tungsten carbide—are embedded. Micrograin carbides of the same composition but with carbide grain sizes below 1 µm possess greater hardness and resistance to compressive stress than conventional carbides with a grain size of roughly 1 to 3 µm. Tungsten-carbide and cobalt-based carbides with average tungsten-carbide grain diameters ≤ 0.5 µm are termed ultra-micrograin carbides.

Micrograin carbides are also characterized by their very high bending and tensile strength, since both hardness and bending strength can be raised with a WC-crystal size below 1 µm. Modern manufacturing technologies also produce extremely fine-grained homogeneous microstructures. A product of this kind, consisting, for example, of 94% WC and 6% Co, measured by mass, achieves a hitherto unattained combination of hardness (2000 HV 30) with bending strength (4000 N/mm2) (Fig. 2), which would have been considered impossible even a few years ago (Refs. 4, 5 & 11).

The rise in hardness as the tungsten-carbide grain size decreases reduces abrasive wear, while the 50% increase in bending strength, which has positive effects on edge stability, and its suitability for machining hardened materials with minimal allowances to grinding quality recommend this tool material for gear production (Ref. 7). Combined with improved coating technologies, it opens the way to reducing the chipping of the cutting edge, which determines tool life and increases process reliability.

Coating Technology

The use of coated carbides and high-speed steels in machining is state-of-the-art technology. The hard, thin film increases the abrasion resistance of the coated tool material, reduces tool-part adhesion and acts as a barrier to diffusion. The substrate material carrying the film must ensure good support and give the substrate-coating composite adequate thermal resistance and toughness. The prerequisite for the wear-protective effect of the film is adequate coating-substrate adhesion, even when the tool is exposed to thermal and mechanical shock. CVD (chemical vapor deposition) and PVD (physical vapor deposition) techniques are employed to apply the coating to the cutting tools (Refs. 4 & 11).

One drawback of the high-temperature CVD method (T > 1000°C) is the risk that the cutting edge will become brittle. The PVD process, in which the coating is deposited on the substrate in a low temperature range (200°C to 600°C), reduces the risk of cutting edge embrittlement. PVD coating of carbide tools is now state-of-the-art technology; titanium nitride (TiN) is the dominant coating material. Other coating materials based on TiN have been developed; and of these, titanium carbon nitride (TiCN) and titanium aluminium nitride (TiAlN) have already become commercially significant (Refs. 4 & 11).

Wear On Coated Carbides

Wear is highly significant for cutting processes, substantially affecting the finished product and the reliability of the process. Tool wear is caused by adhesion, diffusion and oxidation phenomena

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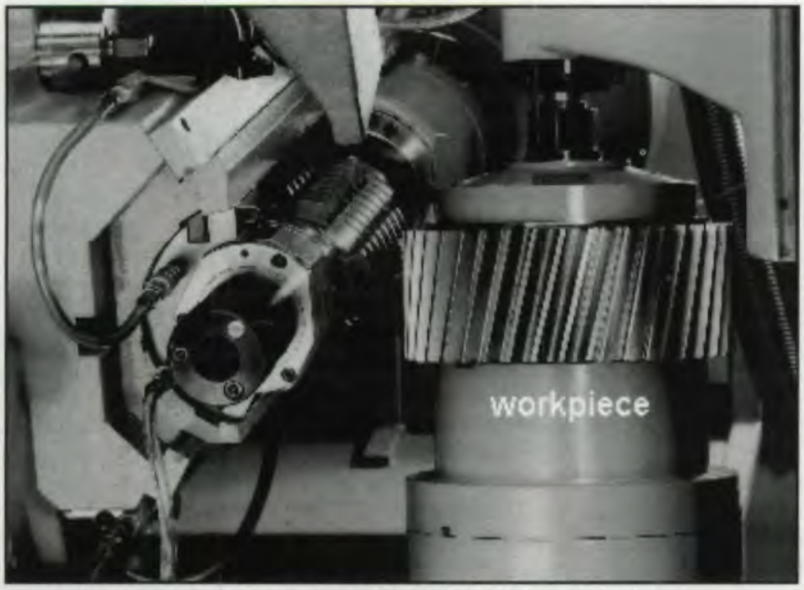

Fig. 3—Tool-workpiece configuration in skive hobbing. Source: Pfauter.

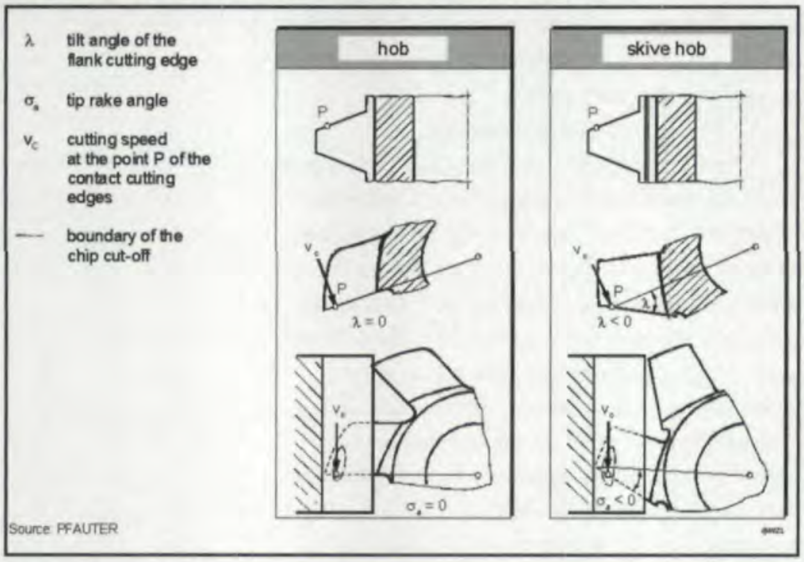

Fig. 4—Negative rake angle on the skive hob.

during the machining operation. Adhesive coating failure and cohesive and adhesive coating wear are potential wear mechanisms during hard finishing with a defined cutting edge (Refs. 3 & 8). Apart from wear mechanisms affecting the film coating, wear phenomena including chipping, transverse and ridge cracks, abrasion, adhesion and diffusion may also occur on the substrate where it is uncoated or unprotected due to coating wear (Refs. 7 & 11).

The wear mechanisms noted above are not independent of one another, but have overlapping causes and effects on wear. For example, abrasive wear or chipping may be promoted or even initiated by adhesion or diffusion on the carbide. In general, however, it is true to say that, together with abrasion at low cutting speeds, adhesion and, at high cutting speeds (cutting temperatures), diffusion and oxidation phenomena are the primary determinants of tool wear (Ref. 7).

Skive Hobbing

Skive hobbing (Refs. 1, 3, 7, 8, 10, 11 & 12) is a continuous process employing a geometrically defined cutting edge in a rotary cutting action with an interrupted cut for finishing pre-cut, hardened gears. Its primary tasks are to eliminate hardening distortion caused by heat treatment and to improve surface quality. Its process kinematics are identical with those of hobbing, enabling both the gear cutting and finishing processes to be performed on the same machine (Fig. 3).

The process kinematics of skive hobbing are based on a generating spiral drive in which the tool and the gear contact one another at an angle. Potential profile modifications of the workpiece have to be introduced, whereas modifications of the flank line can be made by adapting the machine motions. Process kinematics are characterized by a combined generating and spiral feed motion.

The rolling motion results from the differential speeds of rotation of the skiving hob and the workpiece; the speed of rotation varies inversely with the number of teeth. The spiral motion required to machine the full width of the workpiece is superimposed on the rolling motion. In order to achieve this, the tool is shifted along the workpiece axis, entailing a simultaneous additional rotation of the workpiece. The magnitude of this additional rotation is calculated to produce a spiral motion from the axial motion of the tool and the additional rotation of the part. The cutting speed in skive hobbing is equivalent to the circumferential velocity of the tool.

The term skive hobbing is derived from the "skiving cut." This type of cut is essential for creating the small chip cross-sections required to machine the hardened material. As an aid in this task, the tools are given a negative rake angle, which acts as a negative tilt angle on the tooth flanks (Fig. 4). This produces an enlarged active cutting-edge length and a "pulling cut," which is intended to offer greater resistance to the stresses involved in machining hardened steel.

One tool is sufficient for all gears with the same reference profile in skive hobbing. Owing to the process kinematics, the enveloping profile of the tool is based on a worm and has straight-flanked cutter teeth. The workpiece corresponds to the worm wheel. The cutter teeth are arranged spirally over the circumference of the skiving hob and separated by flutes. Each cutter tooth corresponds to one rolling position for profiling the tooth gap and always removes an identical chip. If the skiving hob is worn, it can be sharpened on a separate machine, on which the face of the tool is reground.

Skive Hobbing Process Characteristics and Applications

Prior to skive hobbing, the tooth gap must be rough-machined to a stage at which the tip of the skiving hob does not make contact, and only the flank cutting edges are involved in the machining operation. Otherwise there would be a risk of chipping. The tooth root can be freed by roughing with an increased tip factor or by pre-hobbing with a protuberance. The centering of the skiving hob in the workpiece gap is also of great importance for the finished result. Because of the high forces encountered in machining hardened steel, the skive hobbing machine requires high static and dynamic stiffness in addition to geometric and kinematic accuracy.

Skive hobbing is carried out at cutting speeds of $v_c = 30–110$ m/min for any helix angle of the workpiece and modules $m_n = 1–40$ mm. The cutting speed has to be reduced as the size of the part increases, owing to the longer contact lengths in the machining process and the higher resulting thermal stress. Axial feeds range from 1–5 mm/workpiece revolution; small feeds are selected to match high workpiece accuracy requirements. Owing to the small chip thicknesses concerned, skive hobbing should be performed in climbing cutting, in order to reduce the stress on the cutting edges. The skive hob can be shifted during the hobbing operation to distribute wear evenly over the tool.

Skive hobbing is used as a finishing operation or as a roughing process to prepare for subsequent finishing by eliminating hardness distortions and reducing grinding allowances. This process sequence is frequently employed for large-module workpieces. The quality limits are determined mainly by the characteristic feed markings and enveloping cut deviations. Subsequent gear honing can remove these on small-module gears. Gears which cannot be ground because of their geometry can be skive hobbed. Batch sizes range from one-off to large-series production.

Hard Skiving

Hard skiving (Refs. 1, 2, 3 & 7) is a continuous defined-edge process using an interrupted cut. Although its process kinematics are based on a generating spiral drive as in the case of skive hobbing, hard skiving cannot be carried out on a skive hobbing machine but requires the purchase of its own machine. This is due to the changed tool-workpiece configuration as compared to the skive hobbing principle (Fig. 5).

Because of the generating spiral drive, the skiving gear and workpiece mesh on skewed axes of rotation. A spiral motion is superimposed on the

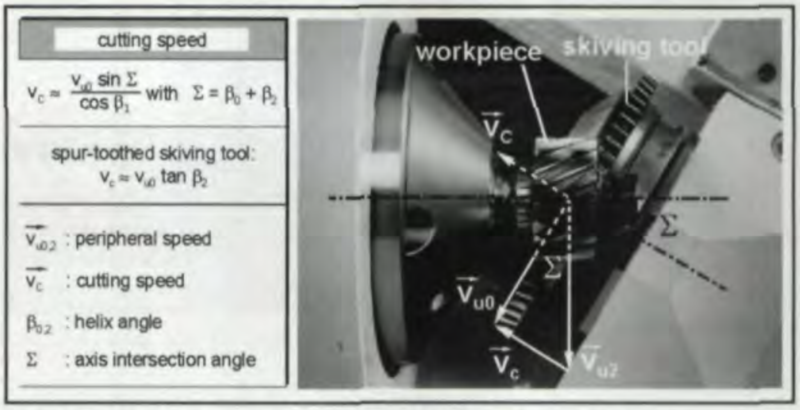

Fig. 5—Tool-workpiece configuration in skive hobbing. Source: Pfauter.

rotation-speed-dependent generating motion. This results from the displacement of the tool parallel to the workpiece axis, entailing an additional simultaneous relative rotation of the workpiece. As a result of this superimposed generating and spiral motion, the cutting edges of the skiving gear slide along the tooth flanks of the workpiece and skive the material over the full width of the gear tooth. The inclination of the skiving path to the generatrix on the tooth flank creates a surface structure favorable to the noise behavior of the gears.

The cutting speed for hard skiving is a product of the difference in the circumferential velocities of the skiving gear and the workpiece. Owing to the generating spiral drive, the component of sliding velocity perpendicular to the cutting edges of the tool is approximately equal to the cutting speed (Fig. 5). It may therefore be stated for a spur skiving gear that

$v_c \approx v_{u0} \bullet \tan ß_2$.

If the helix angle of the gear $ß_2 = 0°$, the cutting speed will be $v_c = 0$ m/min. This means that spur-toothed workpieces cannot be machined with spur-toothed skiving gears. Spur-toothed tools, however, do have substantial advantages as compared to helical tools. For this reason, hard skiving is currently carried out only with spur-toothed skiving gears and is confined to the machining of helical gears.

Hard skiving tools take the form of an undercut cylindrical gear, because the process kinematics determine a cylindrical envelope profile of the skiving gear. They consist of carbide rings with slightly conical or even cylindrical gear teeth on their external cylindrical surfaces.

Hard Skiving Process Characteristics and Applications

Hard skiving is carried out in a module range $m_n = 1–3$ mm and at cutting speeds of $v_c = 40–90$ m/min and axial feeds 0.1–0.25 mm/workpiece revolution. The machinable helix angles of the workpiece are restricted to $ß_2 = 15–40°$. The con-

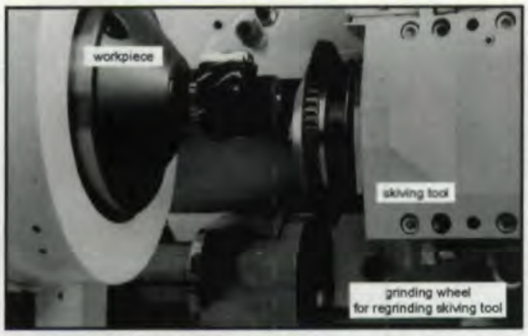

Fig. 6—The skiving tool can be reground in the machine. Source: Pfauter

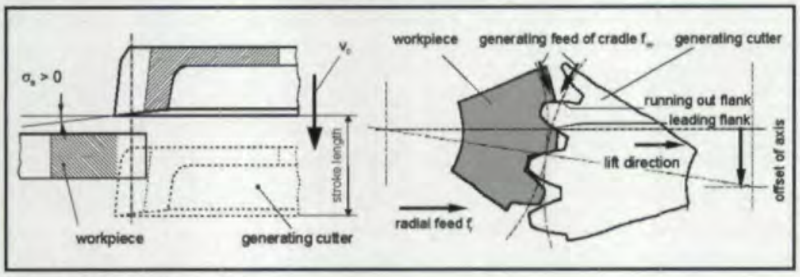

Fig. 7—Shaping kinematics.

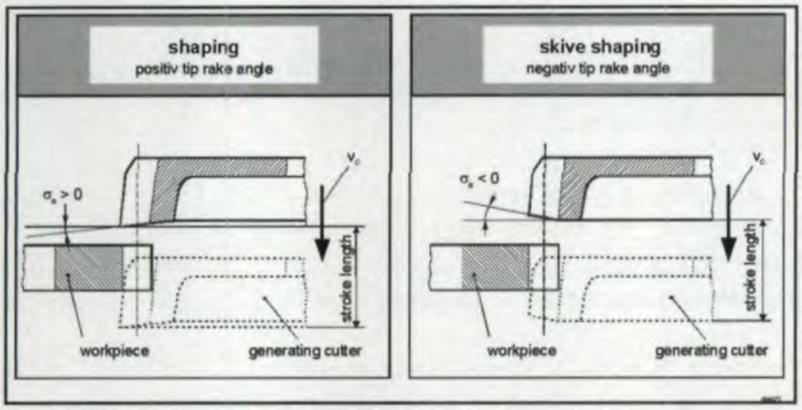

Fig. 8—Negative rake angle on a cutting gear for skive shaping.

ventional cutting is used for hard skiving. An allowance of 0.13 mm per flank can be removed in one cut. The allowance should be as small as possible, in order to save tool costs and keep process forces low.

Hard skiving tools are generally part-specific. A specially designed skiving gear is needed for each workpiece. The rake faces lie in a plane perpendicular to the tool axis. This means that the skiving gear can be reconditioned at the end of its tool life by a simple, low-cost flat grinding operation in the machine (Fig. 6).

Hard skiving is currently performed as a single-flank operation, even though two-flank machining would allow shorter production times. One advantage of this approach is that the right and left flanks of the gear can be machined with different shaft angles, prolonging the tool life of the skiving gear through larger effective tool orthogonal clearances; another is that workpiece quality can be improved by a more uniform passive force curve over the axial path.

Hard skiving is suitable only for medium- to large-scale production, especially for large-series production in the automotive industry. The gears involved usually have profile bearing and crowning. Desired depth crownings can be taken into account through a modified skiving gear profile. Crowning is generated by means of adapted machine motions.

Skive Shaping

Skive shaping (Refs. 4, 9 & 11) is a discontinuous defined-edge process that uses a translatory cutting motion to finish rough-cut hardened cylindrical gears. Its process kinematics are identical with those of shaping (Fig. 7), enabling soft machining and hard finishing to take place on the same machine.

The sequence of motions is characterized by the generation between a cutting gear and workpiece mounted parallel to one another. Chips are removed in the direction of the flank line through an axial cutting motion of the tool gear, referred to as a working stroke. During the subsequent reverse stroke, the work table or the tool is lifted to prevent a collision between the cutting gear and the workpiece. Skive shaping is performed without any axial offset, i.e. without lateral displacement of the machine stand. This is the only means of ensuring uniform infeed on both flanks. Collision problems that are encountered in roughing operations with a shaping machine do not occur in skive shaping, owing to its nature as a finishing cut (Ref. 9).

In order to withstand the initial cutting stresses on hardened steel more effectively, the rake angle of the shaping gear used in skive shaping is negative, causing a negative tilt angle on the tooth flanks (Fig. 8).

The involute tooth flank is profiled by means of generated cuts. A cutting-gear tooth generates a workpiece gap. The flanks of the cutting-gear tooth are involute in form and, as is in skive hobbing, the tools are not part-specific except for necessary profile modifications. The face of a worn shaping gear is reground on a separate machine in order to sharpen the cutting edge.

To achieve a generating motion, the workpiece and cutting gear move simultaneously with the axial stroke motion, in accordance with the ratio between their numbers of teeth. The generating feed is the distance described at the pitch circle per double stroke (double stroke DS = working stroke + reverse stroke). The number of generated cuts is dependent on the generating feed. An increase in generating feed reduces the number of generated cuts.

Skive Shaping Process Characteristics and Applications

In skive shaping operations, it is necessary to ensure that machining takes place only with the flank cutting edges. The rough-cut workpiece gap must be machined appropriately and the cutting gear properly centered. In order to prevent the tip corners of the shaping gear from participating in the cut, an allowance of 0.1 mm/flank should also be left. Cutting speeds are in the range v_c = 20–40 m/min. Gear deviations characterized by a pitch-circle gap are still an unsatisfactory feature. Profile-corrected tools and higher stiffnesses of the overall system may lead to improved profile accuracy.

Hard gear finishing in cases where the contact point is severely restricted by neighboring design elements may be very difficult or impossible to realize. The special advantages of skive shaping, manifested in the short tool run-on, are apparent in these applications. Both continous double helical teeth and double helical gears can be hard finished using this process, as can gears on stepped shafts or even crown gears. The machining of clutch gears is also conceivable. Batch sizes may be small or large.

One potential application for skive shaping lies in hard finishing of internal gears. Internal gears are a major component of planetary gear systems, which represent an increasingly large proportion of mass-produced gear systems. Owing to enhanced performance requirements for power gear trains, users are demanding cost-effective hard finishing technologies for internal gears. Whereas hard broaching is economically feasible only in large-series production, an unsatisfactory tool transition, e.g. via neighboring design elements, is often the only obstacle to the use of such technologies as skive hobbing, gear grinding and gear honing. Skive shaping, by contrast, is inherently suitable for finishing operations on internal gears.

Conclusions

The finishing of hardened tooth flanks after heat treatment is of growing importance due to increasing demands for high gear quality and smooth running. Currently, the dominant finishing process for elimination of hardening distortion is gear grinding. Sophisticated tool materials however, already point the way to defined-edge technologies.

Skive hobbing, hard skiving and skive shaping are defined-edge processes suited to the hard finishing of gears. These generating techniques make use of micrograin carbide tools. Skive hobbing tools are spirally shaped; hard skiving and skive shaping tools are cylindrical. There are also differences in process kinematics and potential applications.

Skive hobbing can be used with any batch size from one-off to large series production across a broad range of geometrical workpiece dimensions. Hard skiving, by comparison, is suited only to series and large-scale production of helical gears with dimensions customary in the car industry. A common feature of both processes is their low-noise surface structure.

In cases where the contact point is severely restricted by neighboring design elements, hard gear finishing can preferentially be achieved by skive shaping. One potential application of skive shaping is the production of internal gears, which have come to represent an ever-increasing proportion of gears manufactured in series production and which frequently cannot be machined by other processes. Skive shaping is fundamentally suited to this task. O

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