A CROWNING ACHIEVEMENT for Automotive Applications

The following article explores the feasibility of center-less finishing of the pinion with a modified tooth surface in the mass production of gears in the automotive industry.

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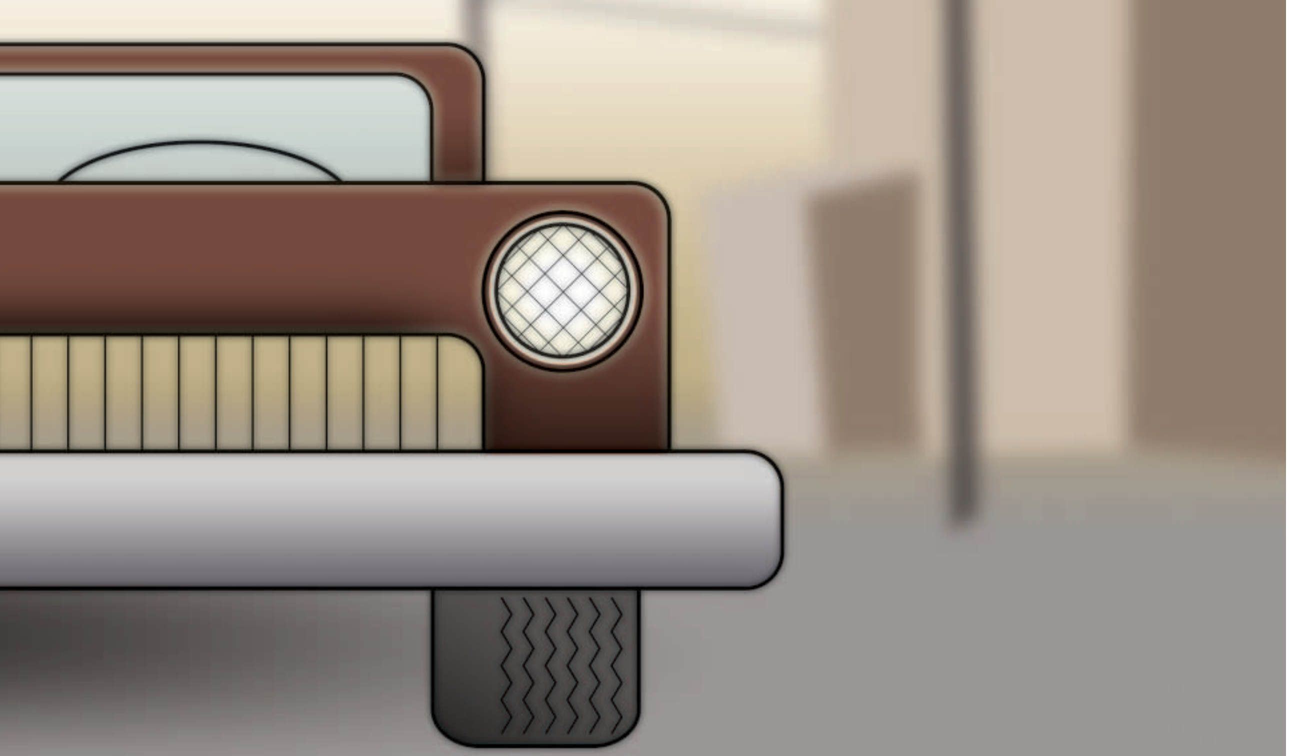
THIS

This paper is dedicated to engineers who work in the field of machining precise gears for the needs of the automotive industry. Crowning of the pinion provides a localized bearing contact and a favorable type of transmission error for misaligned gears in car transmissions. A new method for gear crowning—i.e. a method for lengthwise modification of the pinion tooth—is proposed by this author. Crowning of the pinion tooth could be performed simultaneously with the pinion tooth profile modification (which is usually uniform across the pinion face width). The reported method of finishing a precision pinion could be easily expanded to the gear chamfering operation. Due to high productivity, this method of pinion crowning—and the method of gear chamfering as well—could be applied to the mass production of gears for the needs of the automotive industry, e.g. for the crowning pinion for low-noise car transmissions.

Introduction

Involute and non-involute spur gears are very sensitive to gear axes misalignment. This misalignment causes the shift of bearing contact toward the edge of the gear tooth surfaces and transmission errors that increase noise excitation. Many efforts have been made to improve the bearing contact of misaligned spur gears by crowning the pinion tooth surface (Ref. 1). Wildhaber has proposed various methods of crowning that can be achieved in the process of gear generation (Ref. 2). MAAG engineers have used crowning for making longitudinal corrections; modifying involute tooth profile uniformly across the face width; combining these two functions (Ref. 1, 3, 4); and performing topological modification that can provide any desirable deviation of the crowned tooth surface from a regular involute tooth surface (Ref. 4).

The main purpose of these crowning methods is to improve the bearing contact of the misaligned gears, which only partially addresses the problem. Another problem of prime importance is gear noise. The transmission errors of misaligned gears are the main source of gear noise. Transmission error can be absorbed with the application of the pinion with a modified tooth surface. Many engineers (Ref. 5-9) have studied the problem of gear noise. The application of the pinion with a modified tooth surface significantly reduces noise excitation in car transmissions. Usually the pinion tooth surface is generated as a lengthwise-modified surface. The gear tooth surface is not modified: it is generated as a screw involute tooth surface. A favorable function of transmission errors is provided for meshing of the pinion and the gear tooth surfaces. The desired function of transmission error



enables reducing vibration and noise excitation of the gear drive that is caused by errors of alignment.

Literary Survey

New trends in gear design are directed toward the substitution of an instantaneous line tangency of contacting tooth surfaces by instantaneous point contact (Ref. 10). If the proper design is achieved, this enables a reduction of the sensitivity of the mating gears to misalignment and reducing the shift of the bearing caused by errors of alignment. In addition to the observation of point contact of tooth surfaces, it is also required to reduce the vibration of gears. This can be obtained by a reduction of the magnitude of transmission errors and observation of a favorable shape of function of transmission errors. Transmission error is the predominant cause of gear noise.

The application of a pinion with a modified tooth surface has been understood for many years. Modification of the pinion tooth surface is required to avoid the effects of transmission errors and the shift of contact between the gear and the pinion tooth surfaces. Theoretically, transmission errors are inevitable if the axes of crossed helical gears become intersected. Actually, if the gear misalignment is of the range of five to 10 arc minutes, the transmission errors are very small and may be neglected. The main problem for this type of misalignment is the shift of the bearing contact to the edge. In addition, the transmission error must be kept to a low level in order to stabilize the bearing contact. Our investigation shows that this goal can be achieved by proper modification of the pinion tooth surface. Actually, the bearing contact cannot cover the whole pinion tooth surface. The reason for this is that the instantaneous contact ellipse moves across, but not along, the tooth surface. For economical reasons, only the pinion tooth surface is modified, while the gear tooth surface is kept as a regular screw involute surface.

A method of synthesizing the modified tooth surface of a pinion that provides a localized bearing contact and a favorable type of transmission error for misaligned gears is developed in Ref. 11. Umezawa (Ref. 9) introduced the "bias-modified helical gear pair." In this instance, he proposed to distinguish the so-called "bias-in, bias-out" kinds of modification of a pinion tooth surface. An asymmetrical relationship between vibration magnitude and the direction of each deviation is observed. For further noise reduction, investigation of the effects of the shaft, bearing, and gearbox on vibration is of immense importance.

Through an intense "Advanced Gear Design" analysis, Ameridrives International has optimized the geometry of the existing fully-crowned gear tooth to increase capacities by 20 to 300 percent greater than the existing conventionally designed tooth (Ref. 12). This analysis was developed through years of finite element analysis, strain gage testing, dynamic testing, and field testimonials from users.

The application of the pinion with a modified tooth surface allows for minimizing variations in working transmission error owing to the difference in working torque, thereby reducing the working transmission error in a wide working torque range.

Methods for finishing the tooth surface of a modified pinion on a conventional gear finishing machine appear in many sources (Ref. 13-15). Usually pinion crowning—i.e. modification of the pinion tooth in a lengthwise direction—is performed in an axial shaving operation. In axial shaving, in order to induce lead crown, it is required to rock the machine worktable by using the built-in crowning mechanism (Ref. 14).

The implementation of a rocking worktable action for crowning during conventional shaving operation is considered in Ref. 16. Litvin proposed a method of pinion crowning that is based on the application of a surface of revolution that slightly deviates from a regular finishing tool conical surface (Ref. 1, 17). We refer to such a surface of revolution as "the machining surface T of a cutting tool." Gear finishing tools of such design are recommended for application as a grinding wheel or as a shaving cutter.

However, in mass production of gears for the needs of the automotive industry, the problem of finishing precise gears with lengthwise modification of their tooth surface does not yet have an appropriate solution. At present, there are no highly productive methods for finishing crowned pinions that fits the needs of mass producing gears in the automotive industry.

Methods and Apparatus for Center-Less Finishing of the Pinion

Here we consider an operation of center-less finishing of a precise gear with an involute or some other tooth profile (i.e. the operation of polishing and/or grinding of pinion tooth surfaces, finishing pinion tooth surfaces with a shaving cutter-like gear finishing tool such as a cutter with small teeth that are uniformly distributed circumferentially, with small pitch over the machining surface T).

For a pinion with the given face-width F_p, lengthwise tooth modification of the gear to be finished (Fig. 1) can be specified by value δ of tooth modification. The finished pinion tooth surface can be easily approximated with a surface of revolution, or with the helical surface of a corresponding tooth and/or thread profile.

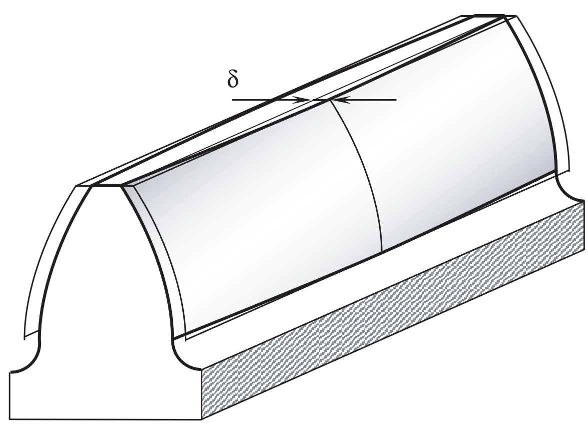


Figure 1 — Design of a crowned, i.e. lengthwise modified pinion tooth.

In order to develop a method and apparatus for high productive center-less finishing of a precise crowned pinion, the basic principles of analytical mechanics of gears are used (Ref. 18). Finishing a pinion with a crowned tooth surface can be performed via the process outlined in *Machine Tool for Finishing a Crowned Gear* (Ref. 19). A pinion 1 (Fig. 2) is finished with a gear finishing tool 2 that is located inside the bandage 3. The machining surface T of the gear-finishing tool could be generated as an enveloping surface to consecutive positions of the auxiliary phantom rack $\mathscr{R}$. In that event, the auxiliary rack $\mathscr{R}$ rotates about the axis of rotation O_T of the gear-finishing tool, the machining surface of the gear-finishing tool is represented with a surface of revolution. The auxiliary rack $\mathscr{R}$ can perform a screw motion. In this case, the machining surface T of the gear-finishing tool is represented with a screw surface of axial pitch P_X. The axial pitch P_X is equal to $P_X = n \bullet p_X$. Here it is designated: p_X – pitch of the auxiliary rack teeth, and $n = \pm 1, \pm 2, \ldots$ – is an integer number. By the way, for the above-mentioned, the machining surface T is represented with the surface of revolution $n=0$. Due to this, a screw surface of the pitch $P_X = n \bullet p_X$ degenerates to the surface of revolution, for which $P_X = 0$.

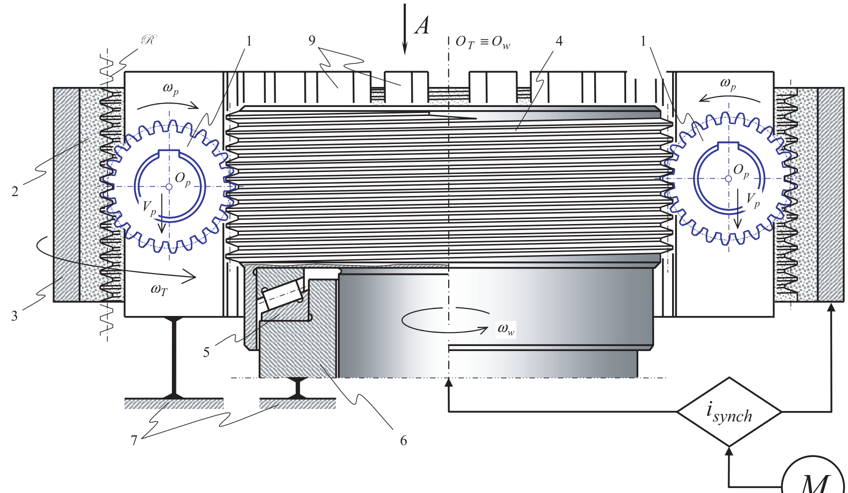


Figure 2 — To the concept of a method and apparatus for finishing modified pinion.

The angle Σ of crossing of the axes of rotation of the gear finishing tool O_T, of the driving worm O_W from one side and of the axes of rotation of the pinions to be finished O_P from another side, are synchronized in a certain way. Design of the gear-finishing machine could be simplified significantly if the crossed-axis angle Σ is equal to the right angle (see Fig. 2). In order to maintain the crossed-axis angle Σ equal to 90° , the proper synchronization of the pinion helix angle ψ_P and of the setting angles ζ_T and ζ_W (of the gear finishing tool and of the driving worm respectively) is required. The necessary synchronization of the angles ψ_P, ζ_T and ζ_W could be derived from the following fundamental relationship (Ref. 20):

$$d_{bT} = \frac{m Z_T \cos\alpha_T}{\sqrt{1 - \cos^2\alpha_T \cos^2\zeta_T}},$$

where d_{bT} – base diameter of the gear finishing tool
m – modulus
Z_T – number of starts of the gear finishing tool
α_T – normal pressure angle
ζ_T – setting angle of the gear finishing tool.

The similar relationship is valid to the driving worm, and the interested reader is referred to Ref. 20 for details about setting the angle of the gear-machining tool.

The driving worm 4 is installed inside the gear-finishing tool. The direction, or "hand" of the threads of the driving worm is opposite to the hand of the threads of the gear-finishing tool. The axis of rotation O_W of the driving worm aligns with the axis of rotation O_T of the gear-finishing tool (i.e., $O_T \equiv O_w$, see Fig. 2). The driving worm is rotating on bearing 5, which is installed on the support 6. The support 6 is rigidly connected to the gear finishing machine housing 7.

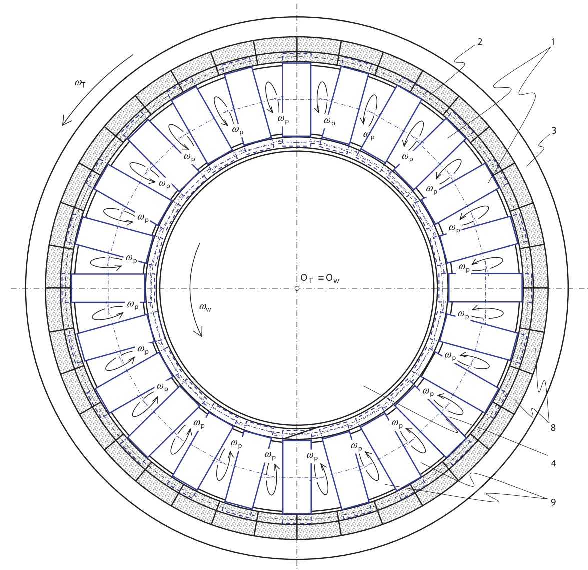


Figure 3 — Top view of the apparatus for finishing modified pinion.

The gear-finishing tool can be assembled with a certain number of cutting elements 8, which are uniformly distributed circumferentially inside the bandage 3 (Fig. 3). The bandage protects the gear-finishing tool from damage under the action of centrifugal forces while finishing pinions.

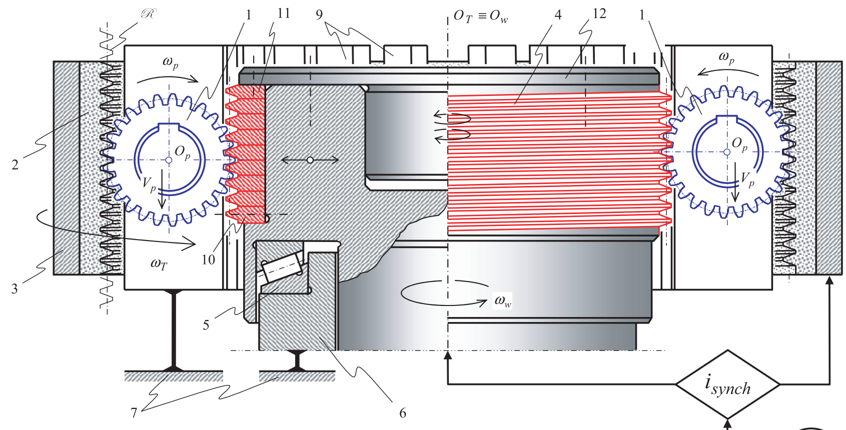


Figure 4 — Application of spring-like threads of the driving worm for feeding pinions onto the gear finishing tool.

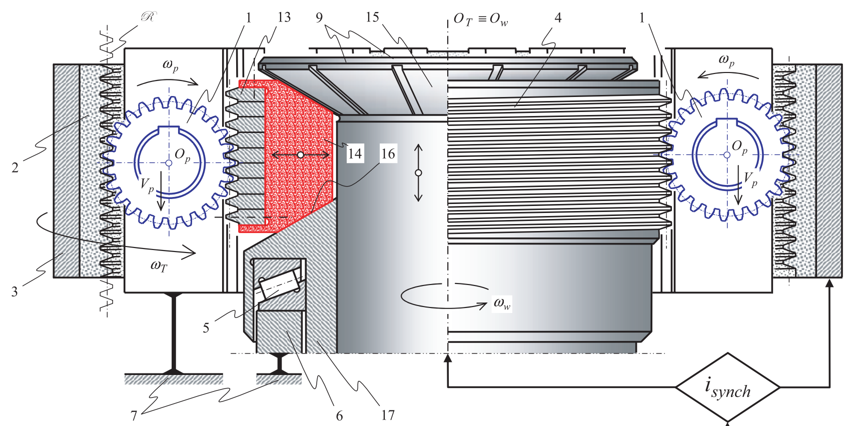


Figure 5 — A feasible way for increasing the stiffness of the spring-like threads of the driving worm.

The supporting screens 9 subdivide the room between the gear finishing tool and the driving worm into a number of chambers. While finishing, the pinion passes through the chamber. The supporting screens have planar working surfaces, and they are evenly distributed circumferentially inside the gear-finishing tool.

When finishing the helical gear, supporting screens with planar working surfaces can also be applied. A certain synchronization between the number of starts N_T of the gear finishing tool, and the number of starts N_W of the driving worm, their diameters, and their setting angles ζ_T and ζ_W is required in order to make feasible application of the supporting screens with planar working surfaces (Ref. 10). The proper synchronization of the above-mentioned parameters allows for avoiding the necessity of the application of support screens with the screw working surfaces. The axis of rotation O_p of the pinion must be at the right angle with the axis of rotation of the gear-finishing tool ($O_p \perp O_T$).

From the electric motor M, rotation is transmitted to the gear finishing tool and the driving worm. The gear-finishing tool is rotating with a certain angular velocity ω_T. The driving worm is rotating with the angular velocity ω_w. Rotation ω_w of the driving worm is synchronized with the rotation ω_T of the gear-finishing tool. The synchronization of rotations ω_T and ω_w depends upon the shape of the machining surface $_T$ of the gear finishing tool, and upon the number of starts of the gear finishing tool N_T and of the driving worm N_w. The machining surface $_T$ of the gear-finishing tool with shape of a surface of revolution can be considered as screw surface of number of starts N_T=0.

In a gear finishing operation, the pinion 1 is traveling through the chambers made by the gear finishing tool, the driving worm 4, and the supporting screens 9. The pinion is rotating about its axis O_p with angular velocity ω_p, and is moving along the axes $O_T \equiv O_w$ with a certain speed V_p. The pinion rotation ω_p is synchronized with the rotations ω_T and ω_w in a manner that allows for at least one complete revolution of the pinion while traveling through the chamber between the pinion supporting screens 9. Electrical or mechanical (gearbox) devices could be used for the synchronization (i_{synch}) of rotations ω_T, ω_w, and ω_p.

While finishing the modified pinion tooth surface, the gear-finishing tool quite naturally performs the required lengthwise modification of the pinion tooth surface. For computation of the parameters of design of the gear finishing tool that is required for finishing a pinion with a specified value of tooth surface modification, an advanced approach (Ref. 20) developed by the author could be applied.

The gear finishing operation can be performed simultaneously with gear deburring. In order to perform gear finishing during the deburring operation, it is required to provide the supporting screens with cutting edges. It is also convenient to orient the cutting edges in the direction parallel to the axis O_T.

Loading and unloading of the gear-finishing machine can be performed very easily. In order to load the pinions to be finished, a bunker (not shown in this article's figures) can be applied. Unloading the pinions could be performed by another bunker, which is also not shown in previous figures. The simplified loading/unloading of the gears into and out of the gear finishing machine results in easy automation of the gear finishing operation, which is critical for the mass production of gears for the needs of the automotive industry. This approach, which is similar to that listed previously (See Fig. 2, and Fig. 3), could be applied for the operation of enforcement of the pinion tooth surface-by-surface plastic deformation (Ref. 21).

In order to feed the pinions to be finished onto the gear-finishing tool, the threads of the driving worm 4 can be designed in the form of a spring (Ref. 22). One end 10 of the spring-like thread is rigidly connected to the body of the driving worm (Fig. 4). Another end 11 of the spring-like thread is rigidly connected to the ring 12. The ring 12 is installed onto the driving worm with the possibility of turning about the axis relative to the body of the driving worm. It can be fixed in a proper angular orientation relative to the body of the driving worm.

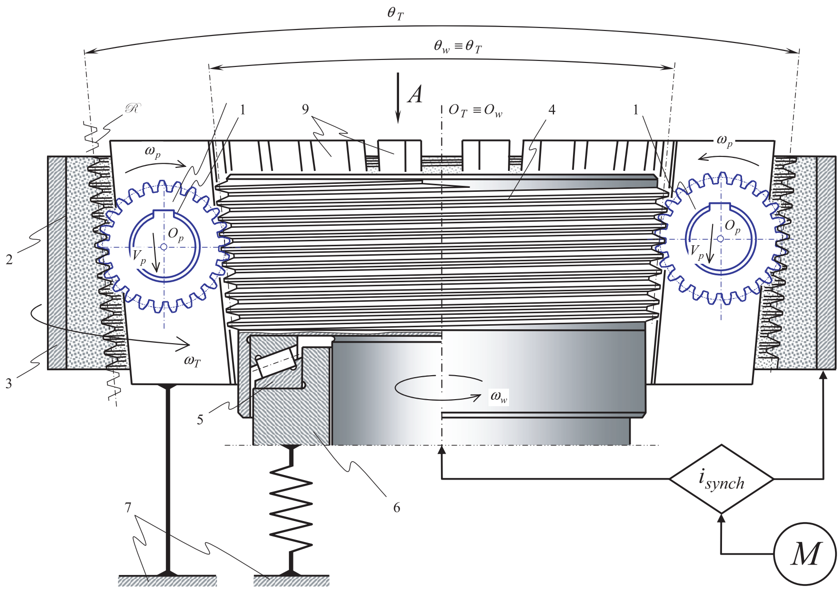


Figure 6 — To the concept of a method and apparatus for finishing modified pinion with conical gear finishing tool, and with the conical driving worm.

Turning the ring 12 relative to the body of the driving worm results in a change to the outside diameter of the spring-like threads. The diameter of the threads becomes smaller, or larger, depending on the hand of the threads of the spring-like threads, and upon the direction, the ring is turned in.

Each redressing of the worn gear-finishing tool causes an increase in the diameter of the grinding worm. In order to compensate for this change in the diameter of the gear-finishing tool, it is necessary to "unfix" the ring 12, to turn it about the axis O_w on a certain angle in the proper direction, and to fix it again in a new position that corresponds to the new required diameter of the gear finishing tool after redressing. The required changes in the diameter of the driving worm can be performing gradually, only from time to time, but another opportunity to control the diameter of the driving worm is also available.

In order to permanently control the value of diameter of the driving worm, the ring 12 can be connected to CNC. CNC performs gradual or permanent turning of the ring relative to the body of the driving worm, corresponding to the change in diameter of the gear finishing tool, and on the value of its wear while finishing pinions. The application of CNC makes the pinion finishing operation more fragile. Application of the spring-like threads of the driving worm is especially recommended for applications in the design of multi-thread gear finishing tools. The driving worm with the spring-like threads yields equal distribution of feeding forces in the axial direction of the gear finishing tool, and circumferentially. The approach, similar to that mentioned previously (see Fig. 4), could be applied for enforcement of the pinion tooth surface-by-surface plastic deformation (Ref. 23).

In order to increase the stiffness of the gear-finishing machine, the spring-like threads 13 of the driving worm can be supported by wedge-like supports 14 (Fig. 5). The wedge-like supports are evenly distributed circumferentially on the driving worm (Ref. 24). The top and bottom surfaces of the wedge-like supports 14 are inclined and make a certain angle with the axis of rotation O_w of the driving worm. These surfaces interact with the conical surface 15 of the body of the driving worm, and with the conical surface 16 of the lower support 17.

The body of the driving worm can shift up and down along the axis of rotation O_w of the driving worm. The lower support 17 remains motionless in the axial direction of the gear-finishing machine. The axial motion of the body of the driving worm results in the corresponding motion of the wedge-like supports 14 in a horizontal direction. Due to this, the diameter of the spring-like threads 13 changes in a suitable manner.

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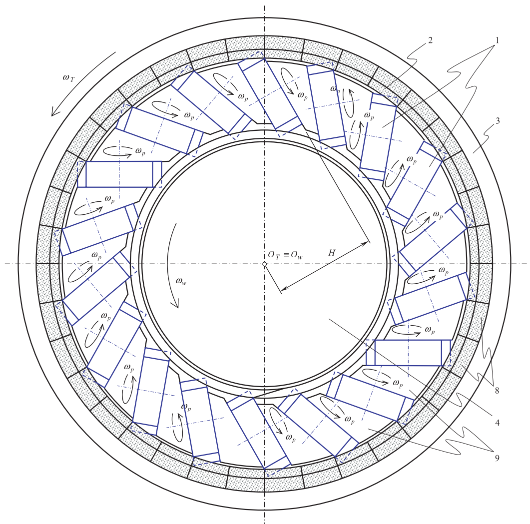


Figure 7 — Operation of chamfering of spur and helical gears.

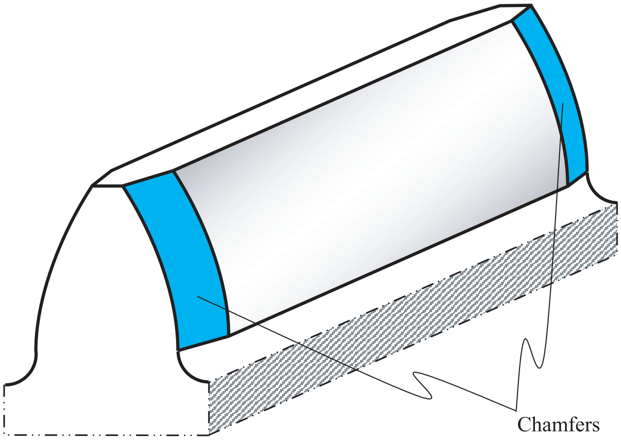
A change in the diameter of the spring-like threads 13 corresponds to the change in diameter of the gear finishing tool caused by wear, and due to the periodic redressing of the gear finishing tool. Shifting of the driving worm body can be performed gradually, or permanently from CNC. Again, the application of CNC makes the pinion finishing operation more fragile.

The pinion to be finished can be fed onto the gear-finishing tool with the application of the conical gear finishing tool and the conical driving worm. Both of these elements—i.e. the conical gear-finishing tool and the conical driving worm—can be generated with the same auxiliary phantom rack $\mathscr{R}$ (Ref. 25). The pitch cone angle θ_T of the gear-finishing tool (Fig. 6), and the similar pitch cone angle θ_w of the driving worm are equal to each other ($\theta_T \equiv \theta_w$). Shifting the conical driving worm up and down results in a change of width of the room for the pinion to be finished, and in such way feeds the pinion onto the gear-finishing tool. Again, the shifting of the driving worm body up and down can be performed gradually, or permanently from CNC.

In order to increase the productivity of the gear finishing operation, a multi-thread gear finishing tool and a multi-thread driving worm are recommended. The multi-thread gear finishing tool and the driving worm are longer in their axial direction. Thus, not one, but several pinions could be finished in each chamber simultaneously. Due to this, an immense increase in the productivity of the gear finishing operation is made possible.

Additional flexibility of the pinion finishing operation can be achieved by connecting the driving worm to the body of the gear-finishing machine not rigidly, but by means of an elastic

Figure 8 — Design of a chamfered gear tooth.



element—for example, by means of a spring 18 (Ref. 26). Application of the elastic element 18 yields a stabilization of force that feeds the pinion to the threads of the gear-finishing tool. In order to enhance the interval of change width of the room for the pinion to be finished, the axial pitch of the opposite sides of the thread profile of the driving worm and/or gear finishing tool can be made unequal to each other (Ref. 26).

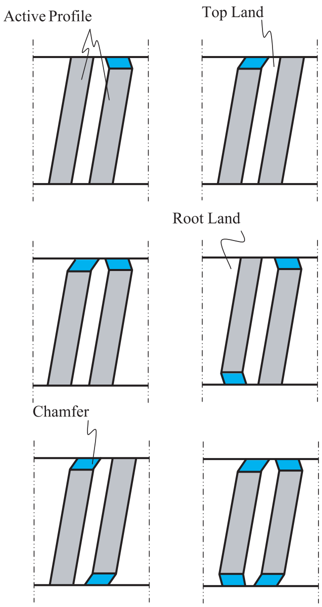
Center-Less Chamfering of Spur and Helical Gears

The gear chamfering operation is sometimes difficult to perform efficiently. The gear chamfering process is usually performed with a gear hob of special design (Ref. 14), and the productivity of this machining operation is usually low. It simply doesn't fit the needs of mass producing gears for the automotive industry.

The approach and apparatus previously described, which have been developed for finishing the crowned pinion, can be expanded to chamfering spur and helical gears. In order to machine chamfers, the supporting screens are made of an asymmetrical shape (Fig. 7). The application of supporting screens of an asymmetrical shape results in the pinion face at which the chamfer has to be machined shifting from the gear finishing tool axis O_g at a certain distance H. The parameters of design of the chamfer (Fig. 8) to be machined depend upon the distance H. By varying the distance H, any desirable chamfer angle and other parameters of the chamfer can be machined.

For chamfering both pinion faces, two consequent pieces of the gear finishing machine tool are required. Otherwise, after machining one face of the gear, it is required to return it for machining the opposite face in the same chamber, or in the similar

Figure 9 — Examples of design of a gear with chamfered tooth.



chamber, shifted opposite to the first one. The proposed approach allows for the pinion chamfering of any desirable design (Fig. 9).

The problems associated with chamfering spur and helical gears have long challenged both scientists and engineers alike. The method and apparatus reported in this article resolve this complicated engineering problem, and will be of practical value to gear manufacturers.

Conclusion

Several methods and apparatus for the center-less finishing of crowned gears have been reported in this paper. The examples listed (Ref. 19, 21-26, and many others not mentioned) clearly prove the feasibility of this process in the mass production of gears for the needs of the automotive industry. The finishing of crowned pinions can be performed simultaneously with chamfering of the pinion tooth at one and/or both sides. According to the proposed method, any desirable combination of chamfers can be machined. The feasibility and high productivity of chamfering is also made evident in this article. All of these methods and apparatus allow easy loading of the pinion and unloading them to a bunker. Easy loading/unloading of the pinions substantially simplifies the automation of the gear finishing operation, and the gear chamfering operation as well. Adopting these tools and processes could enhance productivity substantially, especially in applications supporting the mass production of precision gears for the automotive industry.

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REFERENCES

[1] Litvin, F.L., Zhang, J., Chaig, W.-S., Coy, J.J., Handschuh, R.F., "Crowned Spur Gears: Optimal Geometry and Generation", *Gear Technology*, September/October, 1988, pp.9-15.

[2] Pat. No. 3,046,844. (USA), *Method and Machine for Producing Crowned Teeth.*/E. Wildhaber, 1962.

[3] MAAG-Taschenbuch, 2nd edition Zurich, 1985, 727p.

[4] MAAG Information 18, *Topological modification*, Zurich.

[5] "Determining Lead Error on a Crowned Pinion," *Gear Technology*, July/August, 2000, pp.55-56.

[6] Flamang, P., "Design for Silence: New Concepts and Techniques for Industrial Gears," *Gear Technology*, September/October, 1999, pp.17-23.

[7] Oswald, F.B., Townsend, D.P., Valco, M.J., Spencer, R.H., Drago, R.J., Lenski, J.W., (Jr.), "Influence of Gear Design on Gearbox Radiated Noise," Gear Technology, January/February, 1998, pp.10-15.

[8] Stadtfeld, H.J., "What "Ease-Off" shows about Bevel and Hypoid Gears," Gear Technology, September/October, 2001, pp.18-23.

[9] Umezawa, K., "Low Vibration Design on a Helical Gear Pair," Gear Technology, January/February, 2000, pp.18-25.

[10] Radzevich, S.P., "Design of Shaving Cutter for Plunge Shaving of Topologically Modified Involute Pinion," ASME *J. of Mechanical Design*, Vol. 125, Issue 3, September 2003, pp.632-639.

[11] Pat. No. 6.112.611. (USA). *Gear with Modified Tooth Surface and Gear Tooth Surface Modification Method.*/H. Maki, Toyota, Japan. May 18, 1998 (May 20, 1997–Japan), 09/080,284, September 5, 2000, U.S. Cl. 74/462.

[12] Herbstritt, W.R., and Paluh, J.H., "Mill Spindle Advanced Gear Design", Association of Iron and Steel Engineers, 1998, 5p.

[13] Townsend, D.P., *Dudley's Gear Handbook: The Design, Manufacture, and Application of Gears, 2nd Edition*, McGraw-Hill, Inc., 1992, New York.

[14] Dudley, D.W., *Gear Handbook. The Design, Manufacture, and Applications of Gears, 2nd ed.*, McGraw-Hill, 1991, New York.

[15] *Modern Methods of Gear Manufacture*, 4th ed., National Broach & Machine Div, Lear Siegler, Inc., 1972, 159p.

[16] Dugas, J., "Gear Finishing by Shaving, Rolling & Honing – Part 1," Gear Technology, March/April 1992, pp.14-21.

[17] Litvin, F.L., *Gear Geometry and Applied Theory,* P T R Prentice Hall, 1994, 724p.

[18] Buckingham, E., *Analytical Mechanics of Gears*, Dover Publications, Inc., 1963, 546p.

[19] Pat. No. 921.727, (USSR), *A Machine Tool for Finishing a Crowned Gear.*/S.P. Radzevich. (Filed: September 26, 1980, Int. Cl. B23F 19/00).

[20] Radzevich, S.P., *Fundamentals of Part Surface Machining*. Monograph, Kiev, Rastan, 2001, 592p. [In Russian].

[21] Pat. No. 969.395, (USSR), *A Machine Tool for Finishing a Crowned Gear.*/S.P. Radzevich. Filed: April 16, 1981, Int. Cl. B21H 5/02.

[22] Pat. No. 984.744, (USSR), A *Machine Tool for Finishing a Crowned Gear.*/S.P. Radzevich. Filed: April 16, 1981, Int. Cl. B23F 19/00.

[23] Pat. No. 1.055.578, (USSR), A *Machine Tool for Finishing a Crowned Gear.*/S.P. Radzevich. Filed: November 6, 1981, Int. Cl. B21H 5/02.

[24] Pat. No. 1.110.566, (USSR), A *Machine Tool for Finishing a Crowned Gear.*/S.P. Radzevich. Filed: June 7, 1983, Int. Cl. B23F 19/00.

[25] Pat. No. 1.000.186, (USSR), A *Machine Tool for Finishing a Crowned Gear.*/S.P. Radzevich. Filed: November 6, 1981, Int. Cl. B23F 19/00.

[26] Pat. No. 1.028.450, (USSR), A *Machine Tool for Finishing a Crowned Gear.*/S.P. Radzevich. Filed: April 26, 1982, Int. Cl. B23F 19/00