PAPER • OPEN ACCESS

Research of grinding process of gears with involute profile to increase its efficiency

To cite this article: T N Ivanova et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. **327** 042046

View the article online for updates and enhancements.

Research of grinding process of gears with involute profile to increase its efficiency

T N Ivanova[1, 2], A I Korshunov[2], I N Sannikov[3], V N Tyukpiekov[3]

[1] Tchaikovsky Branch Perm National Research Polytechnic Institute, 73, Lenin St., Tchaikovsky, 617764, Russia
[2] FGBUN Institute of Mechanics, the Ural Branch of the Russian Academy of Sciences, 34, T. Baramzinoy St., Izhevsk, 426000, Russia
[3] Sarapul Polytechnic Institute (branch), Kalashnikov Izhevsk State Technical University, 8 Truda St., Sarapul, 427960, Russia

E-mail:tatnic2013@yandex.ru

Abstract. Grinding as final processing exerts great influence on quality and accuracy of a surface layer of gears. Gear grinding is the most productive method of abrasive processing providing gears of 3 - 8 degrees of accuracy. However violation of the temperature condition of grinding leads to emergence of burns on the surfaces of gears. Therefore the research of the reasons generating defects and finding the ways of their elimination are relevant. The work presents the research of involute tooth profile grinding by wheels of different types with different ways to form a surface. For every way the movements of a tool and a workpiece in order to receive a contour of the tooth socket are simulated. The advantages and the shortcomings of the tooth grinding using form wheels in a grinding method and using dish, worm wheels in generating the grinding method are revealed. The experience of gear production shows that availability of burns in the certain part of a tooth profile is caused by features of the gear grinding process. Theoretical and experimental researches of the thermal phenomena of gear grinding with different configurations of spots in a contact zone and a trajectory of their movement are conducted. There are recommendations how to choose grinding modes, characteristics of abrasive tools taking into account a non-burnt condition of a working surface of a gear. The right choice of lubricating fluid and the way of its supply greatly affect the efficiency of the gear grinding process. It is established that lubricating fluid with special additives gives the best results to obtain desired roughness of a processed surface. The recommendations of effective fluids and their foreign analogs are made.

1. Introduction
Gear grinding is the most productive method of abrasive processing providing gears of 3 - 8 degrees of accuracy.

   Gear grinding operations are classified according to [1-30]:
- the way of surface generation. There is a generating grinding method with continuous or discontinuous indexing and there is a form grinding method;
- the form of the used abrasive tool. Dish, cone, worm wheels work using the generating method and form wheels work using the form method.

2. Methods

Using the form grinding method, the grinding wheel shape copies the tooth socket shape. In processing, the abrasive wheel makes the rotational movement and sliding feed along the direction of a tooth. Depth feed is made periodically per table stroke or per double table stroke. The contact of teeth with a tool when processing happens along the tooth socket curve and is followed by large removal of metal. Each socket between teeth is processed separately. To grind the next socket, a workpiece is turned at a tooth pitch angle. Total gear processing is carried out at multiple passes. As the tool shape has to match precisely the tooth socket shape, the special tool is necessary for each gear design.

It is established that during consecutive grinding of a large number of teeth, there is a considerable wear of the tool per one pass, and as a result there are essential involute tooth profile errors. To decrease grinding wheel wear, it is recommended to turn a gear workpiece by several teeth.

It is reasonable to use the form grinding method in single-part production of large-size gears or in mass production of small straight-toothed and inclined toothed gears for external and internal gearing of 7 and 8 degrees of accuracy.

The most widely used grinding of involute gearing is the generating grinding method that profiles an exact gear form into the workpiece.

When using tools of dish-shaped profile, there are two ways of their setting on the grinder: with a tilt angle of a face surface or a tilt angle of a side surface of a rack. When setting grinding wheels with zero inclination of a face surface, they are moved apart at the distance equal to the general normal. In this case, the face planes of wheels will reproduce an involute profile of the tooth surface. Generation is carried out along the rolling circle. When setting a grinding wheel faces at an angle 15 … 20 ° to the vertical plane, the initial is the pitch line of gearing.

In both cases, grinding is carried out by two wheels receiving rotation from separate engines. The base cutting movement is made by the abrasive tool which carries out reciprocating feed along the processed tooth surface. The workpiece is rotated around its axis and translated along the imagined rack. The movements are coordinated in such way that rolling of a gear along the initial contour of a rack is modeled. After grinding of one tooth socket, the wheels are brought out of it, the workpiece turns at an angle equal or multiple to a pitch between teeth, i.e. the movement of indexing is carried out. To restore a profile and cutting capacity, the tool is exposed to periodic dressings on a rectilinear contour, which corresponds the profile of a gear rack. The way of processing is considered as the most accurate and allows receiving gears of 3 and 4 degrees of accuracy.

When grinding by using dish wheels, the area of the contact between the processed material and the tool is minimum. Therefore in comparison with other ways of gear grinding, this way provides the smallest thermal stress of the process. Using high-porous dish wheels grinding is possible without the use of lubricating fluid.

The processing by using a worm grinding wheel is carried out by continuous rolling of the cutting rack of the processed gear. The single thread worm profile with the rectilinear side generating line is applied on peripheries of the wheel modeling a profile of a direct edge rack. The worm wheel is engaged with teeth of the processed wheel. Indexing coincides with generating rotary motion of a workpiece and translational motion of the abrasive worm thread in the axial direction. When grinding by a worm wheel the spindle axis is in vertical position, in all other cases in horizontal. The worm wheel is made of the standard tool of a flat direct profile by generating with a diamond roll.

Worm wheel grinding provides high accuracy of a circular pitch and allows grinding serrations (0.2 – 0.5 mm). Tooth processing is carried out by the module from 7 to 1 mm on a previously cut groove. If the module is less than 1 mm, fluting is made from the whole workpiece. The accuracy of gear production by using worm wheels does not exceed 5 degrees of accuracy, but productivity is 4 - 5 times higher than when processing by using a dish wheel.

Havingidentical gear grinding modes (wheel speed, parts supply, and penetration depth), the material of the processed gear and other equal conditions, the largest productivity is reached using profiled wheels in comparison with dish-shaped ones. It is due to the size of the contact area of the

grinding wheel and the tooth surface. The profiled wheel, using the form grinding method, processes simultaneously the whole tooth socket surface. When grinding with the generating grinding method, processing is conducted using the narrow cutting edge. Respectively, the cutting capability of a wheel in the first case is higher than in the second one. When shaping, using the generating grinding method, the highest cutting capability is reached using worm grinding wheels. The machine-tools provide the most 2 - 4 degrees of accuracy of the processed gears working with one disk wheel that is explained by the shortest kinematic chain of coordination of movements. But productivity in this case will be the smallest.

Grinding straight bevel gears of 5 and 6 degrees of accuracy is carried out using one or two dish wheels. When processing by using one wheel, grinding of each side of teeth is carried out separately. In mass production, it is reasonable to make these operations using two machine-tools: one machine-tool grinds one side of a tooth, and another one grinds the second.

When grinding teeth irrespective of the type of applied wheels, great demands are made on quality of a surface. Therefore the projected grinding modes and the chosen characteristics of abrasive tools have to guarantee lack of burns, changes of the structure and microhardness of the processed surface. It is noticed that violation of temperature condition of grinding independent of the type of the applied wheels leads to emergence of burns on gear surfaces and harmful residual tensile stresses. Therefore the research of the thermal phenomena during gear grinding with various configurations of spots of a contact zone and the trajectory of their movement are actual [1-30].

The general formula of calculation of the temperature in a zone of gear profile grinding will be [19, 22]:

$$Q_c - Q_0 = \frac{q}{2}\sqrt{\frac{2\pi h}{\lambda \gamma C V}} \,, \qquad (1)$$

where Q_c – the temperature in a contact zone; Q_0 – the initial temperature of a part; q – the density of a thermal stream; λ – the heat conductivity factor of the material a part is made of; γ – the specific weight of a part; C – the specific heat capacity of the material of the processed part; V – wheel speed; $2h$ – width of the cutting edge.

For example, when grinding gears using a worm abrasive wheel, let us take the density of thermal stream q and a tangential component of cutting force Pz, carried to one side of a tooth as following:

$$q = \frac{P_z V_w}{JS} \text{ and } P_z = 6{,}2 s_r^{0.8} s_t^{0.2} m \qquad (2)$$

where V_w – the circumferential speed of a worm grinding wheel on major diameter; J – mechanical equivalent of warmth; S – the area of a contact spot of a side surface of an abrasive worm thread of a grinding wheel with a tooth profile; m – the module of the ground gear; s_r – radial in feed; s_t – table feed.

After substitution of expressions (2) in (1), one will receive the temperature in a zone of gear grinding by using a worm abrasive wheel:

$$Q = \frac{4 \cdot 10^4 s_r^{0,6} s_t^{0,2}}{\left(27 s_r^{0,5} + s_t\right)\sqrt{\lambda \gamma \tilde{N}}} K_D K_Z K_m K_n \qquad (3)$$

where K_D, K_Z, K_m, K_n – the experimental coefficients considering respectively the change of the diameter of a grinding wheel at wear D, numbers of teeth z, module m and frequency of rotation of wheel n.

The distribution of temperature in depth when grinding by using a worm wheel can be calculated by a formula:

$$Q_y = \frac{4 \cdot 10^4 s_r^{0.6} s_t^{0.2}}{\left(27 s_r^{0.5} + s_t\right)\sqrt{\lambda \gamma C}} K_D K_Z K_m K_n \times \left[1 - erf\left(\frac{x}{2}\sqrt{\frac{mn\gamma C}{28\lambda\sqrt{r_0 s_r}}}\right)\right] \,, \qquad (4)$$

where r_0 – the radius of the rolling circle; x – the occurrence depth of changed structures of the ground surface.

The results of calculation for expressions (3, 4) allow determining temperatures, both on the ground gear profile surface, and at various depths that will give the chance to determine the depth of a defective layer (burns).

In surface, the layers of gears made of tempered steel during the grinding process above critical point As_3 there are transformations of the initial structure of martensite into austenite. The rate of cooling of the ground surface can reach 5000 – 6000 degrees per second that considerably exceeds critical temperature of 300 degrees per second necessary to transform austenite into martensite. In this regard, when the processed surface leaves the grinding zone, the layer of martensite of the repeated strengthening is formed. Therefore, let us take the depth of penetration of phase transformation temperature as the depth of a burn of repeated strengthening.

For example, at t = 0.03 mm / pass, n = 1200 rpm, s_{pr} = 1.5 mm / rev., m = 3 mm, z = 30, D = 300 mm, material of a part 3415 (12X2H4A Russian State Standard (GOST)), a wheel E9A10SM2K10 (Russian State Standard (GOST)), one will receive, according to (3), maximum temperature Q = 1000 °C in a contact zone of a gear using a worm wheel. According to experimental studies, temperature of phase transformations for steel 3415 (12X2H4A Russian State Standard (GOST)) is 800 °C, then using expression (4) it is possible to determine depth x = 0.013 mm of a defective layer, i.e. at this depth there is a burn of repeated strengthening, and at a temperature of 500 °C the depth of a defective layer will be 0.037 mm, at the same time there is a burn of temper.

As a result of the researches, it is established that if the speed of heating of a gear surface layer by using a worm wheel depending on the modes is increased to 30 000 degrees per second, then the critical point of structural transformations is displaced towards smaller values of temperatures.

It is noticed that when grinding gears of internal gearing using a profile wheel, the burns appear on a tooth tip, and using wheels of external gearing it happens in a zone of a fillet curve. Gears with destruction of teeth using a form grinding method in a transitional zone aren't serviceable.

To decrease probability of formation of burns when grinding hard surfaces of parts, processing is carried out using soft wheels. The type and the size of a grinding wheel are chosen according to the model of the machine-tool and the sizes of a gear. The choice of abrasive material depends on the material of a workpiece [1 – 30].

For example, when grinding alloys based on iron and nickel it is reasonable to use white electrocorundum brand 24A, 25A (Russian State Standard (GOST)). Identical temperatures in a zone of grinding can be received when using dish wheels of type 14 with hardness R, disk wheels of type 1 hardness O– N.

Ceramic bond is recommended as it holds grains from extraction and at the same time allows profiling a wheel. The application of Bakelite bond is possible. Here are the basic principles to choose granularity: with the increase in granularity, the roughness of the processed surface increases; and with the decrease in granularity, the probability of emergence of grinding burns increases.

It is also necessary to consider that with the reduction of the module the absolute value of the tolerance decreases, therefore requirements to wear resistance of the tool increase. Other things being equal, the dimensional wear resistance of the tool increases with the reduction of granularity, then with the reduction of the module it is desirable to use wheels of smaller granularity (tab. 1).

Setting the grinding modes starts from the wheel speed 25 - 35 m/s. It is necessary to carry out the first rough passes with bigger values of depth feed and a gradual reduction to 0.03 – 0,04 mm. Finishing pass feed decreases to 0,01 – 0,02 mm when grinding by using the generating grinding method and 0.01 – 0.03 mm by using the form grinding method. Depth feed when grinding by using the generating grinding method is determined in radial direction, and when grinding by using the form grinding method it is determined by a normal to a tooth profile. The less the value of roughness parameter, the smaller the value of feed. The number of passes increases with the reduction of the module and the diameter of a wheel.

Table 1. Characteristics of grinding wheels

Wheel type	Module, mm	Characteristics of wheels		Degree of accuracy
		Granularity	Degree of hardness	
	0.2 – 0.4	M40	L - O	4, 5
	0.5 – 0.7	F280	K - L	4, 5
1	0.8 – 0.9	F220	J - K	3, 4
	1.0 – 1.5	F180	J - K	3 ,4
	1,5 – 10	F120, F90 – F46	K - L, J - K	3 – 6
12, 14	1.5 – 12	F90 – F46	J - K	3 – 5

Selecting the grinding modes and characteristics of wheels, it is possible to influence the amount of the released heat in a contact zone. With the increase of wheel speed and movement of a part, the amount of the released heat increases. However, if one limits time of action of a source on the processed surface, then there is the decrease in temperature of grinding in a contact zone. The increase of cross feed and cutting depth leads to the temperature increase. But the higher heat conductivity of material of a part and a grinding wheel, the less the probability of the emergence of burns. The application of porous wheels due to the decrease in friction, the best placement of waste of grinding in interstices of a wheel and self-sharpening of grains of a wheel lead to the decrease in temperature in a contact zone and to a non-burnt condition of a surface. It is experimentally proved that high-porous wheels are recommended to be applied when grinding steels, containing large amount of chrome, vanadium, and cobalt.

The right choice of lubricating fluid and its supply greatly influence the gear grinding process efficiency. It is established that oil lubricating fluids with special additives give the best values of roughness of the processed surface [20, 21]. The result of lubricant action while gear grinding is the reduction of friction of a couplant, metal particles and waste of grinding which have stuck to a working surface of a grinding wheel and in preventing loading while grinding. To implement effectively these functions fresh lubricating fluid has to be supplied continuously and in large volume onto the working surface of a grinding wheel and onto the surface of the ground part, creating strong protective films on them. The efficiency of lubricant action is defined by physical and chemical properties of lubricating fluid. The fluids possessing optimum combination of lubricant properties and penetration will be the most efficient and will provide the high thermomechanical durability of a lubricant film and good moistening of the metal surface and the working surface of a grinding wheel. For example, water-mix cutting fluids such as a molybdenum disulfide, animal or vegetable oil antiscore lubricant or haloid – sulpha - phosphoprous-containing additives of ISE-25 brands, 20% solution of mineral LZ-SOZh-2MO oil Energol GF 55, GFS 80, Grinding Oil 40), MP-1y (Energol CFC, Dortan 37), MP-2y (Dortan 53, Macron Oil C), MP-3 (Mobilmet 25, Schell Garia Oil T) , MP-8 (Mobilmet 455), MP-99 (Mobilmet 29, Sevora 46), OCM-5 (Dortan 32, Supraco 502, 503, 504.

Thus, the paper describes the researches of grinding of an involute tooth profile by using wheels of different types with various ways of surface generating. For each way, the movements of a tool and a workpiece in order to receive the tooth socket curve are simulated. The advantages and the shortcomings of tooth grinding, using profiled wheels by the form grinding method and using dish and worm wheels by the generating grinding method providing gears of 3 - 8 degrees of accuracy, are revealed.

3. Conclusion

The experience of production of gears shows that the existence of burns in a certain part of a tooth profile is caused by the features of the gear grinding process. Therefore theoretical and experimental researches of the thermal phenomena during gear grinding with various configurations of spots of a contact zone and the trajectory of their movement are conducted. The recommendations how to choose grinding modes, characteristics of abrasive tools taking into account non-burnt condition of a gear working surface are made.

The right choice of lubricating fluid and its supply greatly influence the gear grinding process efficiency. It is established that oil lubricating fluids with special additives give the best values of roughness of the processed surface. The recommendations of effective fluids and their foreign analogs are made.

References

[1]   Russian research institute of standardization and certification in mechanical engineering 1986 *Abrasive materials and tools* (Moscow: VNINMASH)

[2]   Evseev D G 1978 *Formation of properties of a surface layer at abrasive processing* (Saratov: publishing house Saratov state university)

[3]   Medvedev V I, Volkov A E, Volosova M A 2015 Mathematical model and algorithm for contact stress analysis of gears with multi-pair contact *Mechanism and Machine Theory* **86** 156-171

[4]   Goldfarb V I, Trubachov E S, Kuznetsov A S 2006 Load distribution in statically loaded spiroid gear *Proceedings on the 2nd International Conference "Power transmissions 2006"* (Novi Sad, Serbia & Montenegro) pp 369-376

[5]   Akimov V V, Lagutin S A, Volkov A E 2007 New approach to the local synthesis of spiral bevel gears *Proceedings of the 10th Int. ASME Power Transmission And Gearing Conference* (Las Vegas, Nevada, USA) pp13-17

[6]   Lebek A O, Radzimovsky E I 1970 The synthesis of profile shapes and spur gears of high load capacity *Trans. ASME* **B 92 #3** 543-551

[7]   Babichev D A, Serebrennikov A A, Babichev D T 2011 Qualitative indexes of flat engagements operation *Proceedings The 7th international Conference Research and Development of mechanical Elements and Systems* (Zlatibor Serbia) 623-630

[8]   Ivanova T N, Belyakova A F, Sannikov I N 2012 The research of influence of chemical composition and structure of hard-to-machine steel on workability when grinding *Natural and technical science* **3 (59)** 165-172

[9]   Ivanova T N, Dolganov A M 2007 *The modern equipment in technology of diamond face grinding of flat surfaces* (Yekaterinburg - Izhevsk: Publishing house of Institute of Economy OURO RAHN)

[10] Lopatin B A , Tsukanov O N 1999 Design cylindrobevel gears in generalizing parameters *Gearing and Transmissions* **2** 24-35

[11] Syzrantsev V N, Yerikhov M L 2000 Novikov-wildhaber gearing. New methods of geometrical analysis, Technology of manufacturing and control. Experimental studies of load capacity and service life *Gearing and Transmissions* **1** 29-37

[12] Sobolev A N, Nekrasov A Y, Arbuzov M O 2017 The modeling of noncircular gears *MSTU «STANKIN»* **1(40)** 48-51

[13] Ivanova T N, Dolganov A M. 2013 *Improvement of technology of grinding of flat surfaces with nonconventional cooling.* (Saarbrücken, Germany: LAP LAMBERT Academic Publishing)

[15] Atanasiu V, Leohchi D 2010 Evaluation of engagement accuracy by dynamic transmission error of helical gears Mechanisms *and Machine Science* **5** 421-428

[16] Goldfarb V I, Kuniver A S, Koshkin D V 2000 Investigation of spiroid gear tooth tangency under action of errors *Proc. of Intern. Conference "Gearing, Transmissions & Mechanical Systems"* (Nottingham) 99-108

[17] Goldfarb V I, Isakova N V 1995 Variants of spiroid gearing from pitch realisation point of view Gearing *and Transmissions* **1** 25-34

[18] Maslov L. 1974 *Theory of grinding* (Moscow*:* Mechanical engineering)

[20] Orobinsky V M 2000 *Abrasive methods of processing and their optimization* (Moscow: Mechanical engineering)

[21] Sipaylov V A 1978 *Thermal processes when grinding and quality management of a surface* (Moscow: Mechanical engineering)

[22] Entelis S G, Berliner E M 1995 *The lubricant cooling technological means for processing of metals cutting* (Moscow: Mechanical engineering)

[23] Khudobin L 1971 *In the Lubricant cooling means applied when grinding* (Moscow: Mechanical engineering)

[24] Yakimov A V 1975 *Grinding process optimization* (Moscow: Mechanical engineering)

[25] Reznikov A N 1981 *Thermophysics of processes of machining of materials* (Moscow: Mechanical engineering)

[26] Volkov D I 2012 Finite-difference calculation of the temperature in belt grinding *Russian Engineering Research* **32 3** 296-298

[27] Kozlov A M 2005 Model-based determination of the parameters of the working surface of an abrasive tool *Proceedings of Institutions of Higher Education* **1** 51-55

[28] Barsukov G V, Vainer L G, Vasilenko Yu V, Kozlov A M 2011 *Modeling of technological processes of abrasive machining* (Moscow: Spectr)

[29] Nosenko V A 2013 *Technology of metal grinding* (Stary Oskol: TNT)

[30] Podzei D V 1973 *Technological residual stresses* (Moscow: Machine-building)