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An adaptive parameter optimization model and system for sustainable gear dry hobbing in batch production†

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Abstract

Gear hobbing technology is one of the most widely used forming processes of gear teeth. And the development of dry hobbing technology provides a solution for realizing productive, economical, and ecological gear production. Since there is no cutting oil for cooling and lubrication in dry hobbing process, the hob tool life, thermal deformation errors of machine tool, and quality of workpiece are sensitive to the cutting parameters, especially the cutting speed and tip chip thickness. Considering this situation, a dry hobbing parameters optimization model with the hobbing efficiency as our objective, and the hobbing cost per piece, gear quality, tact time as constraints was established, in which the cutting speed and tip chip thickness were considered as optimal variables and the material of workpiece, coating of hob, and feed rate were considered comprehensively. An iterative test method is proposed to solve this model. And for the application in automated production line, an online adaptive application system was also developed based on SINUMERIK 840D NC system. The parameters of five different kinds of material gear were optimized by applying this model and system, and the result showed the model and the system were practical.

Keywords: Dry hobbing; Parameters optimization; Target cost; Adaptive system

1. Introduction

Environmental pollution problems have attracted strong attention around the world, and sustainable development is becoming a common choice of the world economic development, which is called sustainable manufacturing in industry [1]. According to Pusavec et al. [2] lower machining costs, environmental-friendliness, minimum energy consumption, waste reduction, and personnel health can be identified as the hallmarks of sustainable manufacturing. A gear is one of the basic mechanical components for transmission of motion and power to keep machines, instruments and equipment operational. Gear manufacturing industry plays an integral role in many industrial segments [3]. And hobbing is considered the most common process for gear teeth forming process in batch production due to its high productivity. In the past years, gear hobbing was running at low cutting speed, and lubricated and cooled with oil, which polluted the shop floor and was harmful to the operator's health. With the development of tool coating and servo-driving technology, dry hobbing technology was realized and provided sustainable gear machining solution. Dry-hobbing not only dramatically improves environmental issues by eliminating the need of cutting fluids and wet-chip disposal, but also effectively improves the machining efficiency and reduces the manufacturing cost by ensuring operation at high cutting speed and with minimum power consumption [4]. However, since there is no cutting oil for cooling and lubrication in dry hobbing process, the hob tool life, thermal deformation errors of machine tool, and quality of workpiece are sensitive to the cutting parameters, especially the cutting speed and the tip chip thickness. Due to this situation, it is always difficult to choose the cutting parameters, especially when the cutting conditions changed.

From the literature, significant work has been done to optimize cutting parameters based on machining science, economic considerations and energy consumption. Li [5] presented a multi-objective optimization approach, based on Back propagation neural network (BPNN), to optimize the cutting parameters in sculptured parts machining, with the machining time, energy consumption and surface roughness as objectives. Yan [6] proposed using weighted grey relational analysis and RSM to solve the multi-objective optimization of milling parameters, and used Taguchi design method to verify the method, with considering the trade-offs between energy, production rate and cutting quality. However, the above-

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mentioned optimization methods of cutting parameters did not involve the dry hobbing process.

For dry hobbing process, recent works began to study the process simulation method, wear principle of hob, chip formation and thermal deviations. Dong [7] built a three-dimensional finite element model to analyze thermo-mechanical conditions on the tools and the workpieces during gear hobbing process. Chen [8, 9] proposed a machine thermal deformation error modeling method based on homogeneous coordinate transformation principle for high-speed dry hobbing machine and built a model to obtain the geometry and thickness of the chip corresponding to each cutting edge with numerical method by discretization in dry hobbing. Kadashevich [10] proposed a simulation approach to determine thermally induced geometric deviations in dry gear hobbing. Klocke [11] developed a dry hobbing simulation model to calculate the workpiece quality including geometry and topography. Cao [12] identified the features of workpiece thermal deformation errors and developed an error compensation model to compensate both machine tool thermal errors and tooth thickness errors in dry hobbing process.

But there are few studies that consider the cutting parameter optimization method for dry hobbing process. Cao [13] presented a hybrid Improved back propagation neural network/Differential evolution (IBPNN/DE) approach to do a continuous optimization decision making of process parameters in high-speed gear hobbing. Thus, the parameter optimization method for dry hobbing process needs to be much more researched.

In gear batch production, optimizing hobbing parameters is the guarantee of high production efficiency and low cutting cost. However, hobbing parameters are influenced by the cutting conditions, such as performance of the machine tool, coating of the hob, tensile strength of the workpiece, and the rigidness of fixtures. Considering this situation, we first developed the calculation method of basic and key technology parameters based on the dry hobbing technological system. Then an adaptive parameters optimization model for gear dry hobbing technology with high hobbing efficiency as objective was established and an online adaptive application system was also developed based on SINUMERIK 840D system. Finally, we proposed a case study of the application for five different kinds of materials gear production to test the optimization model and system.

2. Dry hobbing technology

2.1 Dry hobbing technological system

Dry hobbing is a complex process which contains many relevant technological parameters, so that the relevant calculation method is complicated. Before attempting to improve the efficiency or decrease the cost in dry hobbing process, an analysis should be made of the dry hobbing technological system to identify the influential factors. The dry hobbing technological system is described in an Ishikawa chart (see Fig. 1) which contributes to a deeper understanding of the correlation between the optimization of the technological parameters and the consequences on gear quality, hobbing efficiency, tool life and hobbing cost.

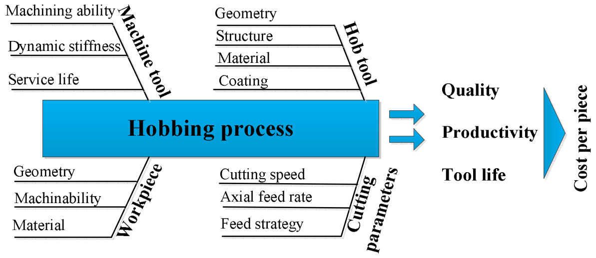


Fig. 1. System analysis of gear dry hobbing technology.

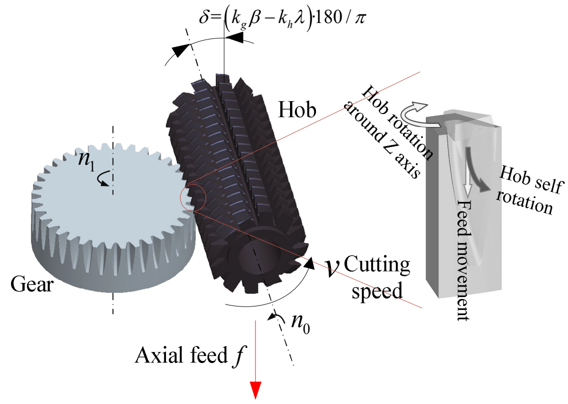


Fig. 2. Principle of dry gear hobbing process.

2.2 Calculation method of basic parameters in dry hobbing technology

According to the Ishikawa chart for the dry hobbing technological system and the principle of dry hobbing process, as shown in Fig. 2, dry hobbing process parameters include workpiece geometry parameters, hob geometric parameters, technological parameters of dry hobbing machine tool, and cutting parameters like axial feed, feed rate, cutting speed, and spindle rotation speed. The symbols of various parameters are shown in the nomenclature. The relationship between some of these parameters which may be used in the follow-up parameters optimization system is shown in Table 1.

3. Calculation model of key parameters in dry hobbing

3.1 Hobbing efficiency

In gear batch production, hobbing efficiency is the key optimal objective. To improve the hobbing efficiency, the cutting time needs to be reduced as much as possible. The cutting time of a dry hobbing process including material removing time and auxiliary time, auxiliary time is mainly related to the

Table 1. Calculation formula for gear hobbing process parameters.

Parameters name	Calculation formula
Tip diameter of gear (mm)	$d_{a1} = m_n z_1 / \cos\beta + 2h_a^* \cdot m_n$
Lead angle of hob (°)	$\lambda = k_h \cdot \arcsin(z_0 \cdot m_n / d_{a0})$
Installation angle of hob (°)	$\delta = (k_g \beta - k_h \lambda) \cdot 180 / \pi$
Cutting depth (mm)	$a_p = (2h_a^* + c^*) \cdot m_n$
Axial feed rate (mm/min)	$F = 1000 f z_0 v / (\pi d_{a0} z_1)$
Rotating speed of spindle (r/min)	$n = 1000 v / (\pi \cdot d_{a0})$

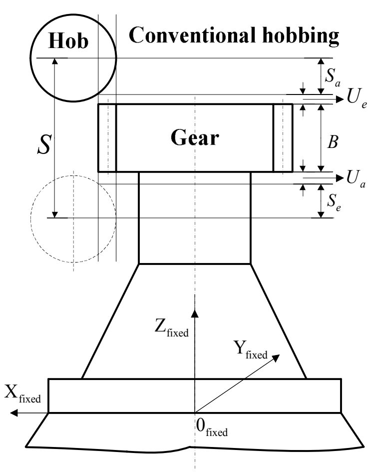


Fig. 3. The axial movement of hobbing process.

automaticity of machine tool so that it can be regarded as a fixed value in the same type machine tool. So, when evaluating the hobbing efficiency, the material removing time is only considered. Dry hobbing process is mainly suitable for machining small or medium module gear, which only need to the feed once in radial direction of workpiece. The axial stroke of hob tool movement is shown in Fig. 3. And the material removing time tm can be calculated by Eq. (1).

$$t_m = S / F \,, \tag{1}$$

where S is axial stroke $S = S_a + U_e + B + U_a + S_e$

F is axial feed rate $F = 1000 f \cdot z_0 \cdot v / (\pi \cdot d_{a0} \cdot z_1)$

S_a is lead length of the hob.

For spur gear $S_a = \sqrt{d_{a0} \cdot h}$.

Helical gear $S_a = \sqrt{[(d_{a0} + d_{a1})\tan^2\delta + d_{a0}]h}$,

U_e is safe distance for approach, $U_e = 2$ mm.

U_a is safe distance for exiting, $U_a = 2$ mm.

S_e is exiting stroke, $S_e = 1.25 m_n \cdot \sin\delta / \tan\alpha$.

Helical gears are taken as calculation object in this paper, so the material removing time for helical gear can be calculated by Eq. (2).

$$t_m = \frac{\sqrt{[(d_{a0} + d_{a1})\tan^2\delta + d_{a0}]h} + 1.25 m_n \cdot \sin\delta / \tan\alpha + B + 4}{1000 f \cdot z_0 v / \pi d_{a0} z_1} \,. \tag{2}$$

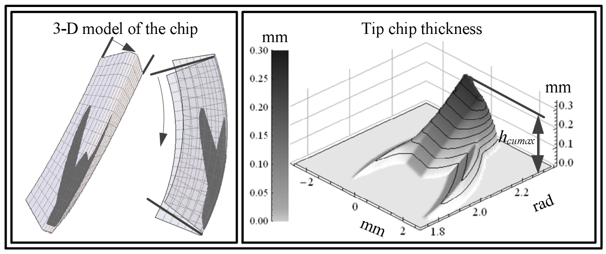


Fig. 4. Tip chip thickness of dry hobbing process.

3.2 Tip chip thickness

The tip chip thickness is the theoretical maximum chip thickness removed by the tips of the hob teeth. The tip chip thickness is one of the key parameters regarded as a criterion for hob stress. High tip chip thickness means high cutting forces and short tool life as demonstrated in Ref. [14]. Hoffmeister established the empirical formula to calculate the tip chip thickness by large number of experiments as shown in Eq. (3). Up to now, this formula has been widely applied to determine the axial feed in production [15]. But when considering the numerical control program for hobbing, the feed rate f is needed. If the tip chip thickness is determined, the axial feed f can be calculated out by Eq. (4).

$$h_{cu\max} = 4.9 \cdot m_n \cdot z_1^{(9.25 \cdot 10^{-3} \cdot \beta - 0.542)} \cdot e^{-0.015 \cdot \beta} \cdot e^{-0.015 \cdot x} \cdot \left(\frac{d_{a0}}{2m_n}\right)^{-8.25 \cdot 10^{-3} \cdot \beta - 0.225} \cdot \left(\frac{n_i}{z_0}\right)^{-0.877} \cdot \left(\frac{f}{m_n}\right)^{0.511} \cdot \left(\frac{a_p}{m_n}\right)^{0.319} \tag{3}$$

$$f = \left[\frac{\frac{1}{4.9 m_n} \cdot h_{cu\max} \cdot z_1^{(0.542 - 9.25 \cdot 10^{-3} \cdot \beta)} \cdot e^{0.015 \cdot \beta} \cdot e^{0.015 \cdot x}}{\cdot \left(\frac{d_{a0}}{2m_n}\right)^{8.25 \cdot 10^{-3} \cdot \beta + 0.225} \cdot \left(\frac{n_i}{z_0}\right)^{0.877} \cdot \left(\frac{a_p}{m_n}\right)^{-0.319}} \right]^{1.957} \cdot m_n \,. \tag{4}$$

Because the Hoffmeister equation is carried out from the wet hobbing process, the applicability in dry hobbing needs to be validated. Chen [11] developed software to simulate the dry hobbing process, by which the 3-D digital model of the undeformed chip is visual and the tip chip thickness also can be calculated, as shown in Fig. 4. The simulation results of the 3-D model are almost the same with the calculation results of the Hoffmeister equation, which validates that Hoffmeister equation can also be used to calculate the tip chip thickness for dry hobbing.

In this paper, Eq. (3) is used to calculate the tip chip thickness, because the FEM (3D) simulation model is difficult to be

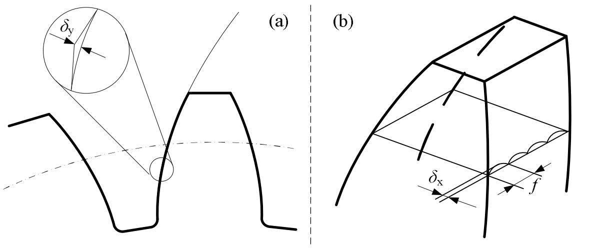


Fig. 5. Generating cut deviations δy and feed marking deviations δx.

integrated into the numerical control system and the Hoffmeister equation is widely used in this area [16].

3.3 Gear quality

The gear quality, which is one of the most important indexes during dry hobbing, is determined primarily by the accuracy of hobbing machine, the quality of the hob, stable clamping of the workpiece and so on. These influencing factors are difficult to quantify and always can be considered unchanged when cutting the gear on the same machine tool. But the process-related shape deviations which result from the kinematics of the hobbing process are always different if the technology parameters are changed. So, to optimize the technological parameters, the shape deviations must be checked in the optimal model. In dry hobbing, as shown in Fig. 5, the deviations are separated into feed mark deviations δ_x and generated cut deviations δ_y which can be calculated by Eqs. (5) and (6). For dry hobbing, both are recommended less than 0.5 um [17].

$$\delta_x = (\frac{f}{\cos\beta})^2 \cdot \frac{\sin\alpha_n}{4 \cdot d_{a0}} \tag{5}$$

$$\delta_y = \frac{\pi^2 \cdot z_0 \cdot m_n \cdot \sin\alpha_n}{4 \cdot z_1 \cdot n_i^2} . \tag{6}$$

3.4 Hobbing cost

Lower machining cost is one of the most important hallmarks for sustainable manufacturing. When considering the hobbing cost, the hobbing cost per piece must be chosen which can eliminate the influence of the number of machined workpiece. The cost in dry hobbing process contains hob tool cost and machine tool cost, which are both heavily influenced by hobbing parameters. The cost for machine tool equipment belongs to the depreciation cost, which is influenced by the cutting efficiency. The machine tool equipment cost of a single gear is positively correlated with the production efficiency; the tool cost of a single gear is usually negatively correlated with the production efficiency. Because, usually, a higher machining efficiency means higher cutting parameters, which would lead to a shorter hob tool life and higher tool cost per piece. The hobbing cost of a single gear can be calculated by Eq. (7).

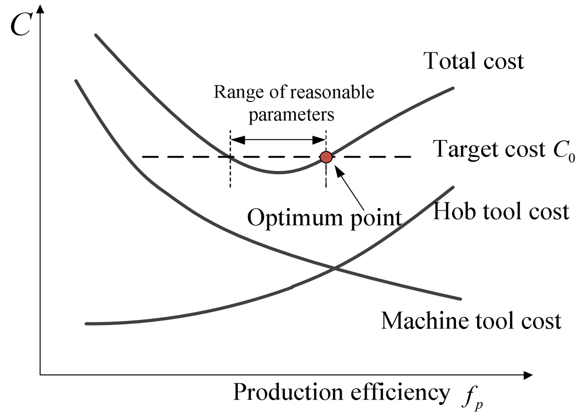


Fig. 6. The relationship between hobbing cost and production efficiency.

$$C = C_m \cdot (t_m + t_f) + \left[C_{t0} + k \cdot (C_1 + C_2)\right] \big/ \left[(k+1) \cdot N\right] , \tag{7}$$

where *C is the* hobbing cost per piece, C_m is depreciation cost of machine tool in unit time, t_f is non-cutting time, C_{t0} is the hob tool purchase cost, *k is* number of times of regrinding and recoating of hob, C_1 is single regrinding cost, C_2 is single recoating cost, *N is the* number of machined gears per regrinding/recoating of hob.

If the cutting parameters are increased, on the one hand, material removal rate is improved, thus production efficiency is improved. And then the cutting time is decreased, so the depreciation cost of machine tool is decreased. But, on the other hand, the hob tool wears faster, which leads to a shorter tool life and higher tool cost. The complicated relationship between machine tool cost, hob tool cost, total cost of a single gear and production efficiency is shown in Fig. 6.

4. Dry hobbing parameter optimization model and application system

4.1 Dry hobbing parameter optimization model

In real gear production, it is necessary to balance the relationship between the production efficiency and the hob tool life. It is often translated to get the highest production efficiency under the precondition that satisfies both the target hobbing cost of single gear accounted by the financial sector, and the takt time, which is limited by the number of orders and the delivery time. Therefore, the optimization of dry hobbing process parameter is transformed to seek the optimum point, which is shown in Fig. 6.

The optimization model of dry hobbing process parameters can be built as shown in Eq. (8), where f_p is the production efficiency function, t_0 is the critical cutting time which just satisfies the tact time; C_0 is the target cost of a single gear, C_{si} is the total hobbing cost of a single gear under number i test condition.

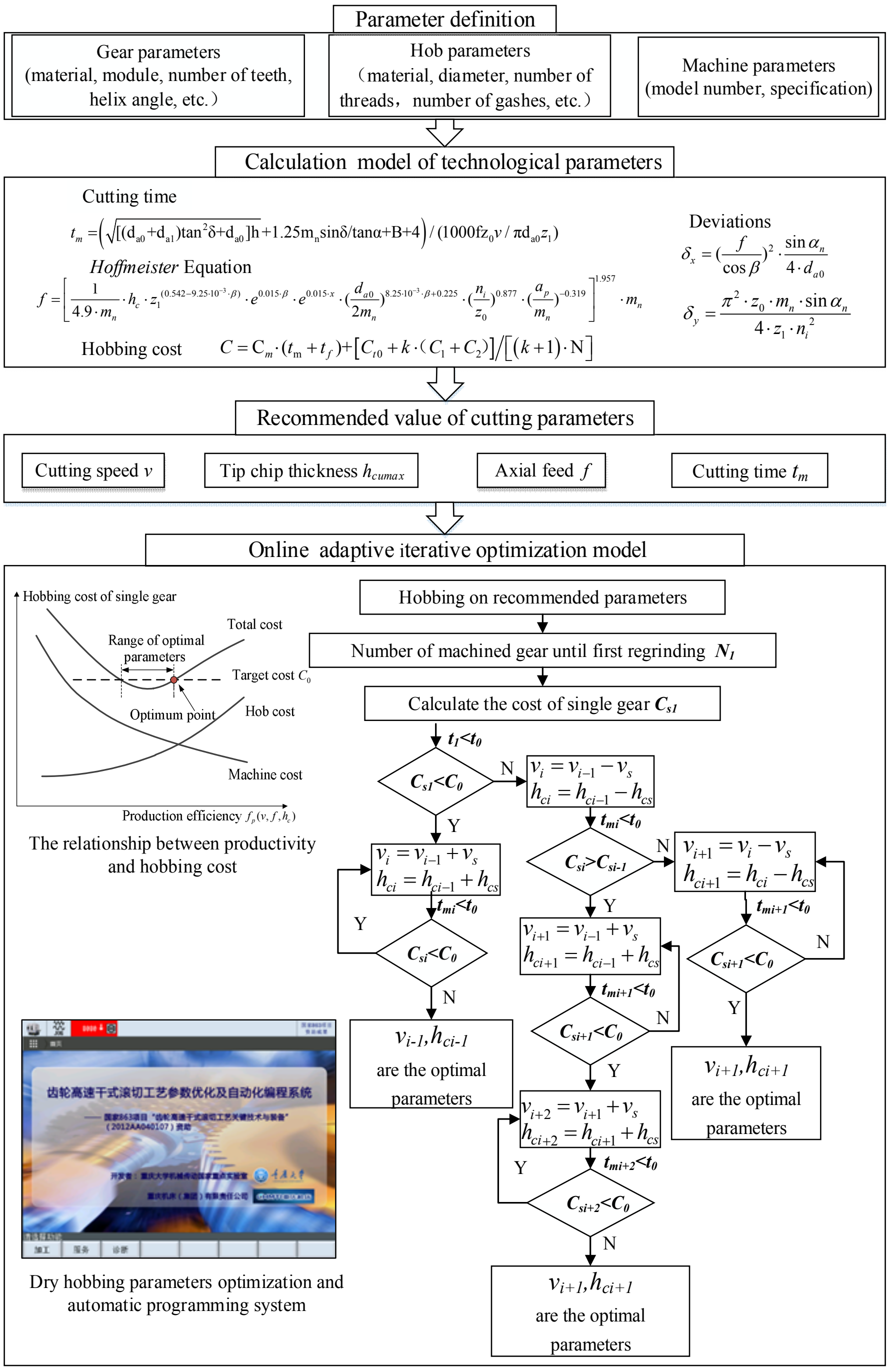


Fig. 7. Dry hobbing parameters optimization process.

$$\max f_p = 60/(t_m + t_f)$$

$$s.t.\ \begin{cases} \delta_x \le \delta_{x0} \\ \delta_y \le \delta_{y0} \\ C_{si} = C_m \cdot (t_m + t_f) + [C_{t0} + k \cdot (C_1 + C_2)]/[(k+1) \cdot N] \le C_0 \\ t_m = \dfrac{\sqrt{[(d_{a0} + d_{a1})\tan^2\delta + d_{a0}]h} + 1.25 m_n \sin\delta / \tan\alpha + B + 4}{1000 f \cdot z_0 \cdot v / \pi d_{a0} \cdot z_1} \le t_0 \\ f = \begin{bmatrix} \dfrac{1}{4.9 \cdot m_n} \cdot h_{cu\max} \cdot z_1^{(0.542 - 9.25 \cdot 10^{-3} \cdot \beta)} \cdot e^{0.015 \cdot \beta} \cdot e^{0.015 \cdot x} \cdot \\ (\dfrac{d_{a0}}{2m_n})^{8.25 \cdot 10^{-3} \cdot \beta + 0.225} \cdot (\dfrac{n_i}{z_0})^{0.877} \cdot (\dfrac{a_p}{m_n})^{-0.319} \end{bmatrix}^{1.957} \cdot m_n\ . \end{cases} \quad (8)$$

In this optimization model, the number of machined gears per regrinding/recoating of hob N is related to various conditions and cannot be quantitatively calculated. So, this model is difficult to solve by the conventional mathematical method. An iterative method is proposed to solve this model. The optimization process is shown in Fig. 7.

First, the basic condition parameters should be defined and input including gear geometric parameters, hob parameters, machine tool parameters.

Second, the recommended technological parameters would be calculated out by the developed system based on hobbing parameters calculation model and the original recommended data of cutting speed and tip chip thickness. The original recommended value of cutting speed and tip chip thickness are set by the operator based on experience.

Third, after the gear quality and cutting time is checked, the NC code would be generated automatically based on the current recommended cutting parameters, and the hob machine start to cutting gears through this NC code.

Fourth, when the wear of the hob is up to the wear criterion, which means it is need to be regrinding and recoating, the system will record the number of machined gear N_1. And then the cutting cost per piece C_{s1} can be calculated out by the hobbing cost calculation model.

Fifth, there is an online adaptive iterative optimization process that through changing the hobbing parameters by a step length (v_s is the step length for cutting speed and h_{cs} is the step length for tip chip thickness) and checking the corresponding single gear cost, cutting time, gear quality again and again until the optimal parameters are found. The detailed process for the adaptive iterative optimization is described next.

If $C_{s1} < C_0$, the cutting parameter is in the region of optimal parameters, and the cutting cost satisfies the need, but the cutting efficiency can be optimized much higher. Then the cutting speed and tip chip thickness are increased by v_s and h_{cs} respectively, and the gear quality, cutting time, hobbing cost are repeat checked, until the hobbing cost is higher than the target cost. The previous parameters v_{i-1}, hc_{i-1} are optimal parameters.

If $C_{s1} > C_0$, there is need to judge whether the parameters are too high or too low, which leads to the excessively high cost. For security sake, the parameters should be decreased by a step length. And the dry hobbing machine starts hobbing with the decreased parameters v_i, hc_i. The cost and cutting time will be checked again.

If $C_{si} > C_{si-1}$, according to Fig. 5, the parameters are too small in current hobbing. So, the next cutting parameters should be increased based on the cutting parameters of i-1th experiment. When the actual hobbing cost is lower than the target cost, the cutting parameters should be increased continually until the hobbing cost exceeds the target cost again, the previous parameters v_{i+1}, hc_{i+1} are optimal parameters.

If $C_{si} < C_{si-1}$, the parameters are too high in current hobbing. Thus, the next cutting parameters should be decreased based on the cutting parameters of i th experiment until the hobbing cost is lower than the target cost; the current parameters v_{i+1}, hc_{i+1} are optimal parameters.

During the whole optimizing process, before starting hobbing, the gear quality and cutting time should be checked, and the step length can be changed according to the real conditions or experience.

Last, the optimal parameters would be saved and the original recommended parameters would be changed to the optimal parameters in this system, which means the database of the recommended parameters is always updated which makes this adaptive system to be a self-learning system. And as the data of the optimization result accumulates, the optimization efficiency will be increased again and again. Because, usually, there is a small difference of optimal parameters if the gear material and the hobbing tool are the same, and the times of iteration can be heavily reduced.

4.2 Dry hobbing parameters optimization application system

To apply this model in a gear automated production line, an online adaptive system of parameters optimization was set up based on SINUMERIK 840D NC system. The basic hobbing condition parameters can be defined and the related parameters can be calculated precisely by this system. The cutting speed and the tip chip thickness can be optimized during the real production process, and the corresponding numerical control code can be generated automatically. Some interfaces of the system are shown in Fig. 8.

5. Experiment and case study

5.1 Design of experiment

To test this optimization model and system, a series experiments were conducted on YE3120CNC7, which is a dry hobbing machine designed and produced by State Key Laboratory of Mechanical Transmission and Chongqing Machine Tool (Group) Co., Ltd, as shown in Fig. 7. This dry hobbing machine tool has been hot in the market because of its high productivity and green properties. From the literature and the users' data, it is found that the tensile strength of the workpiece material is one of the key factors when choosing the cutting parameters. So, for different material workpiece, the recommended parameters are totally different. To confirm this, the cutting parameters of five kinds of commonly used materials of gear were optimized by using this optimization system. ZG45 was used for the unimportant gear in large vehicles, tractors and machine tools. 45 Steel was used for the transmission gear box of machine tool under medium load and speed. 40Cr and 35SiMn were used for the important gear in machine tool and cars under high speed and heavy load, but no strong impact. 20CrMnTi was used for the important gears in cars, airplane under high speed, heavy load and strong impact.

The details of the hobbing conditions are shown in Table 2. Initial cutting parameters for each material which come from the experience date are shown in Table 3.

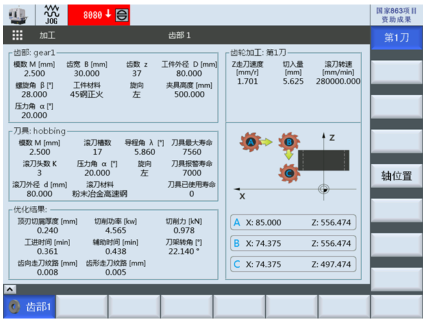
During the cutting experiment, the flank wear of each cutting tooth was measured and recorded with a tool microscope until the hob achieved the judge criterion to tool life, 0.2 mm for the maximum flank wear width. When the flank wear was up to 0.2 mm, the number of the machined workpiece N which is called hob tool life was recorded.

5.2 Results of experiment

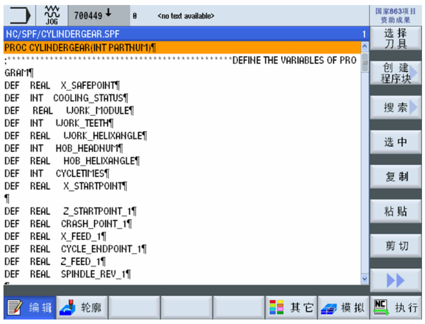
By using this optimization model, the technological pa-

(a) Main interface of the system

(b) Definition interface for hob parameters



(c) Optimization results



(d) NC code generated automatically

Fig. 8. Some interfaces of the system.

rameters of those five kinds of commonly used material gear under the described situation were optimized. Because the optimization process for each material is almost the same, to simplify, the optimization process of 20CrMnTi was only selected to be shown in this paper (see Table 4). And the other four kinds of materials are only shown the optimized results in Table 5.

Table 2. Hobbing conditions.

Hob specifications		Gear specifications	
Coat material	Ap	Module	2.5
Module	2.5	Helix angle	28°
Pressure angle	20°	Face width	30 mm
No. of threads	3	Tooth number	37
Outside diameter	80 mm	Outside diameter	110 mm
No. of gashes	17	Tooth profile	Normal
Length	180 mm	Material	ZG45 45Steel 40Cr 35SiMn 20CrMnTi
Substrate material	PM-HSS(S390)	Direction of turning	Left
Coating state	Full coat	Tact time	0.8 min
Hob machine specifications		Cutting parameters	
Type	YE3120 CNC7	Cutting depth	5.625 mm
Unit price	1500000 RMB	Cutting direction	Conventional hobbing
Service life	10 year (8 h/day)	Cutting method	Dry hobbing

Table 3. Initial cutting parameters for each material.

Material	ZG45	45 steel	40Cr	35SiMn	20CrMnTi
Tensile strength (MPa)	580	647	700	750	1079
Hardness (HV)	182	202	218	233	335
Cutting speed (m/min)	280	260	240	220	215
Maximum chip thickness (mm)	0.263	0.245	0.220	0.215	0.196

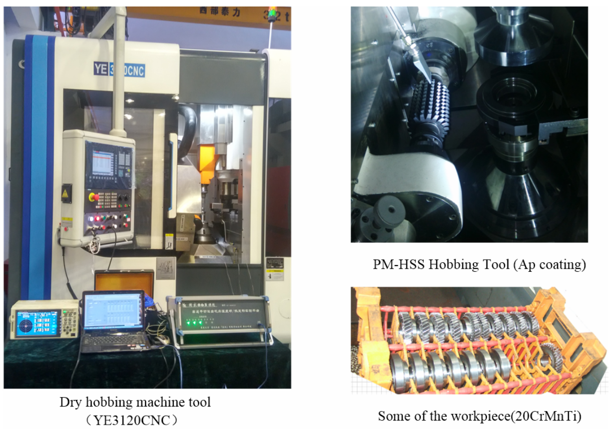


Fig. 9. Dry hobbing experiment on YE3120CNC7.

The market price of finished gear of 20CrMnTi in this geometry is 25*CNY* per piece. The net profit margin of single gear is 4.5 %, which means 1.1*CNY*. The basic material cost is 12.2 *CNY* and the cost for other process is 9 *CNY*. So, the target cutting cost in dry hobbing process for this gear was 2.7

Table 4. Optimization result of 20CrMnTi.

Experiment number i	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Cutting speed v m/min	215	205	195	185
Tip chip thickness h_{cumax} /mm	0.196	0.191	0.186	0.181
Axial feed f mm/r	1.42	1.34	1.28	1.21
Spindle rotating speed n r/min	855	815	775	736
Axial feed rate F mm/min	98	89	80	72
Material moving time t_m/ min	0.567	0.625	0.693	0.77
Feed markings mm	0.0018	0.0018	0.0018	0.0018
Generating cut deviations mm	0.0022	0.0020	0.0017	0.0016
Hob tool life N /piece	600	675	750	780
Machine tool cost C_t/¥	0.71	0.78	0.86	0.96
Hob tool cost C_h/¥	2.27	2.02	1.82	1.75
Total cost C_i/¥	2.98	2.80	2.68	2.71

Table 5. Final cutting parameters after optimization.

Material	ZG45	45 steel	40Cr	35SiMn	20CrMnTi
Cutting speed (m/min)	250	235	220	210	195
Tip chip thickness (mm)	0.248	0.225	0.206	0.202	0.186

CNY per piece. The step length for cutting speed v_s is 10 m/min and the step length for tip chip thickness h_{cs} is 0.05 mm.

By using the proposed optimization model and application system, the initial parameters were optimized to optimal parameters step by step. When machined by the initial cutting parameters (i = 1) and the second cutting parameters (i = 2), the total hobbing cost was 2.98 *CNY* and 2.80 *CNY,* respectively, which both exceed the target cutting cost. But for the third machining experiment (i = 3), the total cost and the material moving time both met the requirements, and for the fourth experiment (i = 4), the total cost was more than the third test. Thus, the third hobbing parameters (i = 3) were the optimal parameters which will replace the initial parameters in the database. After optimizing, the final total cost was 2.68 CNY, which was reduced 11 % from the initial cost, and the cutting time and the deviations also met the requirements. For 20CrMnTi, in this experiment condition, the optimal cutting speed was 195 m/min and the tip chip thickness was 0.186 mm.

To verify the effectiveness of this proposed method, the op-

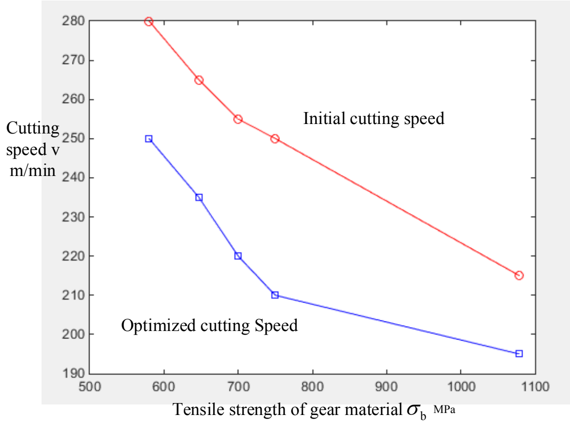


Fig. 10. Cutting speed optimization result.

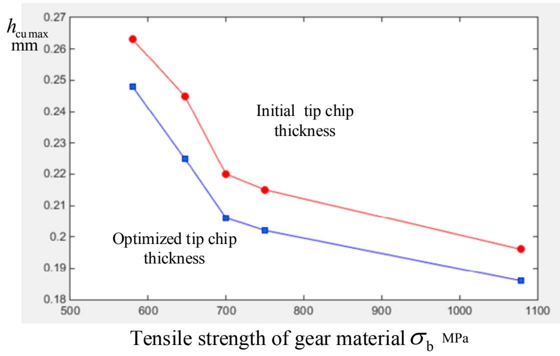


Fig. 11. Tip chip thickness optimization result.

timized cutting parameters and the initial parameters were both used to machine 5000 gears in gear production line on the same conditions. After accounting, the total cost of single piece was 2.73 *CNY* and 3.12 *CNY,* respectively, which means reduced 12.5 % cost after optimization. The verification results are very close to the optimization results, which proves the effectiveness of the proposed method. And when 5000 gears were machined, the current hobbing tool had not just come to its service life, which led to small deviations from the optimization results.

5.3 Discussion of experiment

The optimized results of cutting speed and tip chip thickness are plotted in Figs. 10 and 11, respectively. From these two figures, the cutting speed and tip chip thickness are decreasing as the tensile strength of gear material is increasing, which are both obvious in initial parameters and optimized parameters. And the optimized parameters are smaller than the initial parameters.

6. Conclusion

Dry hobbing technology has developed rapidly, but because of the complexity of the process itself and the sensitivity to the cutting parameters, there is a key problem of how to optimize the cutting parameters to promote the technology properties. Combined with the theoretical model and the production practice, a cutting parameters optimization model was set up and solved by iterative method. To apply this model in automated gear production line, an online adaptive system of parameters optimization was set up based on SINUMERIK 840D NC system.

Through applying this model and system to optimize the hobbing process for five different kinds of gear materials, it can be testified that the cutting parameters can be optimized to adapt the different hobbing conditions by this system. And the hobbing efficiency is improved with satisfying the limitation of cutting cost. Through the accumulation of a large amount of data, a decision-making system for hobbing parameters was developed which can significantly improve the optimization efficiency by combining the optimization model.

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Nomenclature

m_n : Normal module
z_1 : Number of gear teeth
α_n : Normal pressure angle
h_a : Addendum coefficient of gear
c : Tip clearance coefficient of gear
x : Modification coefficient of gear
z_0 : Number of hob origins
n_i : Number of hob columns
α : Axial pressure angle of gear
λ : Lead angle of hob
β : Helix angle of gear
k_g : Direction of gear
k_h : Direction of hob
B : Gear width
d_{a0} : Outside diameter of hob
v : Cutting speed
f : Axial feed mm/r
F : Axial feed rate mm/min
d_{a1} : Tip diameter of gear
δ : Installation angle of hob
a_p : Cutting depth
n : Rotating speed of spindle
δ_x : Feed mark deviations
δ_y : Generating cut deviation
h_{cumax} : Tip chip thickness
t_m : Material removing time
S : Axial stroke of the tool
S_a : Lead length of the hob
U_e : Safe distance for approach
U_a : Safe distance for exiting
S_e : Idle travel distance
C : Hobbing cost per piece
C_m : Depreciation cost of machine tool in unit time
t_f : Non-cutting time
C_{t0} : Hob tool purchase cost
k : Times of regrinding and recoating of hob
C_1 : Single regrinding cost
C_2 : Single recoating cost
C_0 : Target cutting cost of single gear
C_{si} : Processing cost of single gear in number i test
N : Number of machined gears per regrinding/recoating of hob
t_0 : Tact time
t_{mi} : Cutting time in number i test

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