High Performance Gear Hobbing with powder-metallurgical High-Speed-Steel

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Abstract

In the module range of 1.5 – 4 mm hobbing is still the most productive process for external gears. The trend for green manufacturing and the increasing cost pressures lead to an increase of dry hobbing. To apply dry hobbing, the cutting speed has to be increased compared to wet cutting. This paper shows that dry hobbing with PM-HSS is feasible and economic. Additionally, a method to determine guide values for dry hobbing will be presented.

1. Introduction

The trend for modern high-performance gear boxes significantly increased the demand for high quality gears [1]. Gears of case-hardened steel in the module range from 1.5 to 2.8 mm for automobile gear boxes and up to 4 (4.5) mm for truck-gear boxes are produced by hobbing, the most productive procedure (predominantly under automated conditions). Carbide and powder-metallurgical high-speed-steel (PM-HSS) are mainly used as cutting materials. In the last few years the usage of the more productive (because of its high temperature hardness) tungsten carbide in hobbing is decreasing, because of its sensitivity to impacts and its high price. Thus, the importance of PM-HSS has increased [4].

In conjunction with high-performance coatings based on chromium-aluminium, the development of dry cutting is increasing regarding productivity and rising cutting parameters. However dry cutting with high cutting speeds leads to failure and requires a higher technological effort than wet cutting. The present article shows the possibilities of dry hobbing regarding economic benefit and technical applicability.

Currently, the maximum chip thickness of Hoffmeister [2] at the tool tip and the experience of the technologist are used to determine the axial feed. Thus, an objective process design is not yet possible. To optimize the cost of production for hobbing, the program “OPTI” [3] was developed in the past by the authors. This program supports the workpiece and company specific optimization of the process. Concerning the influence of the mechanical stress on the tool life/wear behaviour, there is no scientifically based knowledge, which allows the setting of guide values. This article will demonstrate the possibility to objectify the process design for dry hobbing with high cutting speeds [4].

The most common quantity to define the size range of a gear is its module. The term “module” m is defined as:

\[
m = \frac{\text{pitch circle diameter } d}{\text{number of teeth } z} \tag{1}
\]

In the English/American system the term “diametral pitch (=DP)” is more prominent (DP = 25.4/m). In the following the term module is used.

2. Materials and Methods

2.1. State of the Art

PM-HSS gear hobs with high-performance coatings offer a great performance potential, which is still
growing due to technical development and systematic researches. Currently there are no adequate parameters for a technical and economical usage of PM-HSS hobs. Additionally it was found that the tool life is strongly depending on different load conditions. That is why companies are going to test the durability of dry cutting on only a few parts. Through this procedure different reserves are remaining. It can be assumed that cutting speeds significantly less than 200 m/min are common practice in industry with PM-HSS hobs under the conditions of dry processing. It is known by laboratory experiments [3] that much higher cutting speeds are possible. Unfortunately it is uncertain how they could be transferred to industry. Beyond that the limits of such progressive and productive cutting speeds and the relation to various materials and workpiece dimensions are largely unknown.

In [3] a method for case-related cutting value optimization was developed. The developed program ("OPTI") [3] can only be used partially and not in a broad manner to solve the problem of providing technically and economically cutting values. For many companies the optimization by experiments is too time-consuming in daily practise.

The hobbing process has been studied in various generating positions, which determine the load on the tooth [5]. The generating position describes the characteristic position of a tooth in each tooth gap (Fig. 1). Thus, the relative position of the gear tooth is always the same. The result is that the geometric parameters of the chip remain the same, at least for the full cut. The disadvantages, which are derived from this constancy, were balanced by the so-called shifting, the axial move of the hob. Thus the sum of the load conditions is equal but very complex.

These load conditions are depending on the geometry (hob/workpiece) and the cutting technology, particularly the axial feed and depth of cut. It is reflected in tool life/wear behaviour of the hob.

To define or limit the axial feed, the famous equation of Hoffmeister [2] is used in industry. Based on this the axial feed is calculated (Fig. 2). The maximum chip thickness has to be given and should amount 0.15 to 0.30 mm for PM-HSS.

The mechanical load of the hob tooth is not only a matter of the gear geometry and the axial feed but also depending on the different shape of the chips. In hobbing the chips are classified into one-, two- and three-flank-chips (Fig. 3).

**Fig. 2: Equation of Hoffmeister**

Joppa [8] showed, that the shape of chips is strongly influencing the wear behaviour of the hob. Extensive studies of chip flow disability in hobbing were conducted by Bouzakis [9, 10]. He divided the three-flank-chips in four classes; with class one having the greatest intensity of the hindrance.

**Fig. 3: Different chip geometry**

### 2.2. Solution

The present method is designed for hobbing of case hardened gears in module range from 1.5 to 4 mm. Equi-directional climb hobbing with progressive cutting speeds of 200 to 300 m/min were analysed. The solution approach is divided into three aspects:

- choosing significant primary load parameters for hobbing
establishing the relationship of these parameters for gearing geometry between workpiece and hob
• describing the relationship between the primary load parameters and wear/tool life behaviour by experimental investigations basing on empirical approaches

Other influencing factors are considered by correction factors, basically concerning the cutting speed and the material influence. Additionally, the influence of the chip flow hindrance on the wear behaviour based on the state of the art is taken into account.

The determination of wear/tool life behaviour of tools with geometrically defined cutting edges for conventional methods is based on empirical functions according to Taylor [11]. In literature, there is no empirical approach to describe the wear/tool life behaviour in hobbing considering the geometry of hob and workpiece.

Table 1: Gear parameters of gear 1 and gear 2

| tool                  | PM-HSS (S390) + AlCrN |
|-----------------------|------------------------|
| workpiece             | 20MnCr5 (ZF7b) da2 = 130 mm |
| technology            | analogy trail dry / one cut vc = 220 m/min |
| parameters tool      | gear                   |
| da0 [mm]              | i                      |
| gear 1                | 90 mm                  |
| z0 [mm]               | 3                      |
| mn [mm]               | 1,6 mm                 |
| ß2 [°]                | 15°                    |
| i2 [°]                | 75                     |
| gear 2                | 100 mm                 |
| i [mm]                | 3,85 mm                |
| gear parameters       |                       |

In hobbing it is common, as already described, to use the maximum chip thickness by Hoffmeister as the parameter value to determine the axial feed.

It is obvious that the maximum chip thickness as a guide parameter can describe the mechanical load of the process only to a limited extent.

Fig. 5: Representation of the primary load-parameters

Based on present tests it was decided, that three values have to be considered:
• mean undeformed chip thickness \( h_m \)
• mean cutting length \( l_m \)
• number of impacts \( i_z \)

This choice is also based on the findings of Mundt [6]. In Fig. 5, these three load parameters are shown. To determine the three load parameters the program SPARTApro of WZL of the RWTH Aachen is suitable.

Fig. 6: Result of the ization

Because this program is very extensive and not available at every company an independent method was developed, to determine the parameters with sufficient accuracy. For this purpose, the method of standardization by Mundt [6] was used. In this case standardization means to define a basis gear and referring other gear geometries to the basis. The result of standardization is shown in Fig. 6, as an example of the dependence of the mean undeformed chip thickness \( h_m \) to the module \( m_n \).
3. Experiments

To represent the dependence of tool life to the primary load parameters a power law was used, because of its continuous behaviour:

\[ L = a_0 \cdot h_m^{a_1} \cdot l_m^{a_2} \cdot z_3^{a_3} \]

To determine the constants of the equation \( a_0 \) to \( a_3 \) experiments (analogy test) were carried out. Later they were evaluated in a regression analysis. Furthermore experiments were carried out to determine other remarkable influences. From this the determination of the real state length \( L_{\text{real}} \) is possible:

\[ L_{\text{real}} = L \cdot K_{\text{tooth}} \cdot K_{\text{cutt speed}} \cdot K_{\text{material}} \cdot K_{\text{wear}} \cdot K_{\text{chip flow}} \]

The specified factors were determined in experiments. To define the factor of the chip flow the calculation results of the SPARTApro are needed. A supportive program analyses the chip data, delivered by SPARTApro, (chip thickness in dependence to the unrolled cutting edge and the rotation angle) and classifies the chips according to the classification of Bouzakis [8]. The structure of the program is illustrated in Fig. 7.

For all experimental points of the wear experiments SPARTApro calculations were realized which offer the possibility to calculate a statistical chip analysis. The results as well as the load parameters were calculated with a non-linear regression analysis.

Thereby calculations of tool life not only consider the specific load parameters of hobbing but also the specific chip formation of the particular process.

![Fig. 7: Chip valuation](image)

Tool life investigations were carried out with the analogy test (fly-cutting) by Sulzer [12]. During the investigation tests gears with modules 1.6, 1.75, 2.7 and 3.85 mm and gearing widths of 29, 58 and 87 mm were used. The trials were done with a cutting speed of 220, 250 and 280 m/min in exception also of 200 and 240 m/min. Nearly 62 experiments were used to calculate the constants of the equation. The tools were coated with AlCrN-coating which is needed for dry cutting. Basic experiments were done with 20MnCr5 material. Within the trials helical and spur gears were taken into account.

The final results clarify the dependence of the tool life to the primary load parameters. Considering the fact of a multidimensional dependence, a quantitative description has to be chosen (Fig. 8). As shown in the diagram the tool life decreases with increasing mean length of cutting and the undeformed chip thickness. This can be explained by the rise of the thermal and mechanical load. Because of the strongly dependence of all three parameters the multiple regression analyses resulted that the tool life increases with the increasing number of impacts.

![Fig. 8: Dependence of the tool life from the primary load parameters](image)
4. Results

4.1. Program for Reference Values

A program was developed to transfer the results in industry. The main item of this program is equation (3).

\[ L = f(h_m, l_m, i_z) \cdot K_{tooth} \cdot K_{cut\cdot speed} \cdot K_{material} \cdot K_{wear} \cdot K_{chip\ flow} \] (3)

with \( h_m, l_m, i_z = f(\text{geometry, axial feed}) \)

Equation (3) comprises geometric kinematical values, empirical detected wear/tool life-correlations and experimental detected correction values. But the core of the equation is the geometric kinematical influence. Equation (3) is used in three different ways:

first: axial feed and cutting speed are given while tool life is wanted,

second: axial feed and tool life are given while cutting speed is wanted,

third: tool life and cutting speed is given while axial feed is wanted.

To calculate the reference value of each variant three different cases have to be considered (Fig. 10):

- **case 1**: The tool life is detected in dependence on the load parameters (bars to the left). No SPARTApro calculations are needed. The load parameters are calculated with geometrical equations.

- **case 2**: The tool life is calculated depending on the load parameters. Additionally the hindrance of the chip flow is considered (bars in the middle of the diagram). To identify the hindrance SPARTApro is needed.

- **case 3**: The tool life is calculated depending on SPARTApro load parameters. Additionally the hindrance of the chip flow is considered (bars to the right). For calculation of the load parameters as well as the hindrance of the chip flow SPARTApro is needed. The bars are showing the average values and the thin line indicates the spread of the values.

It has to be considered that the values are only showing the results for the combination of PM-HSS S390 and AlCrN. Deviations of the characteristics of substrate and coating can result in a spread increase. Additionally alternating characteristics of the workpiece material regarding the machinability can take effect.
Hence, the results are showing that the values have guidance character. Thereby the application to industry cannot be guaranteed, but the results show that it is promising.

The calculations can be adapted to changing conditions (new tool material, different workpiece material, more efficient coating) by means of some experiments.

Fig. 10: Accuracy of the results

4.2 Field trial

An industry trial in three different gear companies was performed. Another trial was performed at IFQ Magdeburg. Within the trials the axial feed used in industry was maintained and the cutting speed was increased up to 220 m/min. Two of four companies used wet cutting before the tests. It could be demonstrated that:

- cutting speeds above 200 m/min are possible with acceptable tool life results,
- within the trials with high cutting speeds no sudden or abrupt tool failure appeared.

Due to the positive results there was a major interest of the employees, in particular in companies with wet cutting. Furthermore it has been proven that dry hobbing with cutting speeds above 200 m/min is possible. This cutting speed range also works at optimal costs [3]. Regarding the quality and accuracy of the gear no differences to wet hobbing were noticed. The surface integrity is not investigated within this project, but influences are not expected. More specific information about the tests are listed in [4].

5. Conclusion

Following objectives were realized:

- getting information about the behavior of PM-HSS in dry hobbing with high cutting speeds depending on workpiece material and gear geometry,
- to prepare load depending guide values for PM-HSS in dry hobbing with high cutting speeds and
- to prove them in industry.

A clear correlation between geometrical and kinematical values of the tool/workpiece pairing and the load parameters were determined. This correlation is independent of the workpiece material. It was possible to determine guide values for some typical gear materials in dry hobbing for a module range of 1.5 to 4 mm.

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