Manufacturing of Twist-Free Surfaces by Hard Turning

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Abstract

Currently grinding is commonly used as the finishing operation to manufacture seal mating surfaces and bearing surfaces, especially in the automotive industry. It would lead to more resource-efficient production if the cost- and energy-intensive grinding process could be replaced by machining with geometrically defined cutting edges, such as hard turning \cite{1, 2}. However, turning operations usually cause a twist structure on the surface, which can convey lubricants like a pump. Several methods exist to overcome this problem, for example, tangential turning, rotation turning and turn broaching, etc. Due to the high costs of tools and special machines required by these methods, the industrial application is still limited. This paper describes a more efficient approach by applying a modified feed kinematic. When using this approach, hard turning produces twist-free surfaces. The results of the latest twist test methods have confirmed that the surfaces are free of twist, hence free of conveying effect of lubricant and that they are suitable for application in manufacturing of seal mating surfaces and bearing surfaces. Furthermore, this method requires only minimal investment in any turning machine.

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1. Introduction

The conventional process chain for the production of rotationally symmetric components with a high level of hardness, such as crankshafts and camshafts, is characterized by several manufacturing processes and long non-productive time, such as for transport, storage, etc. The extension of the scope of turning steels with high hardness allows the increase in productivity due to complete finishing in one single stage. Compared to grinding, hard turning does not only save cost and time but it is also environmentally friendly (omission of treatment and less disposal of slurry) \cite{2, 3}. However, many grinding applications cannot easily be replaced by hard turning. This is the case for manufacturing seal mating surfaces and bearing surfaces. The reason for this phenomenon is that the feed motion of the tool will cause twist structures, which will then lead to the conveying effect of lubricant between contact surfaces and sealing or plain bearing \cite{4, 5, 6}, which will be further described in this paper.

2. State of the art

Twist structures are characterized by microscopic structures which are comparable with a thread structure on a shaft surface. Figure 1 shows the surface of a turned shaft schematically. The parameters are described in the Mercedes-Benz standard MBN 31007-7 \cite{7} in 2009.

Fig. 1. Twist characteristics of a turned shaft
The parameters shown in Fig. 1 describe the properties of twist structures, which are dependent on process parameters (feed, nose radius etc.) and theoretically can be calculated for turning as follows:

Twist angle $D\gamma$ [°] is the angle between the circumferential direction and a periodic spin structure; in case of turning it can be calculated as follows:

$$D\gamma = \arctan\left(\frac{f}{D \cdot \pi}\right)$$  \hspace{1cm} (1)

Twist depth $D_t$ [$\mu m$] is the vertical distance between wave peaks and troughs of a structural profile, and while turning it is equal to:

$$D_t = R_z = r_e - \sqrt{r_e^2 - \left(\frac{f}{2}\right)^2}$$  \hspace{1cm} (2)

Lead number $D_G$ is the number of pitch distances advanced in a single rotation (360°) of the shaft; during turning $D_G$ is equal to:

$$D_G = 1$$

Conveying cross section $D_F$ [$\mu m^2$] is the cross-sectional area of a twist structure in an axial section, during turning $D_F$ can be calculated as follows:

$$D_F = \pi \cdot r_e \cdot \frac{2 \cdot D\gamma}{360^\circ} \cdot \sin D\gamma \cdot r_e \cdot \cos D\gamma \cdot r_e$$  \hspace{1cm} (3)

Conveying cross section / turn $D_{Fu}$ [$\mu m^2$] is the cross-sectional area of a period length in an axial section of the twist surface multiplied by the lead number $D_G$:

$$D_{Fu} = D_F \cdot D_G = DF$$  \hspace{1cm} (4)

Period length $D_P$ [mm] is the length between two successive periods in the axial direction. During turning the characteristic is equal to the feed:

$$D_P = f$$  \hspace{1cm} (5)

Percentage of support length $D_{Lu}$ (in %) is the size of the theoretical confinement of the surface in circumferential direction by the sealing lip support in relation to the total circumference.

During the rotation of a turned shaft, the liquid entrains in the circumferential direction and is deflected axially because of the twist structures [8]. Therefore the liquid (e. g. lubricant) will be conveyed depending on the rotational direction of the shaft, see Figure 2. This will cause many problems, for example, leakage in the sealing system, a local deficiency and irregular distribution of the lubricant in the plain bearing system.

Shaft surfaces such as seal mating surfaces and bearing surfaces are currently manufactured by grinding [9]. This method is widely used, but it is expensive and not 100 % successful. A very long spark-out time is required for the grinding process in order to ensure a twist-free surface [3]. However, due to cost pressure, this spark-out time could not be considered in practical applications. In addition to that, grinding is a machining process with geometrically undefined cutting edges, which inhibits the reproducibility of the process. The undefined surface texture may cause excessive pumping effects in response to the rotation of the shaft, which is much more critical than the roughness of the surface. [10] Therefore industry is currently looking for alternative manufacturing processes, for example hard turning, milling, burnishing or laser polishing. This applies especially for the industries of automotive and automotive suppliers.

Hard-turning has been used increasingly in recent years to produce twist-free shafts. [10] The latest research shows that hard turning is a very suitable alternative to grinding. Thus a number of patents have been developed with different methods:

- 1993 Vibration-processing method [11],
- 2001 Tangential turning [12],
- 2005 Rotational turning [13],
- 2007 Twist-free turning with suitable feed motion [14].

The methods of vibration-processing, tangential and rotational turning have the disadvantage of requiring a special machine structure and thus demanding significant investment. Furthermore, the special tools are expensive because of the required high quality at the cutting edge. Moreover, only a limited length can be processed on the shaft surface with tangential or rotational turning. The method of suitable feed motion has the disadvantages of the processing time being significantly prolonged and the machine requiring a very stable repeatability for the repositioning of the tool.
3. Experimental Setup

Due to the development of tool technology (cutting material, geometry etc.), surfaces with fine and defined microstructures can be produced by hard turning [15]. Therefore, in the performed investigations the shaft surfaces were manufactured purposefully by hard turning using different tools and concepts of kinematics. Then the surfaces were analyzed according to the assessment criteria, such as twist angle, conveying cross section etc.

Cylinders of hardened 42CrMo4 with 58-60 HRC with a diameter of 20 mm and a length of 20 mm were selected as processing elements. Due to its high performance in static and dynamic strength and toughness, this material is widely used for powertrain components of motor vehicles.

Inserts with wiper geometry (see Fig. 3 a)) and conventional inserts (see Fig. 3 b)) were used as tools. According to the specification of the tool manufacturer, much lower roughness can be achieved by inserts with wiper geometry compared to conventional inserts at the same feed.

subsequently calculated using state of the art software, which is specifically designed for twist analysis by the Company Digital Surf.

4. Results and discussion

Fig. 4 shows the surface macrostructure of a sample turned with conventional insert. The typical repetitive twist structure via turning can be clearly seen. In contrast Fig. 5 shows that the machining track is significantly lower on the surface turned using wiper insert. Significant reductions are observed both in the twist depth (by 96%, from 4.64 μm to 0.185 μm) and in the conveying cross section (by 96.8%, from 546 μm² to 17.2 μm²). It means that theoretically the conveying effect should be much lower, but this needs to be demonstrated in practice.

![Fig. 4. Twist structure machined with conventional insert](image1)

![Fig. 5. Twist structure machined with insert with wiper geometry](image2)

The shaft surface must be machined in such a way that the conveying cross section per turn Dfu is approximately zero, therewith there is no pumping conveying effect in the sealing system. According to Formula 4, this means either the conveying cross section Dfu tends to zero, which in practice is almost impossible, or the lead number of the twist structure DG is equal to zero, i.e., the feeding tracks are exactly in the circumferential direction and closed, see Fig. 6 a). To manufacture such microstructured surfaces the tool has to stay in a position until the workpiece turns at least
once by itself, and therefore the feeding track is completely eliminated. The path-time diagram of feeding kinematics is shown in Figure 6 b). The feeding time \( t_f \) is the time within which the tool moves between two stop positions. The linger time \( t_l \) is the duration of the tool staying at a stop position. The path between two stop positions is described by the feeding width \( s \) which should not be longer than the wiper width so that no feeding traces are left on the surfaces.

The concept of start-stop-turning is still not optimized and has shown certain disadvantages in the experiments. The most problematic issue is to realize the repeatedly starting and braking of the tool. The application of start-stop-turning requires an immediate reaction and a rapid acceleration of the machine spindle for feed. This requirement can cause a dynamical overload to the machine tool. Furthermore, the cutting time with the start-stop-turning can be five to seven times longer than hard turning with a continuous standard feed (with a diameter from \( \Omega \) 20 mm to \( \Omega \) 40 mm), if the start-stop-turning is exclusively controlled and realized by a CNC system. Therefore a suitable feed kinematics has been developed to ensure a faster and more reliable start-stop-turning. The function of the start-stop kinematic is achieved by the superposition of the movements of the machine spindle with a continuous feed, see Fig. 8 (a) and the additional drive system with an oscillated motion, see Fig. 8 (b).

A drive system will be developed for generating the described oscillated motion, which can fulfill the requirements of the machining with start-stop-turning, e. g. cutting force to 400 N, frequency to 50 Hz, short response time and rapid acceleration. Currently Technische Universität Chemnitz is working with AeroLas GmbH (manufacturer for high-performance drive systems) on this topic. In respect of the requirements for the start-stop-turning the air bearing drive system is the ideal solution. This drive system can realize high acceleration and jerk due to the contact free construction.

![Fig. 6. (a) Feeding kinematics of Start-Stop-Turning (b) Path-time diagram of Start-Stop-Turning](image)

![Fig. 7. Microstructure machine with Start-Stop-Turning (Tool: CCGW09T308GAWC2, Mitsubishi; \( a_p = 0.25 \) mm; \( v_c = 183 \) m/min; \( f = 0.1 \) s; \( s = 0.2 \) mm)](image)

![Fig. 8. (a) Continuous feeding kinematic of the machine spindle (b) Oscillated motion of the additional drive system (c) Effective start-stop kinematic by cutting](image)
5. Summary and conclusions

The research shows that hard turning is not only an alternative or a substitute for grinding, but it also offers a new manufacturing opportunity for modifying surfaces to obtain desired functions such as surfaces with tribological function. Using this method with geometrically defined cutting edges, the microstructure and roughness of the surface can be controlled by varying the tool geometry (nose radius, wiper, etc.), the machining parameters (depth of cut, feed, etc.) and by applying appropriate methods (feed kinematics, machining with ultrasonic vibration, etc.) which aim to achieve optimized surfaces for specific applications such as seal mating surfaces and bearing surfaces.

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