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Influence of hard turned roller bearings surface on surface integrity after deep rolling

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Abstract

The endurance of highly loaded parts such as bearings is influenced by their surface integrity. Low surface roughness and high compressive residual stresses lead to an increased lifetime. In contrast to grinding and honing, the processes hard turning and deep rolling can induce compressive residual stresses up to σ = -1000 MPa with depths of d_0 = 500 µm in combination with surface roughness values of Rz < 0.8 µm. Combining both processes to the innovative hybrid turn-rolling exhibits benefits with respect to topography and residual stress stability. Developing this process, the interactions of the single processes are analyzed in this paper.

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Keywords: Hybrid machining; Deep rolling; Surface integrity

1. Introduction

The endurance of roller bearings can be increased by a low surface roughness and high compressive residual stresses in the near surface area [1]. The performance of bearings can be improved by a specific surface integrity design. Due to the fact, that micro contacts between the rolling elements and the runways are caused by roughness peaks, runway surfaces must have a plateau surface to increase the bearing ratio and reduce near surface shear stresses [2]. A stable compressive residual stress depth profile raises the tolerable hertzian contact stresses. The maximum shear stress in the rolling element-runway contact is reduced so that the endurance of the bearing is increasing [3]. Considering the surface integrity, the manufacturing process becomes more important. Conventional processes such as grinding and honing can reduce surface roughness but it is impossible to induce a stable residual stress state [4]. High precision hard turning processes can lead to a surface quality comparable to grinding processes [5]. An additional deep rolling process induces high compressive residual stresses and smoothens the surface [6]. Both processes can be conducted in one machine and have similar process procedures. Therefore, a hybrid hard turn-rolling process is invented at the IFW, based on the concept of Denkena et al. [7]. The aim of this process is to combine hard turning and deep rolling in one process step to shorten the process time and to improve the surface integrity. Higher and stable residual stresses are supposed to be induced by a warm deep rolling process. The generated heat of the turning process is used in the hybrid process. The surface roughness can be reduced, because of a better positioning of the rolling tool on the surface roughness peaks.

Hard turning and deep rolling are well known in literature. Hard turning is capable of producing mean surface roughness values Rz of less than 1 µm [8]. One of the main effects on surface roughness is feed f. In hard turning feed values of less than 0.1 mm are used. In that case, the minimum uncut chip thickness h_{min} becomes more important due to the ploughing effect in machining than the feed value [9]. With an increased cutting edge radius r_β the minimum uncut chip thickness h_{min} increases [9]. An increased cutting edge radius also induces more compressive residual stresses [10].

In deep rolling a rolling ball with a diameter d_k is pressed with the rolling pressure p_w on the surface of a rotating part. The contact stresses can be calculated by the hertzian contact theory. Very high contact stresses lead to a plastic deformation at the surface which reduces the surface roughness [11]. Within the near surface area high compressive residual stresses occur.

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Hard turning with new and worn tools induces very different residual stress states, an additional deep rolling process with the exact same parameters lead to the same residual stress state in roller bearing manufacturing [12]. As a consequence the initial residual stresses from hard turning can be ignored in the surface integrity design. This is true for residual stresses, microstructural changes by hard turning cannot be compensated in deep rolling. However, in case of the surface roughness the interactions of hard turning and deep rolling cannot be ignored. Here the initial roughness after turning has to be considered [13].

2. Hybrid process turn-rolling

In hard turn-rolling the deep rolling ball is mounted right behind the cutting edge which will lead to a warm deep rolling process. The deep rolling tool can be positioned relative to the cutting edge in feed direction (Fig. 1). A lower surface roughness can be reached if the rolling element is positioned on the peaks of the surface profile by the parameter x_f. The positioning can only be applied, if deep rolling does not superimpose surface roughness of the hard turning process. The aim of the process is to reduce friction by creating a plateau surface with reduced roughness peaks values Rpk. If the roughness is fully deformed by the deep rolling this effect will not occur. To improve this process and describe the interactions between turning and deep rolling in the combination first the effects of the initial surface roughness has to be understood in the two single processes.

The aim of this research is to analyze the effects of the initial surface roughness after hard turning on the surface quality after deep rolling of roller bearing inner rings in the classical, serial processes chain. The knowledge about the interactions are very important to identify the technical limits of the hybrid process and helps to design the hard turn-rolling process.

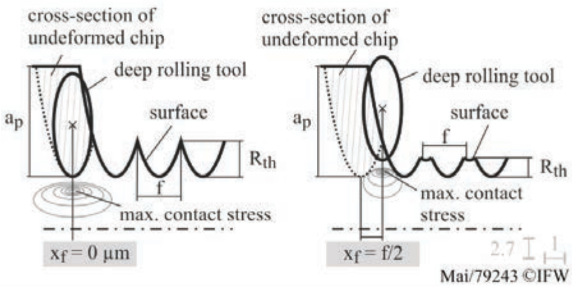

Fig. 1. Surface roughness after hard turn rolling

3. Experimental Setup

Roller bearing inner rings, type NU 206, made of AISI 52100 steel with a hardness of 62 HRC are machined on a high precision lathe Hembrug Microturn 100. Hard turning and deep rolling are conducted in the same clamping system, a hydraulic expansion mandrel. The inner rings are pre-machined by a bearing manufacturer. Only the finish machining is conducted within the experiments. In the hybrid turn-rolling tool a tool holder DDJNL2525 is modified and used with coated carbide inserts DNMA150616. The same tool is used in this experiments. The carbide tools are coated with a Ti(C,N) + Al_2O_3 CVD coating. The rake angle is γ = -6° and the clearance angle is α = 6°. For the deep rolling the ECOROLL HG3 hydrostatic rolling tool is used, which is also mounted in the hybrid tool. The rolling ball is made of ceramic with a diameter of d_k = 3.175 mm. For additional tests the ball diameter is changed to 2.2 mm and 6.3 mm.

Table 1. Experimental parameters to analyze the effect of rolling process on surface quality.

rolling parameter	rolling pressure p_w *(bar)*	rolling feed f_w *(mm)*	ball diameter d_k *(mm)*
minimum	200	0.011	2.2
maximum	400	0.311	6.3

The experiments are conducted in two steps. In a first step the influence of rolling parameters on the surface roughness is analyzed. Rolling pressure p_w, rolling feed f_w and ball diameter d_k are varied, due to table 1. In a second step the influence of the initial surface roughness after hard turning on the surface quality in deep rolling is analyzed by three different hard turning parameters (table 2). Besides feed the cutting edge geometry is changed by means of chamfer angle γ_f and cutting edge radius r_β. For each turning process, seven inner rings are machined with the same cutting insert to avoid any tool influence. The inner rings of each turning process are deep rolled by five different feed values f_w with three different rolling pressures (table 3).

Table 2. Turning parameters to produce different surfaces.

process	cutting speed v_c *(m/min)*	feed f *(mm)*	Depth of cut a_p *(mm)*	Cutting edge geometry
turning 1	100	0.1	0.1	γ_f = 15°
turning 2	100	0.05	0.1	γ_f = 15°
turning 3	100	0.05	0.1	r_β = 100 µm

The specimens are machined by hard turning in full length and deep rolled only in the first half of it. Surface roughness improvement can be identified for each inner ring. The surface roughness is measured tactile. A perthometer Concept (Mahr) is used for the tactile measurements with a cut-off λ = 0.8 mm. The length of the deep rolled area is less than 5.6 mm, so the number of measurement lengths is decreased to 2. Each specimen is measured five times to detect the mean values.

Table 3. Deep rolling parameters for the different turning operations

rolling parameter	rolling pressure p_w *(bar)*	rolling feed f_w *(mm)*	ball diameter d_k *(mm)*
minimum	200	0.011	3.175
maximum	400	0.311	3.175

4. Influence of initial surface roughness for deep rolling

Typical topographies for turning processes can be seen in Fig. 2. Due to the corner radius and the feed a periodical profile arises. Describing the surface topography just by the surface roughness, important information can be lost. The ratio of profile height and distance is described as surface ratio A_{surf}. The height is equal to the mean surface roughness Rz or in theoretical analysis the theoretical surface roughness Rth. The distance of the periodic profile is always the feed per revolution. Therefore, the surface ratio can be calculated as

$$A_{surf} = \frac{Rth}{f} \tag{1}$$

In Fig. 2 three different surface profiles can be seen. Surfaces A and B are machined with the same feed value but different roughness values. This can occur due to different cutting edge radii and subsequent differences in minimum uncut chip thickness h_{min}. Surface B and C have the same roughness value but different feed values.

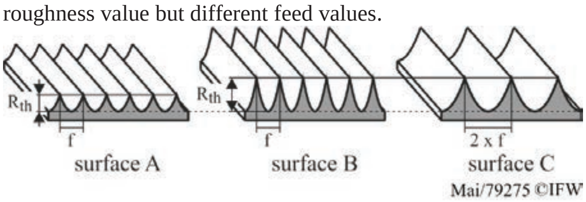

Fig. 2. Hard turned surfaces with different surface ratio

In Fig. 3 the effect of feed on surface ratio can be seen for a theoretical surface roughness. For ideal sharp tools without any minimum uncut chip thickness (h_{min} = 0 µm) the theoretical surface roughness increases for higher feed values. Considering a real cutting process including h_{min} the surface roughness will decrease at the beginning and increase after reaching a minimum value. The surface ratio A_{surf} increases almost linear for an ideal process. In real cutting the curve can be separated into two areas by a critical surface ratio $A_{surf,crit}$, which is the minimum value of the curve. If the feed is lower than for this critical value, $A_{surf,crit}$ can be influenced by the cutting edge radius. For higher feed values, the surface ratio will increase always linear.

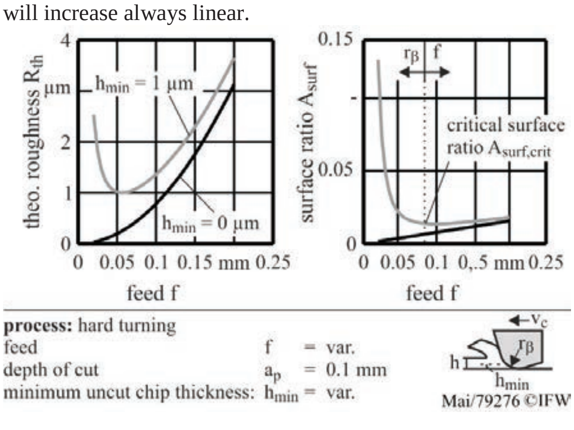

Fig. 3 Influence of feed on surface ratio

The used turning operations within the experiments create the three different surface types (Fig. 4). Depending on the surface type deep rolling has an effect on the surfaces.

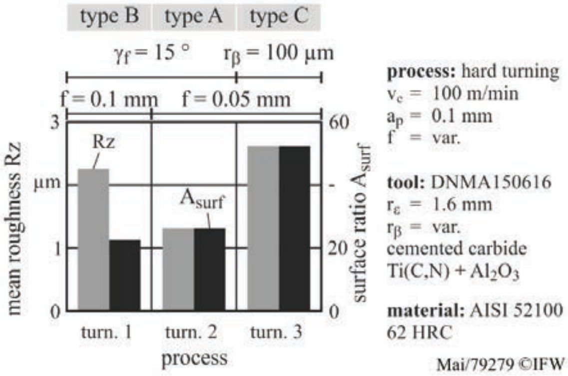

Fig. 4. Used hard turning processes from surface types A, B and C

Analyzing the influence of process parameters in deep rolling on surface quality, the experiments show a significant parameter. Fig. 5, left shows the effects of rolling pressure p_w and ball diameter d_k on surface roughness Rz. Using the same overlap factor u = 72 % the surface roughness is always between Rz = 0.9 – 1.5 µm. There is no systematic change in surface roughness with increasing parameters. While the results for an increasing overlap show a clear effect on surface roughness. If the overlap u increases (feed decreases), the surface roughness becomes smaller. For u = 44 % a Rz-value of 2 µm occurs. Increasing the overlap to almost 100 % the rolling feed marks come closer together and Rz decreases to 0.5 µm. Due to the plastic deformation in deep rolling the feed and ball diameter creating the finished surface. The overlap is a suitable parameter to describe the effect of feed independent of ball diameter.

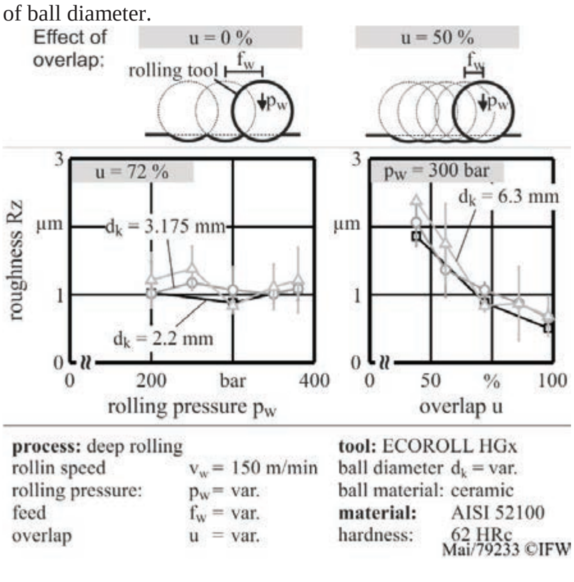

Fig. 5. Influence of rolling parameters on surface roughness

Due to the fact, that overlap u is the only significant factor, it is assumed that u will also influence the surface roughness for different turning processes. The second experiment shows that independent of initial surface roughness in case of small overlap factors the surface roughness increases in deep rolling. This effect increases for small initial roughness values (Fig. 6).

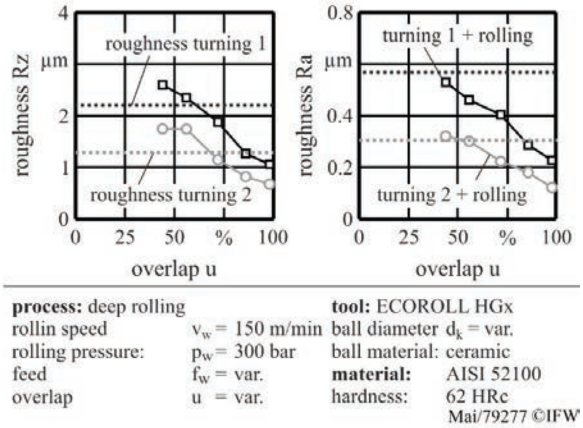

Fig. 6. Effect of initial surface roughness on surface quality after deep rolling

The roughness improvement dRz, which is the difference between turning and rolling surface compared to the turning surface roughness, illustrates this effect (Fig. 7). No deep rolling parameters and initial roughness values can be found, to eliminate the surface topography induced by hard turning. The surface improvement is always the same, if overlap factors close to 100 % are used. With respect to productivity the interactions have to be considered.

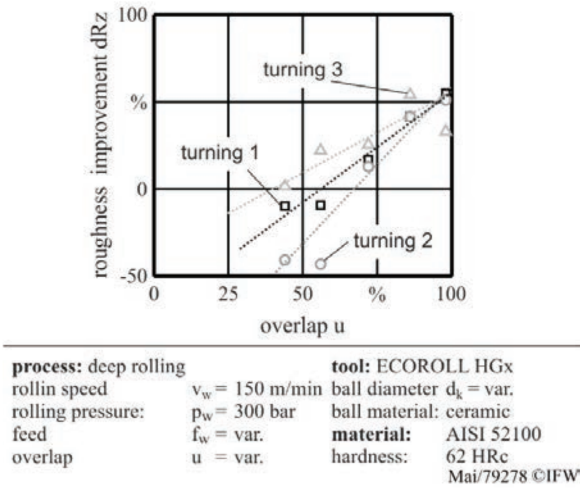

Fig. 7. Improvement of surface quality after deep rolling

5. Conclusiones and Outlook

To analyze the effects of the interactions of hard turning and deep rolling two sets of deep rolling experiments are conducted. In a first step the effects of deep rolling parameters on surface quality are analyzed. It can be seen, that the surface roughness is mainly influenced by the overlap factor. Rolling pressure and ball diameter do not affect the surface roughness.

In a second step the interactions between hard turning and deep rolling are analyzed. The resulting surface roughness is significantly influenced by the initial roughness. For very smooth surfaces (Rz = 1 µm) large overlap factors have to be used in deep rolling to improve the surface quality. However, even very small initial roughness values and overlap factor close to 100 % will not eliminate all surface roughness valleys after deep rolling. The hardness of the machined roller bearings is too high to smoothen the surfaces in total.

The results illustrate that the hybrid hard turn-rolling process can be applied as presented in Fig. 1. If the rolling tool is positioned on the roughness peaks, the plastic deformation in deep rolling does not lead to a fully elimination of the roughness. The peaks will be deformed. The hybrid turn-rolling process will improve the surface integrity of roller bearings and will lead to an increased endurance due to the reduced friction and the compressive residual stresses. Further steps to develop the process will be to apply hard turn-rolling.

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