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PROUCTION PROCESS

Influence of the cutting edge radius on surface integrity in hard turning of roller bearing inner rings

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Abstract Hard turning is used as a finishing process to machine hardened parts with very high accuracies. During the last decades it asserted as an alternative to conventional grinding processes due to higher flexibility and productivity. Furthermore, hard turning also increases positive effects on the surface integrity compared to grinding processes. Process parameters such as cutting speed, feed and cutting edge geometry influence the effect on subsurface area as well as the surface roughness. Many researchers have been analyzing these effects during the last years. However, they all cover one or two aspects of the surface integrity. Due to the fact that all researchers applied different experimental conditions it is almost impossible to compare the effects of hard turning on the surface integrity. The presented paper covers the effects of cutting speed, feed and cutting edge radius on the main factors of surface integrity residual stress, roughness, microstructure and hardness of roller bearings in a summarizing overview to identify the optimal parameter values for machining roller bearings with an increased endurance. Hard turning tests are conducted and the effects on residual stresses, surface roughness, hardness and white layers are analyzed. This overall view on surface integrity of roller bearings is necessary to improve the endurance of bearings due to a specific surface integrity design. The interactions between the surface integrity and the expected resulting endurance are discussed at the end of this article.

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Keywords Hard turning · Surface integrity · Roller bearings

1 Introduction

In the past, materials with a hardness above 47 HRC were machined only by grinding. Due to the development of new cutting materials such as pCBN, ceramics or coated carbide, these hard materials can be machined with defined cutting edge, e.g. turning or milling. These processes are defined as hard machining [1]. Highly stressed components are often hardened to increase their fatigue life. In most cases, the applied stress is close to the physical limit of the material properties. Examples for hardened parts are bearings, gears or guides [2–4]. Hard turning is more flexible and even more ecological due to the resignation of coolant, compared to grinding processes [2]. Another major advantage of hard turning is the larger effect on the surface integrity, which can influence the performance of roller bearings in different ways. The endurance of bearings is described by the classical Lundberg–Palmgren theory as an effect of the maximum shear stress within the contact area [5]. However surface roughness and residual stresses can affect the maximum shear stress in a positive or negative way. Due to surface roughness micro contacts occur, which lead to very high local stresses [6, 7]. Therefore a machining process achieving very low surface roughness values and the material ratio curves is aspirated. An increased loading of roller bearings within the shake-down phase can induce high compressive residual stresses, due to higher hertzian stresses. Results from Neubauer et al. showed that a higher loading during the first 1.5 million revolutions leads to an increased endurance from L_{10} =

25×10^6 to $L_{10} = 45 \times 10^6$ revolutions [4]. This effect can be included into the machining process, if hard turning is applied. Due to high mechanical and thermal loads in hard machining or even in rolling contacts, the microstructure of the workpiece changes. One example for microstructural changes are white shining areas after a metallurgical etching process, which is responsible for their name white layers. White layers are described as martensitic structures with a very high hardness [8]. However, rolling contact fatigue often occurs as a results of white etching cracks [9]. On the other hand studies show, that white layers, created by a hard turning processes, do not influence the endurance of roller bearings [10]. The effects of surface integrity on the endurance of roller bearings are summarized in Fig. 1.

Extensive research on the effect of hard turning process parameters on the surface integrity has been carried out in the past. However, it mainly focused on single aspects of surface integrity, such as residual stress, white layer or surface roughness. Following, the common opinion on surface integrity created by hard turning processes is discussed.

The combination of feed f and cutting edge radius r_β affects the resulting surface quality significantly [11]. The main effect on surface roughness has feed [12]. With feed values of less than $f < 0.1$ mm roughness values of $Rz < 1$ µm can be achieved on high precision lathes [13]. The theoretical surface roughness can be described for conventional turning processes depending on feed and corner radius r_ε. The difference between the real surface roughness and the theoretical roughness increases for small feed values [14]. In this case, the effect of the minimum uncut chip thickness h_{min} becomes more important, so that surface roughness increases [2]. Due to the ploughing effect described by Albrecht [15, 16], material is pressed underneath the cutting edge instead of being cutted out of the surface as a chip. If the uncut chip thickness is equal to the separation point height in the ploughing effect, the minimum uncut chip thickness is reached. An increasing cutting edge radius leads to a changing of the separation point and so the minimum uncut chip thickness increases [16]. From that aspect, the influence of the cutting edge radius becomes significant for the resulting surface quality. For hard turning processes the minimum uncut chip thickness is very close to the occurring chip thicknesses. Therefore, the cutting edge radius has to be considered more closely in machining of hardened parts [17]. Large cutting edge radii ($r_\beta > 50$ µm) smoothen the surface and produce better surface qualities for high feed values of $f > 0.1$ mm. In case of small feeds, the effects reverses and large cutting edge radii lead to a decreasing surface quality [18]. Cutting speed does not affect the residual stress within a common process window [19, 20]. An increasing feed leads to higher maximum compressive stresses, however, in axial direction the surface residual stresses shifts towards tensile stress [20, 21]. Similar to the feed, an increasing cutting edge radius also leads to a higher maximum compressive stress in axial and circumferential direction [18, 20, 21]. The microstructure can also be affected by the cutting edge radius. An increasing cutting edge radius leads to an increasing white layer thickness [20, 21] because of the increasing temperature within the contact area [22]. Due to the different effects of machining parameters on diverse surface integrity aspects, it is almost impossible to choose the optimal process parameters to increase the endurance of roller bearings. A smooth surface roughness, high maximum compressive stresses and the absence of white layers are important values to increase the performance of roller bearings (Fig. 1). These three key properties are significantly affected by the cutting edge radius, however, in a conflictive direction. Previous research did not consider how the cutting edge radius affects the surface integrity and how it interacts with cutting speed and feed with respect to increase roller bearings endurance. Presented results often focus on single characteristic variables of surface integrity. Often the researchers do not use comparable cutting conditions, as cutting material, coating, heat treatment of the bearings or cutting edge preparation, which makes it impossible to predict the effects of machining parameters on the surface integrity. Therefore, this research focuses on the interaction of process parameters and surface integrity to increase the endurance of roller bearings by hard turning.

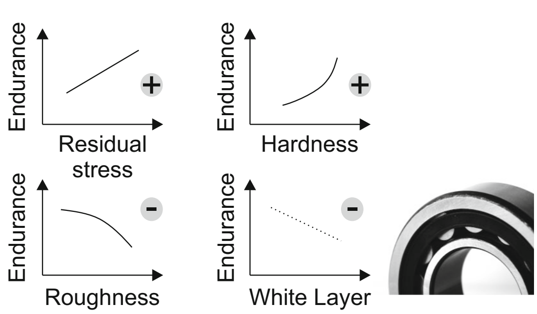

Fig. 1 Surface integrity affecting the roller bearings endurance

2 Experimental setup

The effects of process parameters and cutting edge geometry on the surface integrity of hard turned roller bearings are analyzed within this paper. Inner rings of roller bearings type 206NU are finished on a high precision lathe Hembrug Slantbed Microturn 100. The material of the bearings is AISI 52100 with a hardness of 62 HRC. The material properties are given in Table 1. To machine the

Table 1 Material properties AISI 52100

Parameter	Unit	Value
Material	–	AISI 52100
Material composition	–	86.6 % Fe; 10.9 % C; 1.5 % Cr; 0.7 % Si; 0.3 % Mn
Youngs modulus E	GPa	210
Yield stress $R_{p0.2}$	MPa	1370
Ultimate strength R_m	MPa	1570
Hardness	HRC	62

Table 2 Used cutting parameters for the experiments

Parameter	Unit	Range
Cutting speed v_c	m/min	100, 200, 300
Feed f	mm	0.03, 0.05, 0.07, 0.1, 0.2
Cutting edge Radius r_β	µm	40, 50, 70, 80, 100

rings with a very high accuracy, a clamping with a hydraulic expansion mandrel is applied. This clamping strategy provides an equal deformation around the whole part.

Multiple Ti (C, N) and Al_2O_3 coated DNMA150616 cemented carbide cutting inserts are used. For the coating a CVD process is applied. The tool holder DDJNL2020 creates a nominal rake angle of $\gamma = -6°$, a clearance angle of $\alpha = 6°$ and a tool cutting edge angle of $\varkappa = 93°$. Due to the combination of a nose radius of $r_\varepsilon = 1.6$ mm and a depth of cut of $a_p = 0.1$ mm very low surface roughness values are achieved. Within the experiments the cutting speed v_c, feed f and cutting edge radius r_β are varied (Table 2). The cutting speed and feed are chosen from conventional cutting parameters for hard turning mentioned within the literature. The literature also mentions large cutting edge radii to be positive to induce high compressive stresses, therefore cutting edge radii of 40 µm or greater are chosen for the experiments. The latter is limited to symmetric cutting edges K = 1. The cutting edge radius was produced by a brushing operation. Each cutting edge rounding was measured after the coating process using a GFM MicroCAD. Due to the fluctuation of the brushing process, cutting edge radii with a difference of ±5 % are used for the experiments. To minimize the influence of tool wear on the experimental results a new cutting edge is used for each parameter combination. During the experiment the cutting forces are measured with a three-components dynamometer Kistler type 9121. Dry cutting is applied.

The analysis of the surface integrity is done on several measurement devices. To detect the effect on surface roughness, the inner rings are analyzed tactile at five different positions, using a Mahr profilometer. Additional optical measurements are carried out using a confocal Nanofocus Microscope µSurf once per workpiece. Following DIN EN ISO 4287, in both cases a measurement length of 5.6 mm, a Gaussian filter and a cut-off $\lambda = 0.8$ mm is used. The measurements are applied in feed direction. The tactile measurement is used to create standardized values according to DIN EN ISO 4287. To analyze the material ratio curve more information about a surface area can be measured by optical surface measurements. Residual stress measurements are carried out using a X-ray diffractometer GE XRD 3000 P with Cu-Kα-radiation (35 kV and 30 mA). After the analysis of the residual stress the microstructure of the near surface area is characterized and micro hardness measurements are conducted. The microstructure is analyzed within the specimen of the bearing. The cross-section area is etched and analyzed with SEM. Micro hardness measurements are also applied in the cross-section with Vickers hardness method. All experiments are repeated one time.

3 Results and discussion

Roller bearings are highly loaded parts, which require a very low surface roughness. Tactile surface roughness measurements show that feed and cutting edge radius are the two main factors for surface quality. As known from literature, higher feed values increase the surface roughness due to larger feed marks. With a decreasing feed, the influence of cutting edge radius increases. First the ratio between cutting edge radius and the uncut chip thickness gets improved to create better surface roughness values. At a minimum point the geometric influence of feed and tool nose radius gets dominant and surface roughness increases. For cutting edge radius $r_\beta = 70$ µm within the conducted experiments this effect can be shown, by the surface roughness Rz decreases for feeds $f < 0.07$ mm and increases for higher feed values (Fig. 2). Following [14], this can be explained by an uncut chip thickness below the minimum uncut chip thickness. For large cutting edge radii the same effect occurs, whereas the minimum uncut chip thickness and therefore the critical feed increases as well. From the experiments it is not possible to identify the uncut chip thickness. However, the literature describes an increasing h_{min} with larger cutting edge radii. In Fig. 2 this effect is plotted by the grey lines. It can be seen, that the theoretical roughness, calculated by Brammertz [14], changes because of the increasing minimum uncut chip

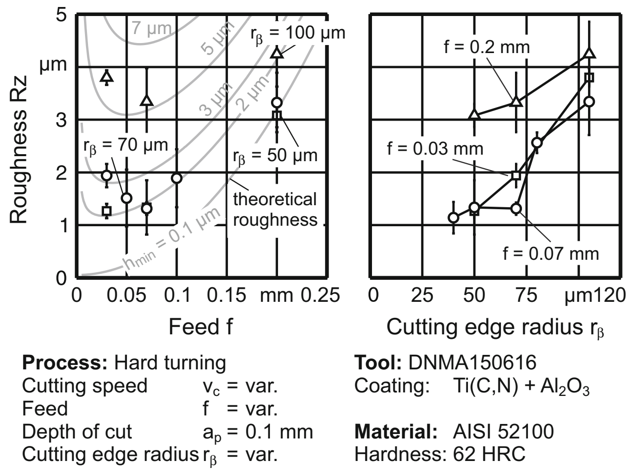

Fig. 2 Influence of process parameters on surface roughness

thickness. A further increase of the feed leads to an increase of the surface roughness. The results demonstrate a strong interaction between feed and cutting edge radius. On the other hand, cutting speed does not affect the surface roughness significantly. For a cutting speed of $v_c = 100\,\text{m/min}$ the surface roughness changes from $Rz = 1.32$ to $Rz = 1.74\,\mu\text{m}$ for $v_c = 300\,\text{m/min}$ ($f = 0.07\,\text{mm}, r_\beta = 70\,\mu\text{m}$).

In order to describe the effects of surface roughness regarding tribological effects, the material ratio curve (Abott curve) is used. The roughness values from the Abott curves (Rk, Rpk and Rvk) are mainly used by bearing manufactures to describe the tribological effects within the bearing. Conventional parameters as Rz or Ra are not suitable for that. Micro contacts between roughness peaks, described by Rpk, or micro dimples for lubrication support (Rvk) can be illustrated by the Abott curve. The Abott curves corresponding to the results above, are depicted in Fig. 3. A very smooth surface is represented by a very flat Abott curve with small inclinations. Typical turned surfaces have got large inclination within the curve. Honed surfaces are very flat with a large depth of profile at the beginning (0–20 %). The curves in Fig. 3 are based on 3D optical measurements. From the Abott curves the surface roughness values, core roughness Rk, peak height Rpk and depth of valley Rvk, can be identified. As seen from Fig. 2 the most important process parameters are feed and cutting edge radius. Feed also increases the core roughness Rk comparable to Rz. This leads to a higher inclination angle of the Abott curve. More important than feed for the functional roughness parameters is the cutting edge radius. Fig. 3 depicts the Abott curves for five different cutting edge radii and constant machining parameter $v_c = 200\,\text{m/min}$ and $f = 0.07\,\text{mm}$. An increase radius from $r_\beta = 40$ to $70\,\mu\text{m}$ results in a flatter curve. The core roughness

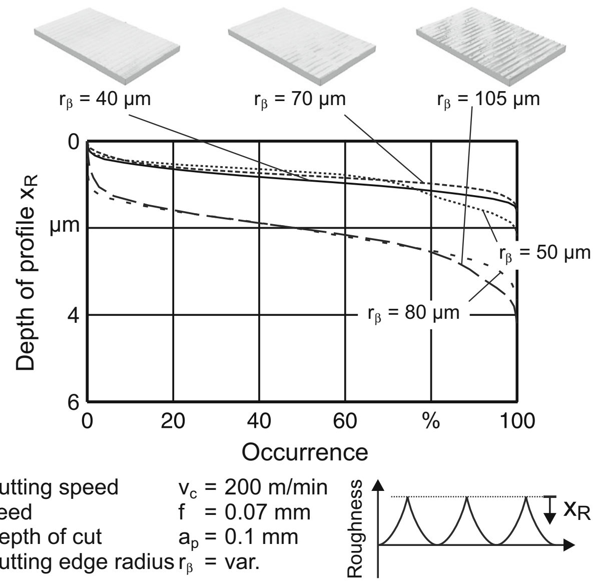

Fig. 3 Influence of process parameters on the Abott *curves*

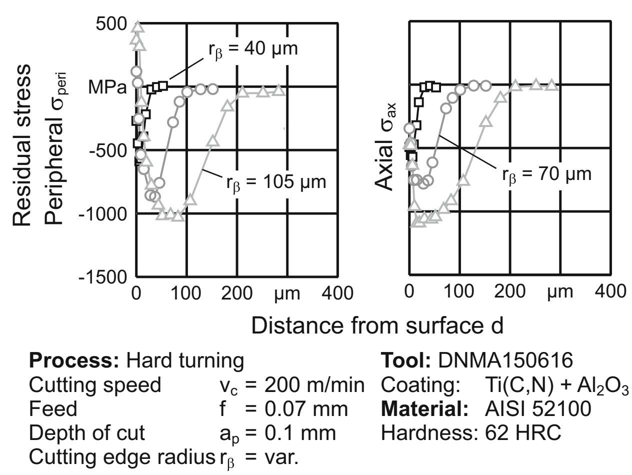

Fig. 4 Effect of cutting edge radius on residual stress profiles

decreases, as well as the peak height. If r_β increases more, the curves get shifted to higher depth of profiles with slight higher inclination angles. To machine smooth surfaces, the minimum uncut chip thickness should be chosen close to $0\,\mu\text{m}$, according to the theoretical roughness model by Brammertz [14]. This can be realized by sharp cutting edges. Due to the fact that large cutting edge radii also increase the tool life [16], feed and cutting edge radius have to be adjusted to each other. For the presented machining operation a cutting edge radius of $r_\beta = 70\,\mu\text{m}$ and a feed of $f = 0.07\,\text{mm}$ represent optimal settings.

The second surface integrity parameter determining the endurance of roller bearings is residual stress. Experiments demonstrate that large cutting edge radii are useful to create large compressive residual stresses within the near

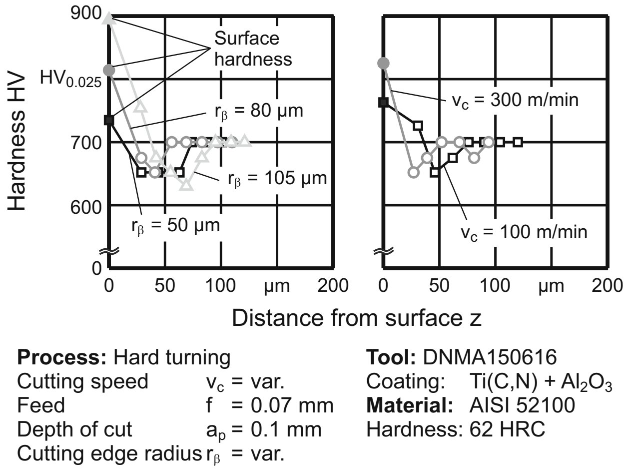

Fig. 5 Hardness affected by hard turning processes

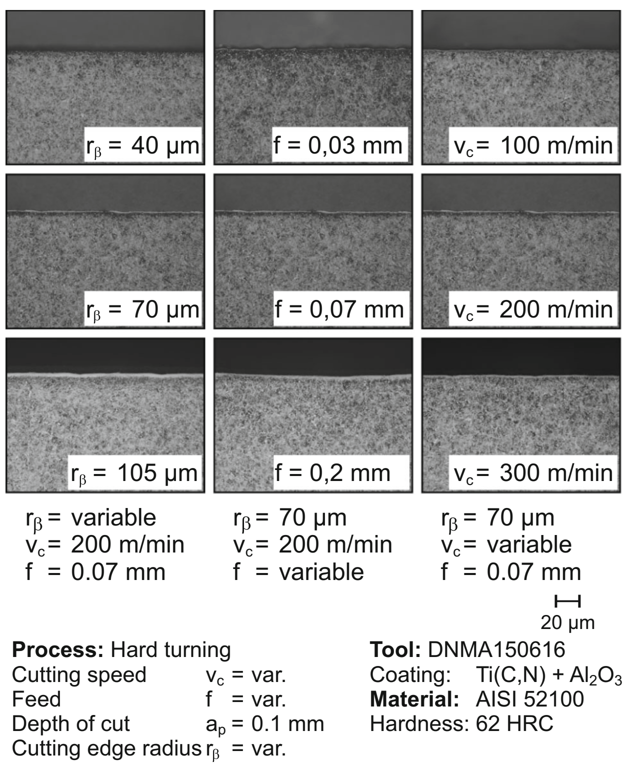

Fig. 6 Influence of process parameters on *white layer*

surface area. The cutting edge radius is the most significant among the analyzed parameters. The residual stress depth profiles are shown in Fig. 4. The maximum compressive stresses for peripheral and axial direction are comparable as common in turning processes. At the surface the experiments show slight tensile stresses in peripheral direction. With an increasing cutting edge radius the maximum compressive stresses raise, as well as the affected surface area. The compressive stresses increase for $\varsigma_{max,peri} =$ 570 MPa ($r_\beta = 40\,\mu m$) to $\varsigma_{max,peri} = 1050$ MPa ($r_\beta = 105\,\mu m$). These correlate very well with the resulting cutting forces. Whereas, the most significant force component is the passive force, which is affected mainly by the cutting edge radius. Therefore, hard turning with a large cutting edge radius causes high passive forces, which lead to high mechanical loads on the subsurface area. These loads lead to high compressive stresses. To increase the endurance of roller bearings, a compromise between surface roughness and compressive stresses has to be found.

In hard turning operations often so called white layers occurs. In general these layers are below 2 µm and occur due to large thermal and mechanical loads. White layers are hard areas, followed by a softer part of the material. The experimental results show an increase of the surface hardness from 720 $HV_{0.025}$ ($r_\beta = 50\,\mu m$) to almost 900 $HV_{0.025}$ for a large cutting edge radius. Again the radius is the most significant parameter affecting the surface hardness compared to cutting speed and feed. Figure 5 illustrates the surface hardness measured in radial direction as well as the depth profile determined in cross sections. The hardness profiles illustrate, how the hardness value at the surface increases with a larger cutting edge radius. At the same time the area beneath the surface also gets softer due to the effect of tempering. Also the affected area increases with higher cutting edge radii.

Figure 6 gives an overview of the resulting microstructure for the analyzed process parameters. The cutting edge radius has also the most significant effect on the occurrence and the thickness of white layer. These results correlate very well with the hardness measurements. For an increasing feed, the thickness of the white layer also increases slightly up to 1.5 µm, due to higher cutting forces. A white layer of less than 1 µm is produced by a cutting speed of 300 m/min. Increasing the cutting edge radius from $r_\beta = 40$ to 105 µm leads from no white layer to a very constant white layer thickness of more than 5 µm. The hardness of these layers can be seen in Fig. 5. Large radii produce big white layer thicknesses. The material is flowing under the cutting edge, due to the ploughing effect. This causes higher passive forces, as the conducted force measurements proof. Hence, higher friction occurs in the contact zone, which leads to higher temperature. As shown by Hosseini [22] an increasing temperature results in thicker white layers.

4 Conclusion

Improving the endurance of roller bearings by inducing a specific surface integrity design by machining requires a deep understanding of the interaction of the machining

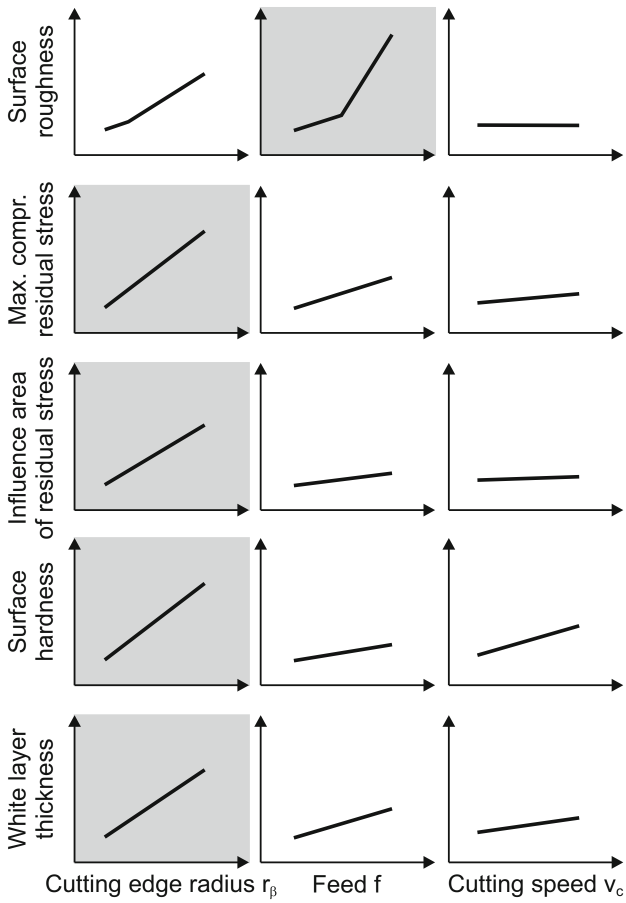

Fig. 7 Summarizing the effects of process parameters and cutting edge geometry on surface integrity

process and the fatigue life of roller bearing. Therefore, the effects of process parameters in hard turning on the surface quality, residual stress profile, microstructure and hardness are analyzed. Literature shows that all analyzed surface parameters can increase the endurance of roller bearings. However, these surface parameters have to be balanced, since due to interaction one cannot be improved without another is worsened. For example high residual stresses and a poor surface finish with $Rz > 1.5\,\mu m$ will lead to a very short endurance, because of an increasing number of micro contacts. Due to this required adjustments, also the process parameters need to be chosen wisely.

The conducted experiments highlight the most significant parameter to affect the surface integrity of roller bearings, which is the cutting edge radius. Large radii lead to bad surface finish, high maximum compressive residual stresses and big white layer thicknesses. Figure 7 qualitatively summarizes the identified correlations.

– Small surface roughness values can be produced by sharp cutting edges and very small feed values. Additionally to the well-known effect of feed for hard turning there is an interaction with the cutting edge radius. Within the conducted experiments the best combination is $r_\beta = 70\,\mu m$ and f = 0.07 mm.
– In order to create high compressive residual stresses within the surface in large distances from the surface, large cutting edge radii are necessary. Cutting speed and feed do not affect the residual stress profile for the analyzed parameter scope.
– Due to a higher cutting edge radius the thickness of the produced white layer increases which correlates with the hardness changes of the surfaces.

A surface integrity design for an increasing roller bearing endurance cannot be performed by a simple hard turning process. Additional processes have to be applied to create the necessary combination of a high surface quality and high compressive residual stresses. One possible process is deep rolling, which smoothens the surface and creates very high compressive stresses within the surface due to plastic deformations.

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