PRECOMPENSATION OF HARDENING DISTORTIONS ON A MACHINE TOOL BY ADAPTIVE SOFT MACHINING

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Abstract - At present mass production of bearing cages for automotive drive shafts requires a process chain with 15 steps. Because of distortion due to hardening half of these steps are hard machining operations. An adaptive machining strategy by means of a closed loop process control can be used for precompensation of hardening distortions. Thus, all hard machining operations can be avoided. This paper analyzes the sensitivity of correction values like tool paths, process parameters and the effects on surface integrity considering residual stresses for a prospective process chain control. The control based approach is implemented and validated on a turn-milling center. Hardening distortions are compensated by using nc-control for milling operations and by using models of residual stresses for turning operations.

Keywords - Predictive model, Process control, Surface integrity

I. INTRODUCTION

Bearing cages for automotive drive shafts have to meet sophisticated quality requirements. They must be able to support high loads and a long operating life. Additionally high accuracy is required during bearing manufacture to ensure that bearings run smoothly and save energy in the application. Thus, the permissible geometrical deviation is within a few microns. The present process chain for mass production of bearing cages consists of 15 steps, divided into soft and hard machining operations. This process chain represents high productivity and process reliability. However, due to high set-up times and resource requirements, the flexibility is restricted. Moreover, half of these process steps are hard machining operations that are necessary because of hardening distortions after case hardening. If these distortions could be compensated by an adaptive soft machining strategy, all hard machining operations can be eliminated. Thereby the new process chain has only five steps. Starting with a synchronous turn-rolling operation for the outer and inner contour, after that the windows are manufactured by an HPC milling operation. The geometric result of all soft machining operations is determined by an in situ check on the machine tool. After the inductive hardening as the final machining operation, the bearing cage is checked in an end-of-line measurement (Fig. 1).

To achieve the demanded surface roughness and to get a defined compressive residual stress depth profile in just one turning operation step a novel machining process is needed. Therefore, a hybrid turn-rolling process has been developed, based on the concept of Denkena et al. [1]. In order to shorten the process time and to improve the surface integrity the approach of this development is the combination of turning and deep rolling in just one process step. In contrast to conventional turning processes, an additional deep rolling process induces high compressive residual stresses and smoothens the surface [2]. In turn-rolling the deep rolling ball is mounted right behind the cutting edge. The deep rolling tool can be positioned relative to the cutting edge in feed direction [8]. As a result, compressive residual stresses can be achieved without a separated process step leading to a reduced process time (Fig. 2). Turning operations often lead to tensile residual stresses because of process temperatures. The innovative turn-rolling process leads to compressive residual stresses like σ = -600 MPa (Fig.2). The highest stresses are measured in axial direction. The current state of the research shows that the mechanical surface strengthening process deep rolling is a suitable method for altering the surface integrity and to increase the strength and lifespan of highly stressed components [3, 4, 5]. The influence of the process parameters on the residual stresses and the surface roughness of turn-rolling as well as the distortions is not known in detail, yet.

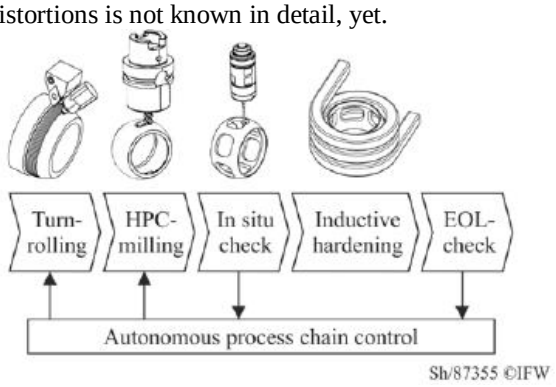


Fig. 1. Novel process chain for mass production of bearing cages

The aim of this research is to analyze and predict the effects of the process parameters on the surface quality and the surface integrity after the turn-rolling process. Besides the hardening distortion must be

minimal, the surface roughness of the workpiece must be limited with $Rz \leq 6.8$ µm so that the conventional hard machining is not necessary anymore.

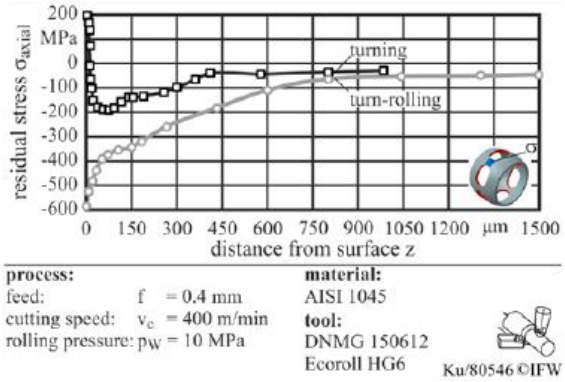


Fig. 2. Residual stresses after tuning and turn-rolling

To increase mechanical properties, like hardness and brittleness of soft machined parts a hardening process is necessary. In case of induction hardening the metal part is heated by induction and immediately quenched. The mechanical improvements are caused by a martensitic transformation but leads to distortions according to the nominal workpiece geometry. For reducing these distortion errors serval research activities are related to the development of special hardening sequences by a power control system [6] or simulation based quenching spray strategies [7]. However, a following grinding operation is still necessary. To eliminate all grinding operations, the following research hypothesis is established: All deterministically hardening distortions can be compensated by an adaptive soft machining on a machine tool.

In order to omit all hard machining operations an adaptive machining strategy by means of an autonomous process chain control is proposed for a precompensation of hardly avoidable hardening distortions (Fig. 1). By adapting the process parameters and the tool path the precompensation affects the turn-rolling process as well as the HPC-milling process to comply all geometric and mechanical demands after the inductive hardening. The presented bearing cage is mainly composed of three geometric shapes. Two spheres for the outer and inner contour and six rounded rectangles for the windows to guide the bearing balls. Therefore, two essential modules are needed:

1. A model providing residual stresses and the surface roughness based on common process parameters as well as considering distortions at turning operations (Chapter 2)
2. An algorithm to adapt tool path in soft machining considering the hardening distortions at milling operations (Chapter 3)

Furthermore, both approaches have to be as accurately as complying the close-tolerance requirements of the bearing cages as well as being executable on an industrial machine tool control.

II. PRECOMPENSATION OF HARDENING DISTORTIONS BY TURN-ROLLING OPERATIONS

The investigated bearing cages are machined of AISI 1045. In the direction of the z-axis they are 41 mm long and have a maximum diameter of 74 mm. To analyze the influence of surface integrity on hardening distortions the following experimental setup is used with the variation of the deep-rolling pressure (Fig. 3). The deep-rolling pressure is set to 0 MPa and 20 MPa. The other machining parameters are kept constant (cutting speed v_c = 250 m/min and feed f = 0.2 mm). The deep-rolling pressure is varied over the circumference. After the soft machining process, the inductive hardening process leads to a hardness of about 54 HRC. Subsequently, a coordinate measuring machine quantifies the deviation of roundness caused by the hardening distortions. Out of roundness is measured as the difference between the maximum and minimum diameters. From the results, it can be seen that the deviation of roundness is minimized by deep-rolling and as an effect by inducing compressive residual stresses (Fig. 3, right). The deviation of roundness can be reduced by 75% from t = 150 µm to $t \leq 40$ µm.

Besides, the surface roughness has to be considered. That leads to a conflict of aims between the desired roughness Rz and the compensation of hardening distortions. For both aims, the hydrostatic pressure of the turn-rolling process is needed, but it is not known how the turn-rolling process has an effect on both aims at the same time, yet.

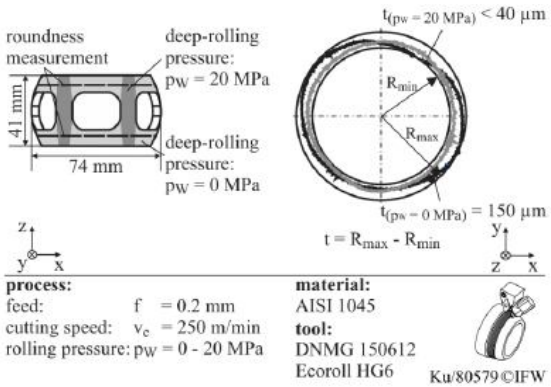


Fig. 3. Influence of surface integrity on hardening distortions

Furthermore, compressive residual stresses are required, which lead to higher lifespans because of preventing crack initiation. Besides this paper shows, that the residual stresses can be used for the precompensation of hardening distortions. The knowledge about the interactions between the process parameters and the effects on the results is essential to realize a specific design of the surface integrity.

2.1. Experimental Setup

The mentioned bearing cages are machined on a turn-milling center type DMG CTX 800 beta 4A. In the hybrid turn-rolling tool a tool holder PDNNL 2525 is used with coated carbide inserts. The turning insert has a D-geometry and an corner radius of $r_\varepsilon = 1.2$ mm (DNMG 150612). The rake angle is $\gamma = -6°$. An ECOROLL HG6 hydrostatic rolling tool is used for deep rolling. The rolling ball is made of ceramic with a diameter of $d_k = 6.35$ mm.

A central composite design (CCD) is used for the experimental setup. All in all, twenty different specimens are machined by turn-rolling. The variable parameters are the deep rolling pressure p_W, the cutting speed v_c and the feed f. The deep rolling pressure is varied between $p_W = 2.6$ MPa and $p_W = 9.3$ MPa. Furthermore, the cutting speed is varied from $v_c = 132$ m/min to $v_c = 468$ m/min. Besides the feed has been set between f = 0.13 mm and f = 0.46 mm (Table 1).

rolling parameter	rolling pressure p_w *(MPa)*	feed f *(mm)*	cutting speed v_c *(m/min)*
minimum	2.6	0.13	132
maximum	9.4	0.47	468

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

The $\sin^2\psi$ residual stress measurements are carried out using a GE XRD 3003 TT X-ray diffractometer with Cr Kα-radiation (30 kV and 35 mA). The tactile measurement of the surface roughness is carried out with a perthometer Concept (Mahr). The measurement of each specimen is repeated five times at different sections to detect the mean values and the deviations.

2.2. Influence of deep-rolling on surface integrity

The current state of research shows a few approaches for modelling residual stresses like Ulutan and De León [9, 10]. De León describes the depth path of residual stresses depending on specific characteristic values. These values build a parabolic function. On the other hand, Ulutan describes the depth profile as a sinus-decay function. In conclusion, the models can be used but for an adaptive soft machining it is very complex to get the required constants. For an adapted model concerning the residual stresses of soft materials, a simplified approach is shown in figure 4, 5. It is based on a regression model. The maximum stress for soft materials is at the surface and the depth profile cannot be described as a parabolic function. This effect occurs because of reaching the yield strength of the material at the surface. As a result, plastic deformation at the surface is a consequence while deep rolling AISI 1045 [11]. Consequently, a significance analysis is done to get a deeper insight in how the process parameters effect the residual stresses (Fig. 4). For this purpose, only the compressive maximal residual stresses at the surface are considered. This leads to a simplified residual stress model while turn-rolling on a machine tool. Subsequently, this leads to a simple way to integrate the model into the machine control later.

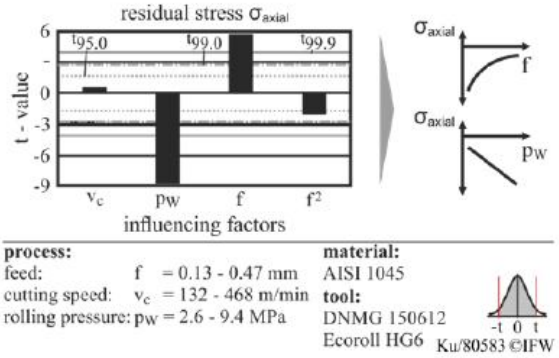


Fig. 4. Significance analysis of residual stresses

As a result, the process parameters deep-rolling pressure p_W and feed f are the most significant parameters influencing the residual stresses. The t-values are negative because of the negative sign of the compressive residual stresses. By increasing the deep-rolling pressure p_W the compressive residual stresses are rising. Moreover, the feed f and the quadratic feed f^2 are significant. Within the limits of table 1 the compressive residual stresses decrease with a higher feed.

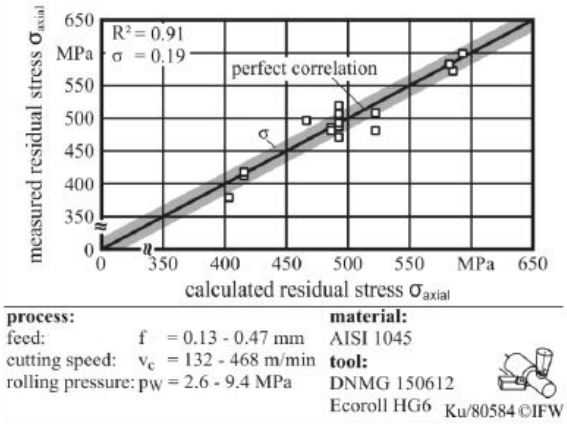


Fig. 5. Regression model of the maximal residual stress at the surface

Figure 5 shows the regression model for the maximum of compressive residual stresses at the surface. The model is valid for the parameters within the limits of table 1. Besides the values of the parameters have to be normalized. The simulated values of the residual stresses have a good consistency with the measured values. The coefficient of determination is $R^2 = 0.91$ with a root mean square error (RSME) of $\sigma = 0.19$.

$$\sigma_{axial} = 35f - 53p_W - 12f^2 - 493 \qquad (1)$$

Besides residual stresses, surface roughness is an important property of surface integrity to improve the life span of machined components. As a significant parameter the surface roughness Rz is analyzed. In a first step a significance analysis is done. As a result, the process parameters feed f and deep-rolling pressure p_W are the significant parameters influencing

the surface roughness Rz (Fig. 6). By increasing the pressure p_W in deep-rolling the surface roughness Rz decreases. In contrast, rising feed rates result in higher roughness values (Fig. 6).

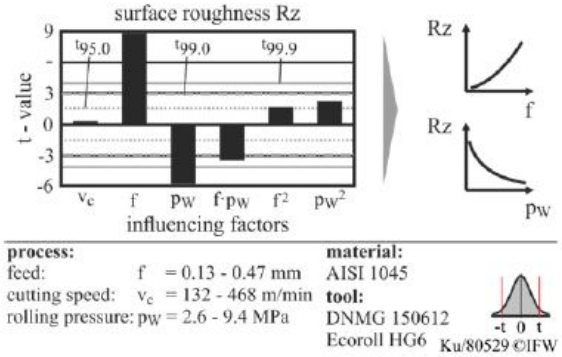


Fig. 6. Significance analysis of surface roughness Rz

The modelling approach for the surface roughness Rz depends on the process parameters deep-rolling pressure p_W as well as feed f and the interactions and is based on a regression model (Fig. 7).

$$Rz = 2f^2 + 2p_W^2 - 3.5f \cdot p_W - 6p_W + 24f + 39 \quad (2)$$

The simulated values of the surface roughness Rz have also a good consistency with the measured values. The coefficient of determination is $R^2 = 0.97$ with a root mean square error (RSME) of $\sigma = 0.23$. As an interim conclusion, it could be shown that simple models are sufficient to model the effects on surface integrity by turn-rolling. This is a necessary requirement for implementing models into a machine control.

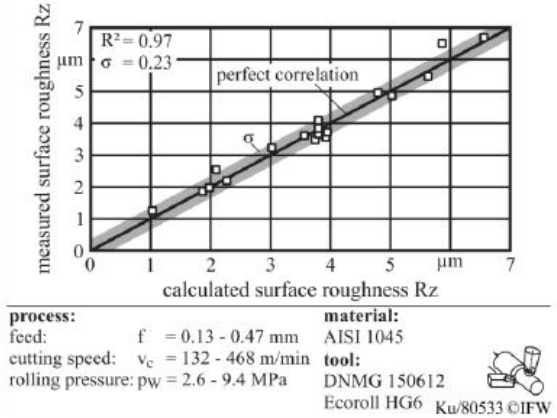


Fig. 7. Regression model of surface roughness Rz

III. PRECOMPENSATION OF HARDENING DISTORTIONS BY MILLING OPERATIONS

To eliminate hard machining operations after the inductive hardening process a higher-level process chain control is required. On the one hand this process chain control considers the effects of each operation and on the other hand selective operations can be used to adapt actuating variables of the control loop. Therefore, the results after soft machining and hardening operation for each workpiece are stringently required. Based on this data an overall process chain control is developed (Fig. 8). For linking all machining operations a cascaded structure is chosen as a control strategy.

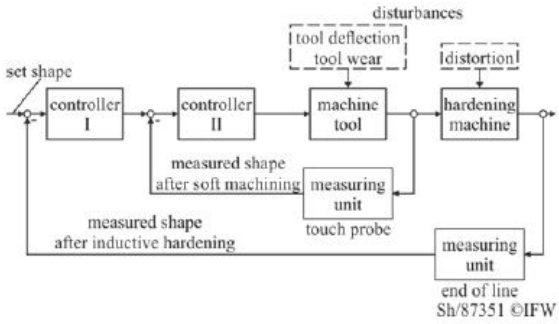


Fig. 8. Cascaded process chain control

The set point of this controller is given by the nominal workpiece geometry (set shape). Measuring the soft machined geometry on the machine tool represents the feedback of the inner control loop. The outer control loop considers the influence trough the induction hardening machine. The inner control loop considers external disturbances like tool deflection and tool wear for turning and milling machining. Major disturbances on the outer control loop are the hardening based distortions, which affect in geometrical errors on finished parts. With regard to shape and dimensional accuracy the windows of the bearing cage have particular requirements. Therefore, in this paper the process chain control is demonstrated for these windows.

Each window is described by four independent points to consider deviations in absolute windows height h_w, window center c_w and skew errors α (Fig. 9).

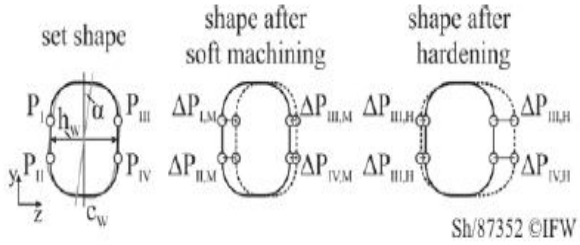


Fig. 9. Window shapes for each process step

These skew errors are affected by thermo-mechanical deviations of the two turrets, which are used to machine the windows in parallel. Tool deflection and tool wear affects directly the window hight h_w after soft machining. To separate the effects of soft machining and hardening operation on the window shape two differential vectors are defined. $\Delta P_{n,M}$ describes the signed deviation in z-direction for each point n=I…IV after soft machining. $\Delta P_{n,H}$ describes just like $\Delta P_{n,M}$ the signed deviation of hardening distortions. A Blum 3D touch probe (TC54-10T) on the sub spindle measures the actual geometrical condition of all six windows, after machining the first

bearing cage (without any compensation) on the main spindle. The repeatability of this touch probe is quantified with 0.4 µm 2σ. Based on this measurement the differential vector $\Delta P_{n,M}$ is calculated for each window and the next workpiece will be machined with these compensation values in z-direction. The control of the window shape is directly implemented on the Siemens Sinumerik 840D SL control of the machine tool.

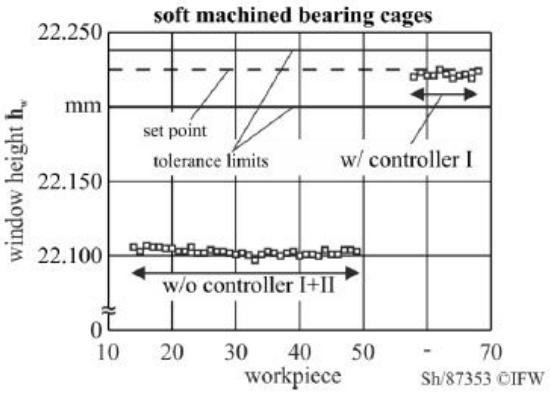


Fig. 10. Result of activation the inner loop (controller II) for soft machined work pieces

Therefore, the tool path of the milling process has to be parametrical to set the control variable for each window point P_n. Thereby overall 24 global variables are required on the machine tool control. Fig. 10 shows the result after activating controller I. Workpiece 1 – 39 are machined without any compensation. It is shown, that the window height is outside the given tolerance as well as the trend of a decreasing window height caused by increasing tool wear. The differential vector $\Delta P_{n,M}$ considers both effects and parametrize the gain of controller I designed as a p-controller. The gain update rate is defined at every tenth workpiece.

After hardening the bearing cages machined with an activated controller I the hardening distortions result in an increasing window height. In this case even a grinding operation to correct the hardening distortion is not required. Thus, each window is measured after the hardening process by the end-of-line measuring unit. With the determined hardening distortion of each window the second differential vector can be calculated and parametrize the gain of controller II which is also designed as a p-controller.

Figure 11 shows the effect by activation of controller II. The measured window height hw after the hardening process is inside of the given tolerance and close to the nominal window height. It is also distinguishable that the window height deviation after hardening is higher than after soft machining. However, the controller is not able to compensate this deviation.

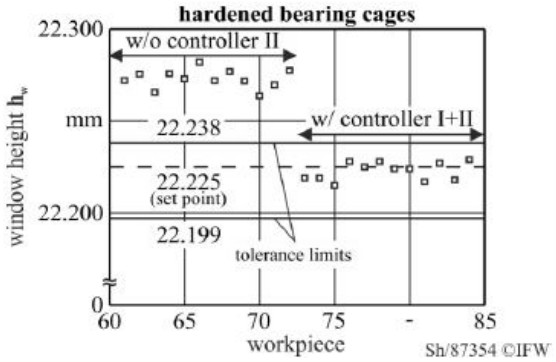


Fig. 11. Result of activation the inner and outer loop (controller I + II) for hardened workpieces

CONCLUSION AND OUTLOOK

The article presents an approach to realize an adaptive machine control by implementation of simple models concerning surface integrity and surface roughness. Within this research, a predictive model for surface integrity and its influence on the hardening distortions are analyzed. Furthermore, a new approach for the precompensation of hardening distortions regarding window shapes is presented. The motivation of the present paper is based on the influence of surface integrity on hardening distortions which is discussed in a first step. Therefore, the deviation of roundness is analyzed. With the innovative turn-rolling process the deviation of roundness can be minimized after the inductive hardening process. The presented example with bearing cages demonstrates the potential of reduction by 75%. In a second step, the influence of deep-rolling on surface integrity is analyzed. Concerning the residual stresses deep-rolling of AISI 1045 leads to nearly linear depth profiles with the maximum of compressive residual stress at the surface. Besides the influence on the surface roughness is analyzed and a regression model is developed as a function of the machining parameters. The feed f and the deep-rolling pressure p_W are the most significant parameters. Thus, simple models for future integration have been developed. Regarding the windows of such bearing cages a new approach is shown for the precompensation in the third step. Therefore, a cascaded control loop with two p-controller is designed. The first controller considers disturbance variables on soft machining like tool wear and tool deflection. It could be shown that the process chain control is able to ensure the nominal shape after soft machining. With this an important precondition was fulfilled to determine the effect of hardening distortions on the bearing cage window height. Based on this dimensional deviation the second p-controller adapts the soft machining tool path. The result of this control strategy was verified in serval machining cycles and demonstrates the feasibility of elimination of hard machining operations after hardening processes.

In future investigations, the presented approach has to be implemented onto the machine control. To that, the individual models must be programmed into the system of the machine control. On this basis the machine control can calculate the required process parameters. The machine operator has only to input the desired result concerning the surface roughness and the residual stresses and then the machine control is able to machine the workpiece with the process parameters that are necessary for the desired workpiece properties autonomously.

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