ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 62 (2017) 329 – 334

www.elsevier.com/locate/procedia

10th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '16

Tool deflection control by a sensory spindle slide for milling machine tools

Berend Denkena[a], Dominik Dahlmann[a], Haythem Boujnah[a*]

[a]*Leibniz University Hanover, Institute of Production Engineering and Machine Tools (IFW)*

* Corresponding author. Tel.: +49 511 762 18327; fax: +49 511 762 5115. *E-mail address:* boujnah@ifw.uni-hannover.de

Abstract

A conventional spindle slide of a milling center is enhanced to a force „feeling“ component for process monitoring and control tasks. The feeling ability is realized by integrating strain gauges in notches machined into the structure. This force sensing allows the identification of the static tool stiffness and enables the online detection of the tool deflection during milling processes. Based on a communication via PROFIBUS between the monitoring system and the machine control, the tool deflection is controlled online in the milling center by adjusting the axis feed. The approach shows considerable improvement regarding surface accuracies.

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Feeling machine; process monitoring; process control; tool deflection

1. Introduction

Nowadays, the trend in the production sector is edging towards more individual products. As a consequence, the producers have to adapt to a further increase in the variance of the product spectrum with decreasing its lot size. This development results in generally higher demands on intelligent and autonomous systems for process monitoring and control, that may help to reduce incurred additional costs in comparison to mostly cost optimized series productions.

Systems for process monitoring in milling are widely used. They allow the early detection of process failures such as chattering [1], tool wear and breakage [2], tool deflection [3], clamping failures [4], etc. However, previously developed control systems are generally restricted to optimizations regarding process load [5] or process stability [6]. Approaches for process quality control have been subject to only little research.

The tool deflection represents one of the most important quality degrading effects in milling. It occurs generally in any cutting process due to the compliance of the used tool and process forces. It causes a deviation between the real and the reference path of the tool and illustrates therefore shape and dimension failures on the workpiece side. Required manufacturing tolerances can no longer be maintained. Furthermore, especially in the processing of complex free form geometries and in finishing processes, the tool deflection has a decisive influence on the productivity.

In order to reduce the tool deflection and to achieve the desired manufacturing tolerances, appropriate cutting parameters have to be determined. Therefore, several tests must be carried out in advance of series production. However, this is very time consuming and often associated with high costs. With respect to single-item-production and especially in the mold and die production, where often very tight tolerances are required, this approach has limited application in terms of its economy.

This paper focuses on the development of a monitoring and control system for the tool deflection for milling. The monitoring system is based on a “feeling” spindle slide of a milling center DMG HSC30 linear. The online control is realized by adjusting the axis feed using a data communication between the monitoring system and the machine control.

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2016.06.059

2. Sensory spindle slide

The integration of strain gauges in mechanical structures represents generally a promising and a cost-effective way to measure occurring forces. With respect to machine tools, the detection of force-dependent strain becomes more difficult since machine tool components are designed to achieve maximal stiffness and positioning accuracy. However, previous works on a spindle slide of a milling center DMG HSC55 linear show that the application of micro strain gauges into small notches on such a stiff structure is a promising approach for the improvement of the sensitivity to load. Because of the small dimensions of the notches, the changes of the slide main stiffness are negligible [3]. A further challenge by the sensor integration is to find optimal positions in the component, where notches and strain gauges can be applied. These positions depend generally on the component structure and the resulting force flux, which is mainly affected by the support, carriage and the load situations. Changes in the force flux in the structure cause a variation in the strain state and influences the distribution of the sensor positions.

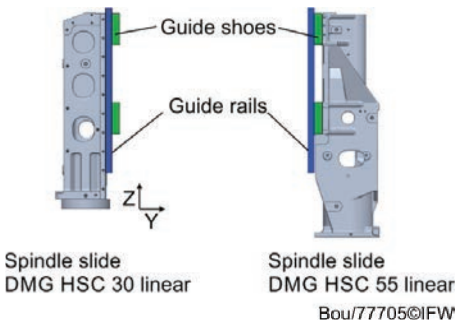

Fig. 1: Carriage situation of the spindle slides in DMG HSC30 linear and DMG HSC55 linear

The spindle slide of the milling center DMG HSC30 linear is subject of the investigation in this work. This slide shows a totally different design and carriage situation to previously investigated spindle slide of the milling center DMG HSC55 linear. The guide rails of the carriage are assembled on the slide side (Fig. 1). While driving the slide along its z-axis, the distance between the lower guide shoes and the free end of the slide is varying and causing changes on the slide stiffness and the force flux. Therefore, these facts has to be considered by determining the sensor positions.

2.1. Approach for sensor positioning

In order to estimate the occurring strain and to determine optimal sensor positions in spindle slide, static structural finite element analyses on ANSYS® Workbench™ are conducted. During simulation, the contact surfaces between the guide rails and the guide shoes are shifted step-by-step equidistantly along the guide rails and are modeled as fixed support by fixing correspondent mesh nodes. Each shifting step corresponds to a new location of the slide along its z-axis with different main stiffness.

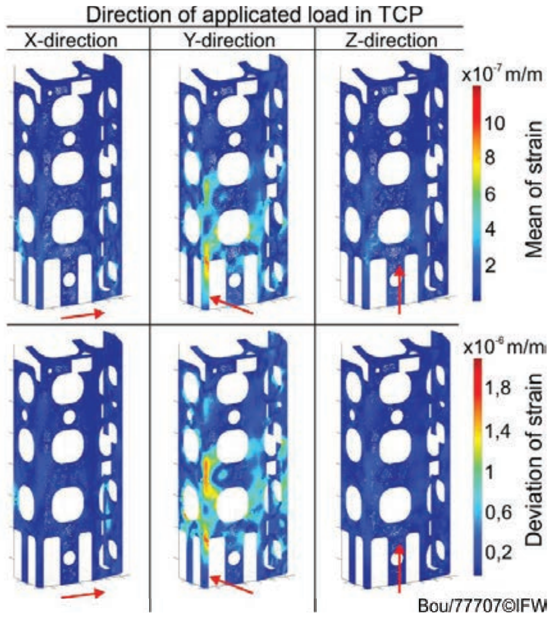

Fig. 2: Mean and deviation values of strain for different load directions

Based on the exported strain values of the slide, each mesh node is statistically evaluated by building the mean value and the deviation of its strain for the simulated load steps (Fig. 2). The strain mean value provides information about the sensitivity of the mesh node to load. Its deviation is a measure of the sensitivity variation while the slide is moving along the z-axis. Accumulations of adjoining mesh nodes showing similar sensitivity behavior represent optimal positions for sensor integration. It can be distinguished between two kinds of sensor positions: the first kind comprises sensor positions that depend on the z-axis position of the slide. Such positions show high mean values of strain and strain deviations. In these positions, strain sensors would generate intense signals showing strong deviation between the z-axis ends. In this case a sensor calibration with respect to the z-axis-position of the slide is indispensable for accurate measuring of the process forces. The second kind of sensor positions is nearly independent of the z-axis position of the slide. These sensor positions show generally lower mean values and lower deviations of strain. However, in such positions, sensor signals with sufficient amplitudes but nearly independent from the actual z-axis position would be provided.

2.2. Realization of the sensing system

After determination of optimal sensor positions, notches are manufactured on the original spindle slide. For strain detection, miniature strain gauges HBM 1-LY11-0.3/120 are integrated into the small notch grounds (Fig. 3). The strain gauges are connected up as a Wheatstone bridge to a new developed miniature electronic device for signal processing. Within the electronic device, the strain signal is filtered, amplified, sampled and finally communicated via CAN-BUS to an industrial PC. The actual version of the device allows sampling rates up to 2000 Hz depending on the used CAN-BUS configuration. In addition, the signal device is able to balance automatically the measuring Wheatstone bridge before starting the signal sampling. The integrated balancing unit is required for active compensation of big signal offsets due to strains caused by the own weight of the slide after mounting in the milling center or by thermal drift of the strain gauges. An aluminum lid is used for sealing and the protection of the whole sensor system against humidity, chips and electromagnetic disturbances while cutting.

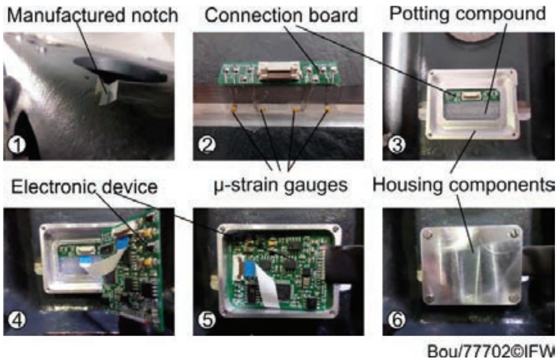

Fig. 3: Integration steps for strain gauges into a notch

Fig. 4 shows the sensitivity of the integrated sensors to loads applied in the directions x, y and z in machine coordinate system, and according to different z-axis positions of the slide. In general, the sensitivity appears greatly depending on the sensor, the z-axis position of the slide and the load direction. It shows that in the z-direction the sensors are less sensitive in comparison to x- and y-directions. This is caused due to the higher stiffness of the slide in that direction. Furthermore some sensors are sensitive only in certain directions like sensor 1 and sensor 4 for the y-direction, and sensor 2 for the x-direction. A strong dependence of the sensitivity on z-axis positions appears by certain sensors like sensor 5 for the x-direction, and sensor 3 to sensor 6 for the y-direction. However, low dependence, appears by sensor 1 and sensor 4 for the y-direction, and by sensor 2 for the x-direction.

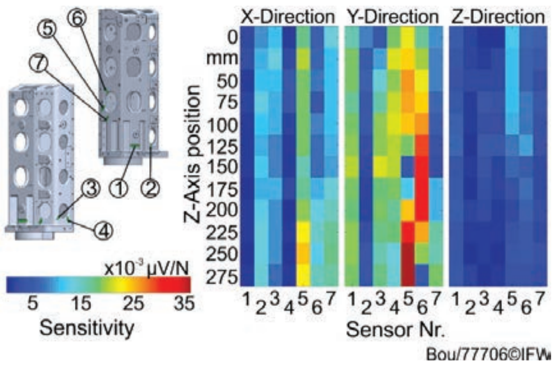

Fig. 4: Sensitivity of the determined sensor positions

2.3. Force calibration and measuring

A force calibration is required to measure the forces by the sensory slide correctly using the strain signals of the integrated strain gauges. Therefore, calibration matrices are computed by linear regression analysis using the strain signals and reference force signals while load application on the TCP of the slide. During calibration measurements, the forces are applied individually in the directions x, y and z in machine coordinate system. The reference force signals are provided by a force sensor HBM U9C with a nominal force of 1 kN. The calibration is made for a fixed z-axis position of 200 mm.

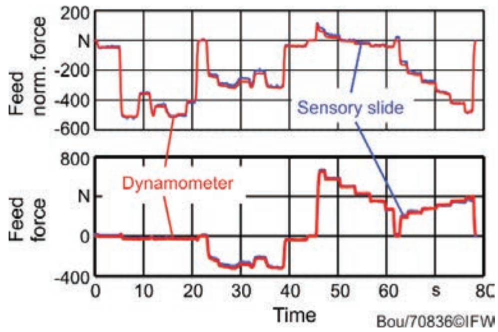

Fig. 5: Force measuring by the sensory slide in milling

After calibration, force measurements while milling are performed to evaluate the calibration quality. The force signals are measured during up-milling operations by varying the cutting width. The reference forces are provided by a dynamometer Kistler 9257B. The filtered reference forces and the filtered slide forces after calibration are plotted in Fig. 5. It shows that the spindle slide forces can be approximated well with standard linear regression for the calibration methods. The calculated deviations of the slide forces to the reference grow up to maximal 10% in the range of 500 N. The force resolution of the spindle slide varies between 20 and 30 N depending on the signal sampling and filtering.

2.4. Detection of tool deflection

For the detection of the tool deflection, the force signals and the bending stiffness of the used tool are required. The force signals are provided online by the sensory slide. The measurement of the bending stiffness can be executed in the machine tool by a soft collision of the tool with the workpiece. Therefore, the spindle slide is moved slowly into the workpiece, until a defined contact force is detected. From that position the slide continues the movement for a set distance. Since the tool is modeled as a cantilever beam, the bending stiffness of the slide can be calculated from the known set distance and the measured force variation. Fig. 6 shows exemplarily the deflection signals at 3 different positions along the tool axis by milling of a pre-machined workpiece with alternating ribs. For a detailed description of the measurement method please refer to [3].

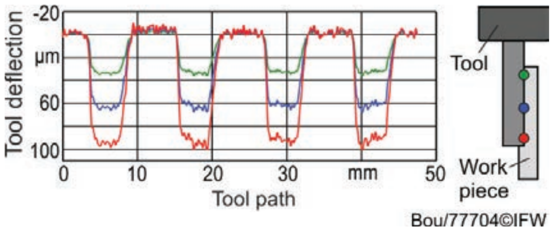

Fig. 6: Online measuring of the tool deflection in milling

3. Tool deflection control

3.1. Control loop for tool deflection

The main objective of the control loop (Fig. 7) is to maintain the actual tool deflection d_{Act} while milling constantly at a desired reference deflection d_{Ref} by adjusting the axis feed of the machine despite of disturbances in process. Such disturbances may be per example unexpected fluctuations in allowances in casting parts, that cause changes in the cutting parameters like the cutting width a_e or the cutting depth a_p within a straight path. The actual deflection is measured by the sensory spindle slide and is compared to a given reference, which can be calculated from the required shape and dimension tolerances of the workpiece. The occurring difference e, called also the residual error, is applied to the control system, which provides the required feed override OVR for the machine control. For safety reasons, a signal limitation is integrated at the input of the machine control, so that the feed override can be varied only between 0 and 120%. For the implementation of the control loop, an industrial PC with real-time controller and programming environment TwinCAT3 from Beckhoff is used.

The used milling center DMG HSC30 linear is equipped with a machine control of type Siemens SINUMERIK 840d. The override signal of the control system and further command signals are transferred between the industrial PC and the machine control via PROFIBUS communication. The Signal transfer on the Siemens control is performed by programming synchronous actions, which are implemented within the NC program. The signals can be read out in the interpolation cycle rate of the controller achieving a sampling rate of maximal 1000 Hz.

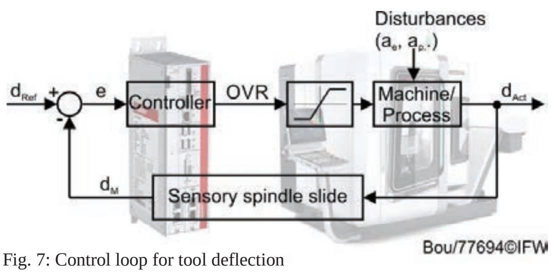

Fig. 7: Control loop for tool deflection

3.2. Control system structure and tuning

The required control for tool deflection should be fast enough to react quickly to changes in the measured deflection signals and accurate to eliminate completely the detected residual error. Furthermore, the control should show a quiet behavior by providing the override signal for the machine control. Disturbances in the override can cause damage to the machining surface and the control application has no more benefits. PID-controllers are probably the most used controller structures in industrial applications. However, for the deflection control, the PID-controller may be unsuitable because of the unrest of its derivative component in combination with noisy signals. Instead, a PI-controller may be more suitable for this control task. It combines the advantage of the P-controller, namely the rapid response to error, with the exact settling of an I-controller. The PI-controller is fast and accurate. Its manipulation algorithm is in (Eq. 1), where k is the number of sample, K_p the gain of the P-controller, the K_i the gain of the I-controller, T_a the sample time and OVR_{mid} the initial override value:

$$OVR_k = K_p \cdot e_k + K_i \cdot T_a \cdot \sum_0^k e_k + OVR_{mid} \quad (1)$$

The initial override value OVR_{mid} is set to 70% to allow the controller settling in both directions.

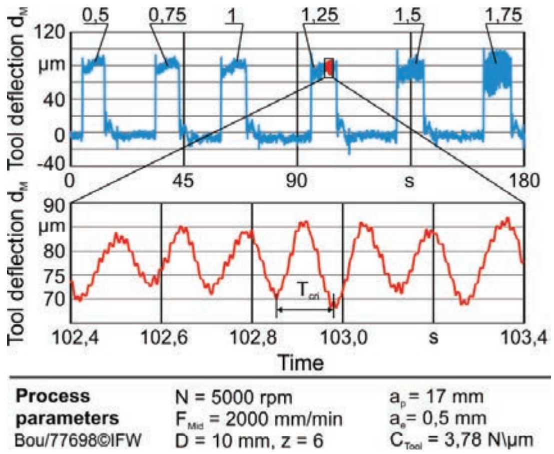

Fig. 8: Deflection signal at stability limit while controller tuning for different values of the gain K_p

To get effective starting point for the controller tuning, the second method of Ziegler-Nichols is used [7]. This method is practicable for systems, whose transmission behavior is unknown or not easily identifiable, and which can be driven to their stability limits without causing damages. Under this method, only the P-controller is activated in the control loop. Fig. 8 shows the deflection signal at the stability limits by applying the Ziegler-Nichols-Method in several milling processes with different values of proportional gain K_p. The test is performed for a reference deflection d_{Ref} = 80µm and constant cutting parameters with exception of the axis feed. The initial override OVR_{mid} of 70% corresponds in this test to an initial feed F_{mid} of 2000 mm/min. The deflection control is started within the air cutting, 15mm before reaching the workpiece. The gain Kp is increased step-by-step up to 1,75. At some critical value K_{cri} =1,25, sustained oscillation in the signal of the measured deflection with corresponding period T_{cri} = 0,145 s occurs for the first time. Based on the notified critical values, the controller gains K_p and K_i can be set with respect to the tuning method as following:

$$K_p = 0.45 \cdot K_{cri} \quad (2)$$
$$K_i = K_p/(0.85 \cdot T_{cri}) \quad (3)$$

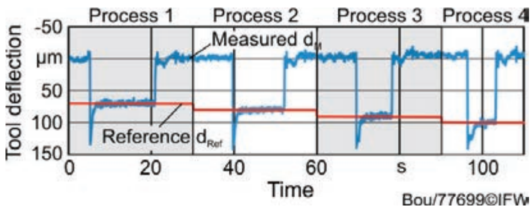

Fig. 9: Deflection control for references between 70 and 100 µm

Fig. 9 shows the deflection signals by using the PI-controller with its determined parameters for varied references between 70 and 100 µm. The process parameters and the control starting conditions are the same as in the tuning test. Generally, it shows that the measured deflection signal follows well the set references. The settling behavior of the controller with respect to determined controller parameter appears accurate and quiet. However, high overshoots appear in the measured signal. They show up also significantly over the first 20 millimeters of the workpiece surfaces. In Fig. 10, the signals of the control test by a reference of 80 µm are plotted. As previously mentioned, the control is already switched on within the air cutting before the tool reached the workpiece. So no deflection is occurring and a positive residual error is established. Consequently, the control begins increasing the feed override in order to increase the tool deflection and to reduce the existing error. However, the tool deflection stay unchanged and the feed override exceeds immediately and significantly the upper limitation of the machine control. As the tool attends the workpiece and the material cutting begins, it comes to a change of sign of the residual error and the I-controller begins reducing its output. That takes time until the output reaches again the upper limit of the override and until the error is settled to zero. In this way, an overshooting is produced at each beginning of material cutting. Such overshooting is a typical problem for control loops with I-controllers in combination with limited system input, and is known as the windup effect.

Technically, many anti-windup solutions and algorithms exist and allow, in such a case, maintaining the controller output at the upper limit. They may reduce the settling time of the residual error. However, they are not able to decrease the overshooting amplitude, because the tool is still hardly entering the workpiece with the maximum axis feed.

A promising solution to damp the overshoots, is to shift the starting moment of the control while cutting. As shown in Fig. 11, starting the control while material cutting allows a significant decrease of the overshooting amplitude and even the settling time, compared to previous starting while air cutting. That is because the tool deflection is occurring while material cutting and is responding to the override changes provided by the controller. In this way the controller output stays mostly within the limitation area of the machine control and the tool is no more reaching the workpiece with the maximum axis feed. Furthermore, starting the control first as the tool deflection reaches the reference shows smoother entering of the tool into the workpiece with only small overshoots.

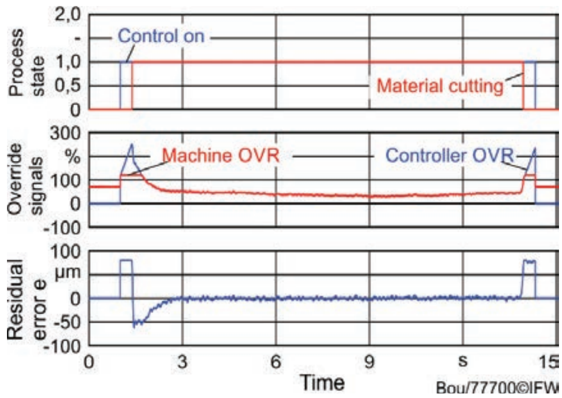

Fig. 10: Control signals while deflection control by 80 µm

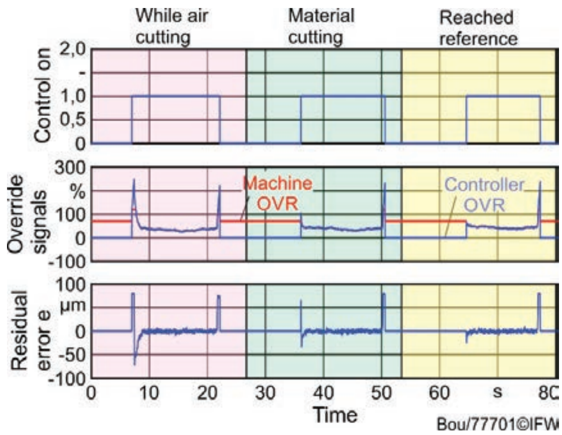

Fig. 11: Different starting strategies for the deflection control

4. Evaluation of the control approach

To assess the presented control approach regarding cutting accuracy and cutting time, milling tests are performed for varying cutting widths and constant cutting depth. The test steps are figured in Fig. 12. In the 1st step, the workpiece is prepared by machining a ramped shape. In the 2nd step the milling of a straight path is performed. During this step, the ramp simulates a variation of the cutting width between 0,5 and 1 mm, and causes a changing in tool deflection. In the final 3rd step, the marginal positions of the workpiece are measured by a touch probe allowing the determination of the resulting shape offset. The process is repeated 10 times, with and without deflection control.

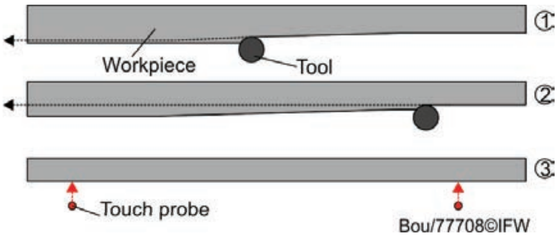

Fig. 12: Setup for tool deflection evaluation tests

In Fig. 13, the results of the process tests are depicted. It shows that processes with deflection control produce considerably smaller shape offsets compared to uncontrolled processes. This means that the milling is performed more precisely by using the deflection control despite of changing cutting width. However, controlled processes take significantly more time due to permanently changing axis feed by the control.

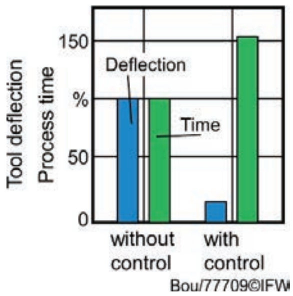

Fig. 13: Results of milling tests

A further control restriction factor for the deflection control is the override limitation on the machine control side. The override limitation bounded the area of the axis feed and limits therefore the permissible cutting width in process (Fig. 14). If the actual cutting width lies outside of the permissive area of the cutting width, the deflection control cannot be done entirely without error. The permissible area of the cutting width grows with increasing reference deflection.

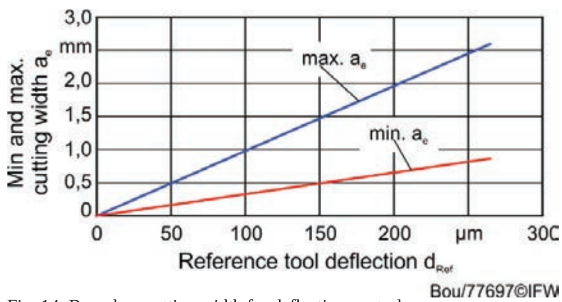

Fig. 14: Boundary cutting width for deflection control

5. Conclusion

As the products are becoming more and more individual, intelligent manufacturing systems are required to reduce additional costs in comparison to conventional series productions. This paper presents an approach for a monitoring and control system for the tool deflection, one of the most frequent process failures in milling. The monitoring system is realized by a new "feeling" machine tool DMG HSC30 linear, which is able, on the one hand, to sense online the occurring process forces by integrated strain gauges in its sensory spindle slide, and on the other hand, to measure autonomously the tool stiffness. Due to a different guidance concept of the spindle slide in this machine compared to an existing feeling machine DMG HSC55 linear, a further challenge for sensor integration is the determination of optimal sensor positions, since the stiffness of the slide is varying while moving along its z-axis. The control system allows to maintain the measured tool deflection constantly at a set reference value despite of disturbances in process like unexpected changing in the cutting parameters. The control loop is based on a PI-controller with the benefits of fast and accurate settling. The controller parameters are determined experimentally with respect to the method of Ziegler-Nichols. It shows that the control starting condition has a big influence on the settling behavior of the controller and on the overshooting amplitudes. Starting the control within the material cutting allows smoother entering of the tool into the workpiece and damps therefore overshoots. Further process tests shows that the deflection control increases significantly the milling accuracy, but also the cutting time.

Acknowledgements

The authors thank the German Research Foundation (DFG) for funding this research within the collaborative research centre 653: „Gentelligent components within their lifecycle", and the company DMG Mori Seiki for the provision of the test machine tool of type DMG HSC 30 linear.

References

[1] Altintas Y, Weck M. Chatter stability of metal sutting and grinding. CIRP Annals - Manufacturing Technology. Vol. 53, Issue 2, 2004, pp. 619–642

[2] Nouri M, Fussell BK, Ziniti BL, Linder E. Real-time tool wear monitoring in milling using a cutting condition independent method. International Journal of Machine Tools and Manufacture. Vol. 89, 2015, pp. 1–13

[3] Denkena B, Litwinski KM, Boujnah H. Detection of tool deflection in milling by a sensory axis slide for machine tools. Mechatronics DOI: 10.1016/j.mechatronics.2015.09.008, 2015.

[4] Denkena B, Kiesner J. Strain gauge based sensing hydraulic fixtures. Mechatronics, DOI: 10.1016/j.mechatronics.2015.05.008, 2015.

[5] Landers RG, Ulsoy AG, Ma YH. A comparison of model-based machining force control approaches. International Journal of Machine Tools and Manufacture. Vol. 44 , Issue 7-8, 2014, pp. 733-748

[6] Bort CMG, Leonesio M, Bosetti P. A model-based adaptive controller for chatter mitigation and productivity enhancement in CNC milling machines. Robotics and Computer-Integrated Manufacturing. Vol. 40, 2016, pp. 34–43

[7] Dorf RC, Bishop RH. Moderne Regelungssysteme (Pearson Studium - Elektrotechnik). Vol. 10, ISBN: 3827373042, 2007