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model based compensation,
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MODEL BASED COMPENSATION OF GEOMETRICAL DEVIATIONS DUE TO PROCESS FORCES

Machining accuracy can be considerably affected by deflections of machine tool components and the workpiece. This work presents a new approach for real-time deflection compensation, based on control integrated models. A real-time material removal rate (MRR) simulation determines the depth of cut which is used for process force calculation by Kienzle-Equations. Machine tool and workpiece deflections are then derived from a mechanical model using the calculated process forces. For this purpose, control based signals are used as model inputs. The total deviation is sent to the position controller as a setpoint offset. A dynamometer was applied to validate the simulated process forces. The presented approach was validated for cylindrical turning operations on chucked steel shafts. The experiments were carried out on a high-precision slant bed lathe. The results show, that geometrical errors could be reduced by more than 70% on average.

1. INTRODUCTION

Production time and quality are two of the most important goals for manufacturing companies. A key factor for production quality is the magnitude of process forces because they cause deflections of workpiece, tool and machine tool components. Furthermore, process forces will increase during machining due to tool wear. This causes varying deflections of single components and a deviation between the planned and actual depth of cut. The consequence of these elastic deformations are surface or dimensional errors of the workpiece. Common approaches for the static and dynamic compensation of such deviations are based on the application of active systems [3]. However, to compensate the deflections with an active system, the integration of an additional complex mechatronic component into the machine tool is required. This results in higher setup time, extra costs and limitation of the machining area. For this reason, other approaches use information provided by the machine control to model the deflection and compensate them using

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the machine axes. In [5] process forces were identified from control signals and used to compensate static and dynamic displacements during milling. A beam model represented the milling cutter and an additional measuring tool determined its static stiffness. An inclinable tool table was used to compensate the angular error originating from tool deflection. For this setup, the model predicted the angular error and transferred it to the Numerical Control (NC). Korajda [7] compensated tool deflection for a three axis milling process using an offline model. A two-step procedure allows to identify and minimize the deflection. In the first step, the deflection is calculated offline during the preparation of the tool path by using a cutting model and a mechanical model at nominal axis speed. Afterwards, the difference between calculated deflection and actual feed rate has to be regarded during the interpolation cycle. Liu [8],[9] used an empirical approach to calculate the workpiece, machine tool and spindle deflection for turning operations, based on the geometry measurement of machined components. Afterwards, he compensated the error by adapting the NC-code for the following workpieces. Hofmann [4] coupled a flexible multiple-body simulation of a machine tool with an analytic beam model of the tool. The resulting cutting forces were determined using a model according to Kienzle. Based on the results he calculated feed rate parameters and embedded them to the NC-Code. Thereby, the geometric errors could be reduced from 250 μm to 10 μm. Mayer et. al. [10] presented a model, which took into account the influence of the different force components on the workpiece deflection. It was proposed that only the radial and axial components of the turning forces are significant for the geometric error. Carrino et. al. [1] presented an analytical model to calculate tool holder and workpiece deflection during cylindrical turning. To estimate the geometric error, process forces, workpiece deflection and the stiffness of tool holder and clamping system were considered. A compensation of the detected error has not been implemented.

Up to the present, researchers developed several methods to predict process force dependent deviations by offline simulations. The compensation values for the position control are determined by post-processing. For this purpose, geometric workpiece errors are identified after the machining. Consequently, the NC-code has to be adapted by correction values to reduce the error. Other approaches have used multi-body simulations to predict the deflections of machine tool, workpiece and tool. However, a process parallel compensation of deflections based on machine control integrated models has not taken place so far.

This paper presents a method to reduce process force induced errors by implementing a process parallel real-time simulation on a machine tool control. Therefore, the compliance of the machine components is investigated and models are created for the machine structure and workpiece. Based on control data an additional model determines the depth of cut. This and further information are used to calculate process forces by an approach according to Kienzle. The calculated passive force is transferred to the compliance models to predict the total deflection. This value is transmitted to the control as a position offset. Thus, the geometric error could be reduced. In a separate setup, the forces are measured with a Kistler dynamometer and used instead of the calculated force. The compensation is performed for different workpiece diameters and depths of cut. Finally, the results of both methods are compared.

2. IMPLEMENTATION ON THE MACHINE CONTROL

Three models for determining the workpiece and machine tool deflection are integrated in a MATLAB/Simulink model (Fig. 1), which is embedded into the control system. One model calculates the depth of cut a_p. To that, the workpiece geometry (length l and diameter d) has to be provided as a voxel model before the cutting process and transmitted to the model. Further, the actual axis positions x and z are used to specify the position of the tool centre point (TCP). To calculate the cutting force the information of a_p and TCP are used for the second model. Additional the Kienzle parameter $P_{Kienzle}$ and tool geometry (tool radius r_{tool} and cutting edge angle κ) are transferred to the cutting force model. Finally, the control signals, feed velocity v_f and rotational speed n_{sp}, are used to determine the remaining input variables for the Kienzle model [6]. Based on the actual workpiece geometry and the calculated passive force F_p the workpiece deflection w_{wp} can be estimated in the third model. Furthermore, the machine tool deflection w_M is calculated by considering the z-position. The cycle time for the compensation is fixed to 10 ms. The total deflection w_{tot} is transferred to the position control as an position offset.

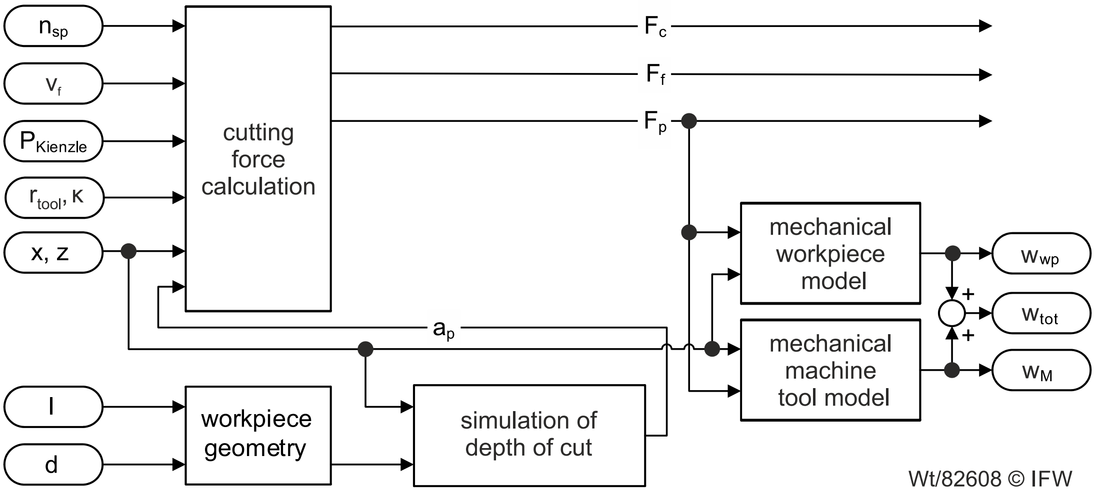

Fig. 1. Simulink model to determine machine and workpiece based deflection

3. MODELLING OF THE MACHINE TOOL DEFLECTION

In this chapter the compensation model is developed. First, the static stiffness of the machine tool Hembrug Slantbed Mikroturn 100 is determined experimentally. Afterwards, a model is realized which describes the compliance of the machine tool structure.

To identify the static stiffness in the x-direction, a slight collision between a tool dummy and a workpiece dummy was performed. The resulting force was measured by a Kistler dynamometer. A laser triangulation sensor was used to determine the stiffness of spindle flange, clamping system and workpiece c_{sp+wp}. Another laser triangulation sensor was used to measure the stiffness of the turret c_{tur}. The total stiffness of the system c_{tot} was measured by the linear scale of the x-axis, as depicted in Fig. 2.

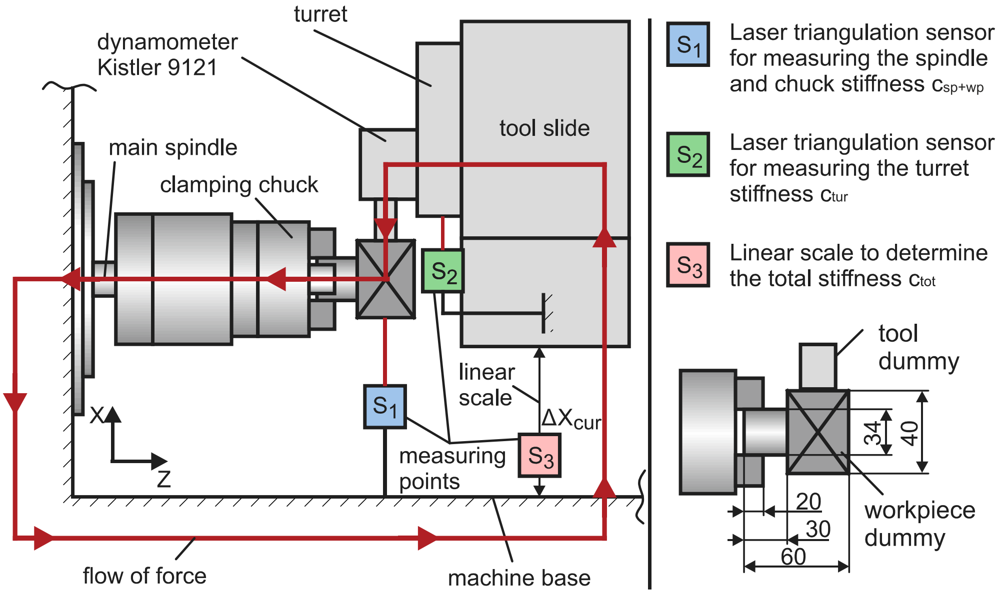

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Fig. 2. Test setup for measuring static stiffness in x-direction

The measurement was carried out for a single z-axis position. The results for this TCP position are depicted in Fig. 3. With $c_{tur} = 102.8$ N/µm the tool turret has the highest stiffness. The stiffness determined on the workpiece c_{sp+wp} is 33.4 N/µm and c_{tot} is measured with 11.3 N/µm. Thus, c_{tot} is three times smaller than c_{sp+wp} and ten times smaller than c_{tur}. Based on these measurements the stiffness of the remaining components inside the flow of force can be calculated by the assumption that the single stiffness's are connected in series. The total stiffness c_{tot} is determined by the ratio of contact force and x-axis travel, measured in the collision. Consequently, the remaining stiffness c_{rest} results by following equations:

$$\frac{1}{c_{tot}} = \frac{1}{c_{tur}} + \frac{1}{c_{sp+wp}} + \frac{1}{c_{rest}} \tag{1}$$

$$c_{rest} = \frac{1}{\frac{1}{c_{tot}} - \left(\frac{1}{c_{tur}} + \frac{1}{c_{sp+wp}}\right)} \tag{2}$$

The remaining stiffness c_{rest} is the smallest with 20.5 N/µm, compared to c_{tur} and c_{sp+wp}. To investigate the influence of the TCP position in z-direction, the tool position was changed in incremental steps off 5 mm over the range of 70 mm. The experiments were repeated for another workpiece dummy and a longer shaft with identical diameter.

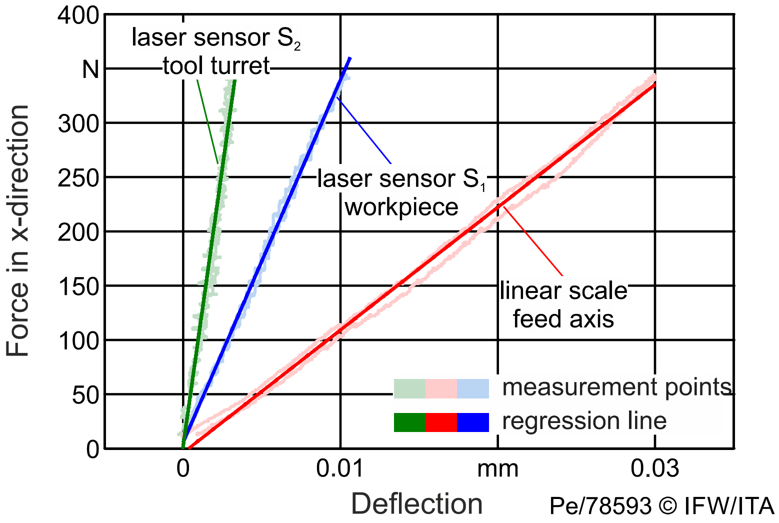

Fig. 3. Determined static stiffness in x-direction

Next, a model was built to assume the compliance of the machine tool structure δ_M. Initially, the position depending workpiece stiffness c_{wp} was considered by building a workpiece model based on Euler-Bernoulli beam theory. Afterwards, the stiffness of the machine tool structure c_M and the compliance δ_M can be calculated using the following equation.

$$\delta_M(l) = \frac{1}{c_M(l)} = \frac{1}{c_{tot}(l)} - \frac{1}{-c_{wp}(l)} \tag{3}$$

At each position, three measurements were performed. The identified stiffness c_{tot} and the calculated stiffness of machine structure are depicted in Fig. 4.

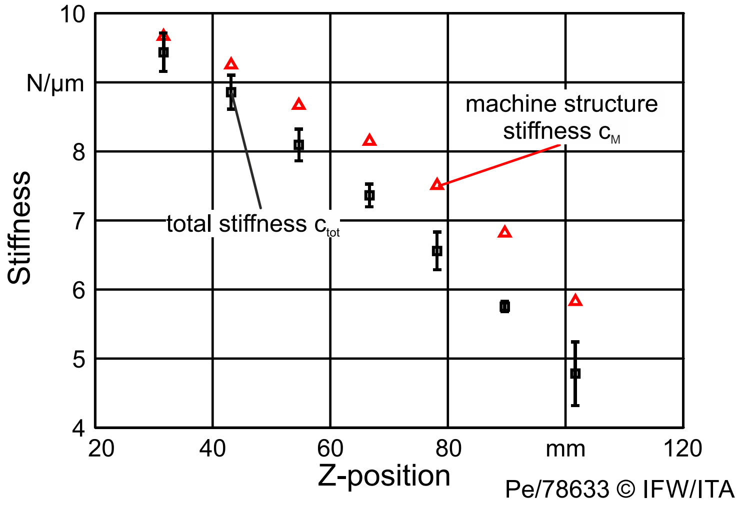

Fig. 4. Z-position dependent stiffness of the machine tool

By increasing the z-position of the tool, the stiffness decreases about 40%. Therefore, a position dependent compensation of δ_M was implemented as a part of the compensation model. Based on the position dependent stiffness of the lathe, an analytic machine tool model was generated. The identified compliance of the machine structure shows a cubic shape, as depicted in Fig. 5.

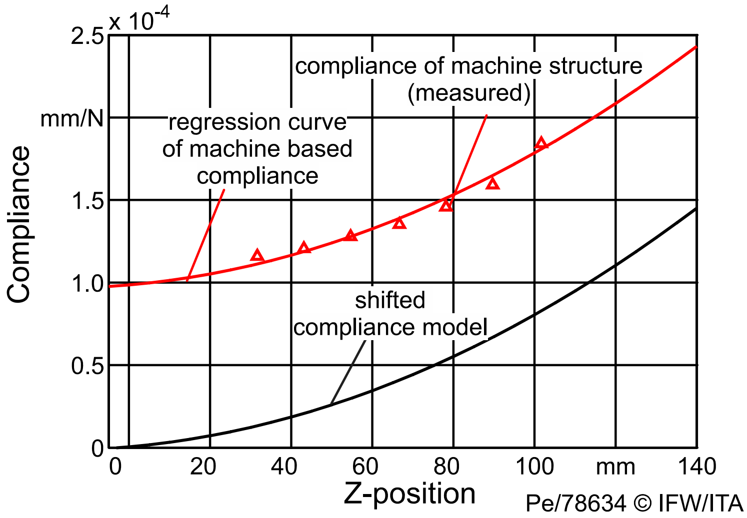

Fig. 5. Modelling of machine based compliance in x-direction

Furthermore, the position dependent change of δ_M is higher than the absolute compliance close to the spindle chuck. However, in this paper only the position dependent compliance is considered for the compensation of deflections. Thus, the cubic function of the axis compliance will be shifted to zero for a workpiece length of $x = 0$ mm. The compliance model w_M calculates the deflection in x-direction based on the z-position and the passive force F_p. It is presented in Eq. 4.

$$w_M(F_P, Z) = \delta_M(Z) \cdot F_P$$
$$w_M(F_P, Z) = (9.26 \cdot 10^{-11} \cdot Z^3 - 6.68 \cdot 10^{-8} \cdot Z^2 + 1.63 \cdot 10^{-5} \cdot Z - 1.34 \cdot 10^{-3}) \cdot F_P \tag{4}$$

4. COMPENSATION BASED ON SIMULATED CUTTING FORCES

To evaluate the introduced model for deflection compensation, a cylindrical turning process was performed. Different workpiece diameters, passive forces and depths of cut were analysed. Shafts made of C35 steel and indexable inserts (Seco CNMG120412-M3) were used. A coordinate measuring machine (Leitz PMM 866) allowed measurements of the contour deviation. The machined shafts are numbered consecutively during the following measurements from one to ten.

In the first experiments the effect of the compensation was investigated. Three steel shafts with different diameters (D_e = 38, 32 and 29 mm) were produced with and without compensation. The process parameters were a_p = 0.5 mm, v_c = 200 m/min and v_f = 300 mm/min. The resulting shaft contour was measured over a range of 95 mm with 325 measuring points. Without compensation, the geometry error increases with decreasing diameters significantly (Fig. 6).

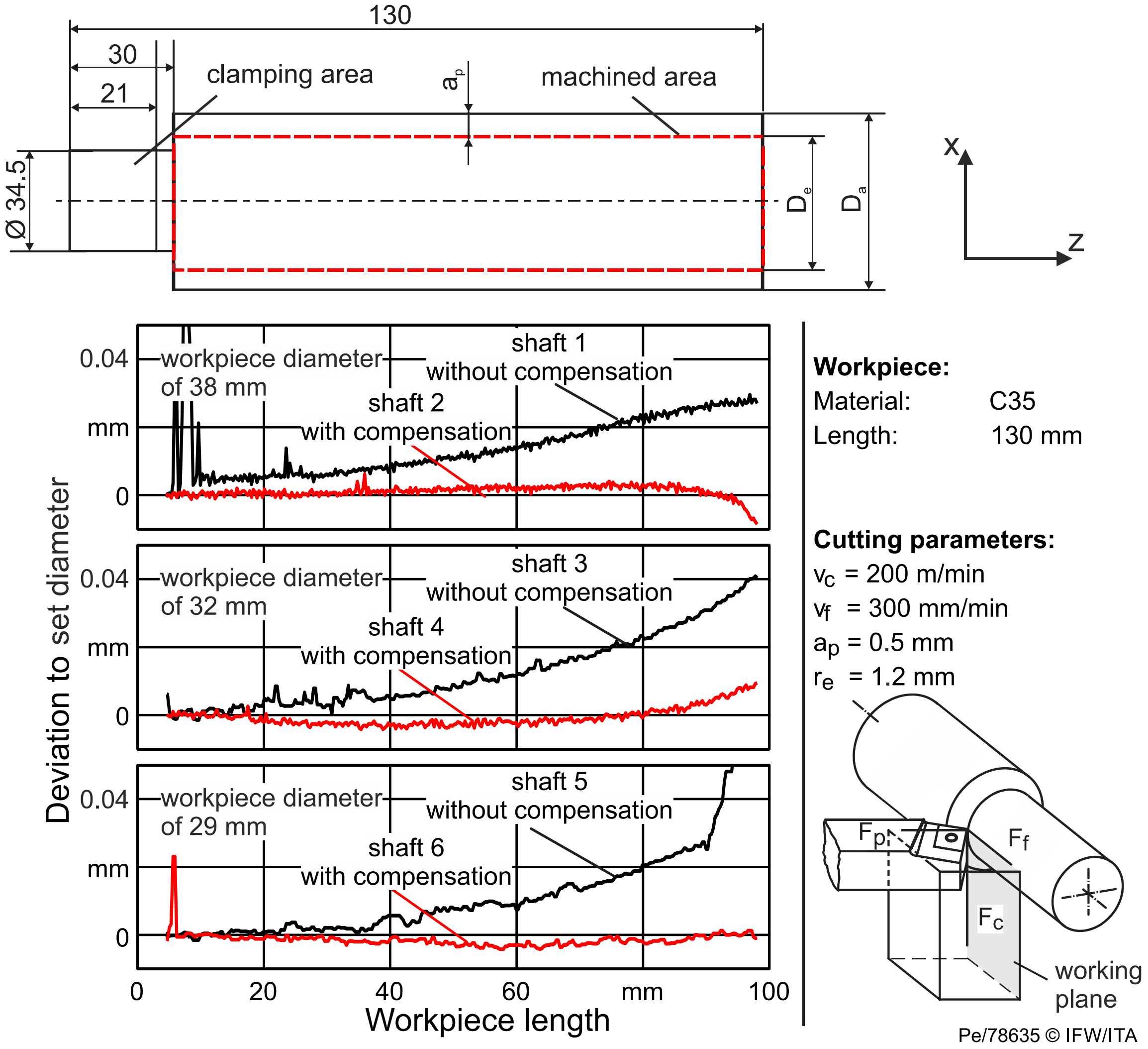

Fig. 6. Compensation of machine and workpiece deflections based on simulated passive forces for different shaft diameters

The results show, that this compensation strategy significantly reduces geometry errors for arbitrary workpiece diameters. The deviation with and without compensation was determined by using the mean value of the last 10 measuring points. It is presented in Table 1. The maximum error of the nominal diameter was reduced from 61.6 µm to 8.2 µm. The compensation significantly reduced the error for every workpiece diameter. For the diameter 29 mm shaft, the error was reduced by nearly 100%. The average value of the percentage reduction is about 90%.

Table 1. Radial geometry error for different workpiece diameters

Workpiece diameter	Without compensation	With compensation	Percentage optimization
38 mm	27.6 µm	-5.2 µm	81.2%
32 mm	39.0 µm	8.2 µm	79.0%
29 mm	61.6 µm	0.4 µm	99.4%

To investigate the compensation on arbitrary workpiece geometries additional measurements are performed. Hereafter, shafts with shoulders of three different diameters D_a and a cylindrical final contour of $D_e = Ø31.5$ mm are machined. One shaft is machined without and the following with activated compensation. For the process parameters, a cutting speed of $v_c = 200$ m/min and the feed rate of $v_f = 150$ mm/min were selected. Based on different shoulder diameters the depth of cut a_p is increasing from 0.5 mm to 1 mm, as depicted in Fig. 7.

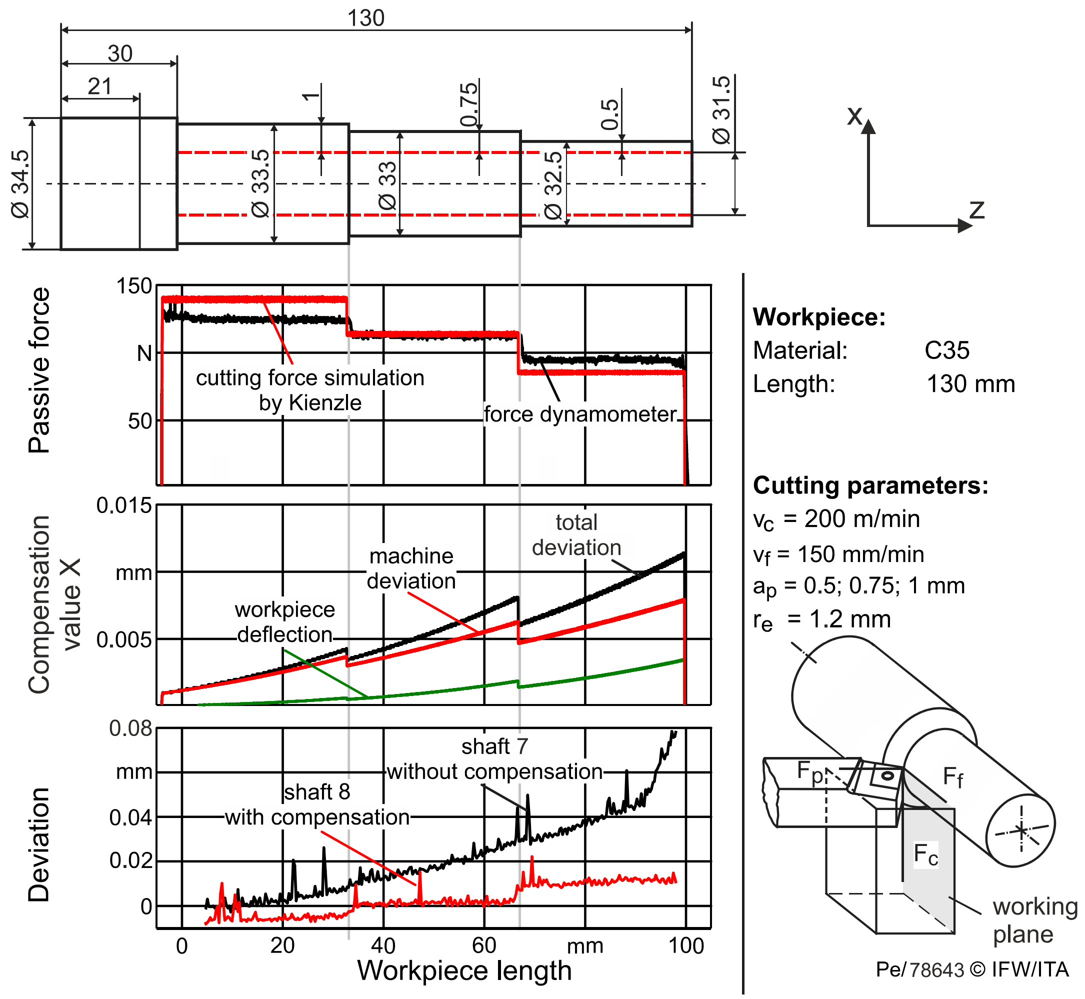

Fig. 7. Compensation of machine and workpiece deflections based on simulated passive forces for different depths of cut

The process parameters v_c and v_f were constant during the machining process. The measured and simulated passive forces increased from 96 N to 122 N and from 86 N to 141 N respectively. The Kienzle parameters were determined for a_p = 0.75 mm. Therefore, the calculated passive forces are showing a deviation. If the depth of cut is smaller, the calculated F_p is below the measured once. Otherwise, with a bigger a_p the predicted force is higher. Similar to the calculated passive forces a cutting depth variation led to a step in the simulated deflection. A reduction of the geometric error was detected for the process with activated compensation. In the first and third section, a remaining deviation was noticed. This could be led back to the error during the passive force calculation. With a too low predicted F_p the deviation is under-compensated on the right end of the shaft. Otherwise, the deviation is over-compensated based on higher predicted F_p on the left end.

The geometric error with and without compensation is calculated by using the mean value of the last 4 mm on the right end of each subsection. It was measured by the coordinate measuring machine. For the depth of cut of 0.5 mm the area around *z*-position of 90 mm is measured because of the bigger deflection at the beginning of the shaft. A reduction of the geometric error between 59% and 88% could be achieved by the compensation. The results are presented in Table 2.

Table 2. Radial geometric error for different depths of cut

Depth of cut	Without compensation	With compensation	Percentage optimization
0.5 mm (section 88 – 92 mm)	47.0 µm	14.2 µm	70%
0.75 mm (section 60 – 64 mm)	26.2 µm	3.2 µm	88%
1 mm (section 24 – 28 mm)	4.8 µm	-3.4 µm	59%

5. COMPENSATION BASED ON MEASURED CUTTING FORCES

During a separate setup measured forces by a Kistler dynamometer are applied to the model. This setup can be used for a wide range of feed parameters without teaching a cutting force model. A shaft of C45k was machined by a cylindrical turning operation with and without compensation. The process parameters were a_p = 0.5 mm, v_c = 200 m/min and v_f = 300 mm/min. With activated compensation the predicted deviation was fed back to the position control. For smoothing the measured passive forces, a 5 Hz low-pass filter is used. Nevertheless, during entering the material of shaft 10 the passive force is overshooting. This could also be recognized by determining the geometric error, depicted in Fig. 8.

To validate the compensation strategy, the geometry error on the free shaft end was measured. The compensation reduces the geometry error by 82% from 44.1 µm to -7.8 µm. Therefore, the compensation with predicted and measured process forces both show good results, as presented in Table 3.

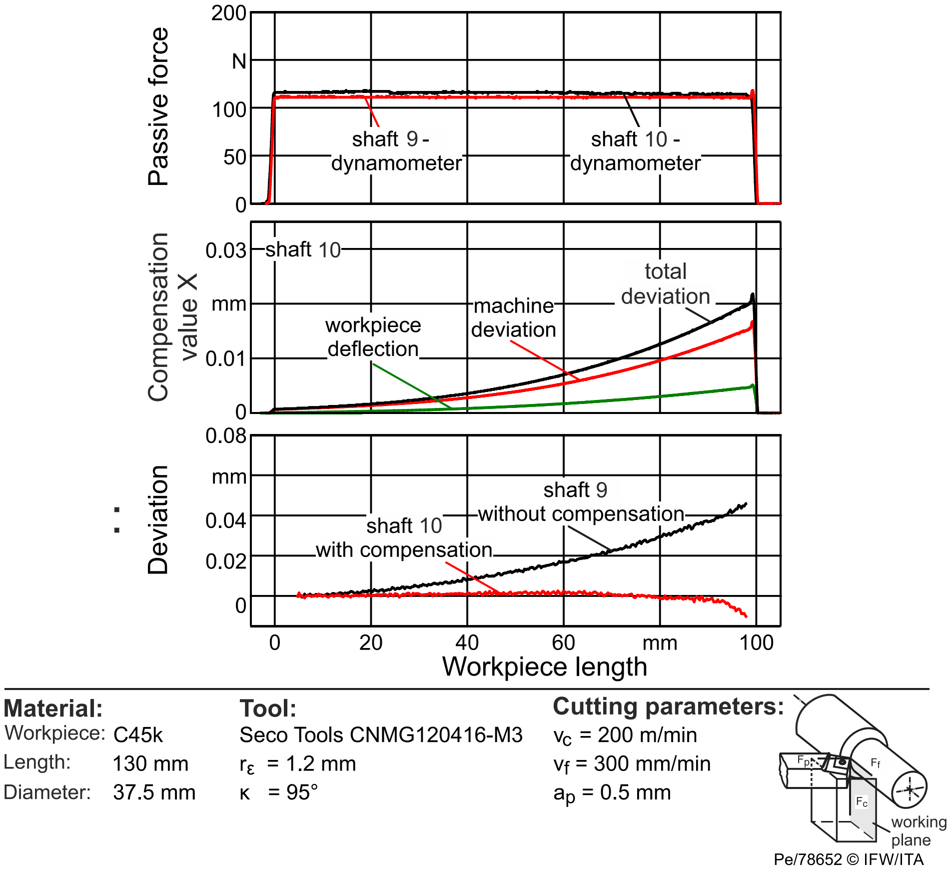

Fig. 8. Compensation of machine and workpiece deflections based on measured cutting forces

Table 3. Geometric error with and without compensation based on simulated and measured passive forces

	Without compensation	With compensation	
Name	shaft 9	shaft 10	shaft 2
Passive force	116 N (Kistler)	111 N (Kistler)	126 N (Kienzle)
Geometry error	44.1 µm	-7.8 µm	-5.2 µm

The compensation based on predicted passive forces results in a smaller geometric error. Furthermore, the calculated signal is smooth without noise. An overshooting of the signal during entering the material did not occur. However, the advantage of measuring the forces is flexibility. It is not necessary to identify Kienzle parameters beforehand and the change of the process forces during machining can be considered additionally.

6. CONCLUSION

In order to compensate process force induced geometric errors, various approaches are known. Usually, empirically identified models or offline simulations are used to determine the deflections. The results of these approaches are static correction values, which are only applicable for a specific process.

This paper presents a method to reduce force dependent geometry errors by integrating a real-time simulation into a machine tool control. The machine tool characteristics have been investigated for various axis positions. In addition, the current workpiece shape is identified and used to qualify the workpiece deflection according to Euler-Bernoulli beam theory. All required input signals are obtained from the machine control. The process force is predicted by Kienzle Equations and, alternatively by a Kistler dynamometer. To compensate the geometrical error both forces are transmitted in separate experiments to the model. The predicted total deflection of tool and workpiece is fed back to the x-axis position control in order to adapt the position during machining. The process parallel compensation was verified for a cylindrical turning process of different workpiece diameters and various depths of cut. A good correlation between the assumed and measured geometry error could be achieved. Overall, due to the model-based optimization, the deviation could be reduced by more than 70% on average.

The Collaborative Research Centre 1153 Tailored Forming investigates the production of hybrid workpieces of two different materials by solid forming. In general, it is necessary to use a machining process after manufacturing the components by forming technologies. Because different materials have different properties like Young's modulus, ductility and thermal behaviour, the machining of hybrid workpieces bears challenges for a cost and quality optimized machining process. For this reason, the presented approach is going to be expanded on workpieces formed by a combination of different materials. Furthermore, a process monitoring model will be added to detect the transition zone between different materials and adapt the process parameters accordingly. The dynamometer will be replaced by a sensing machine component [2]. Therefore, strain gauges will be attached in notches on appropriate locations of the turret. Thus, the process force of various cutting operations can be measured without using additional equipment.

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