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Feeling machine for material-specific machining

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ABSTRACT

In the machining of material compounds, materials with differing properties must be identified during the process and process parameters must be controlled accordingly. Structure integrated strain gauges in feeling machines are a promising approach for providing signals for monitoring and control tasks. This paper presents the first investigation and implementation of this technology for a turning machine turret. Firstly, the simulation based positioning of the sensors is discussed. Secondly, disturbance variables such as cooling temperature and assembly tolerances of machine components, which affect the strain measurement, are investigated. Finally, the successful material-specific machining based on the feeling machine is presented.
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1. Introduction

Mono-material components reach their material and manufacturing-specific limits attempting to reduce the mass of components in the automotive and aircraft industries and thus reduce fuel consumption as well as CO_2 emissions [1]. Hybrid high-performance components with locally adapted properties offer a promising approach of designing components for energy-efficient applications while reducing the use of high-alloy materials. Due to different material properties and chemical compositions, the cutting properties and chip formation mechanisms change during machining, thus influencing component quality and process reliability. Consequently, material-specific adaptation of the process parameters for the machining of hybrid workpieces is required to improve the workpiece quality and process productivity [2]. At the same time, a high degree of process reliability must be attained to increase the degree of automation. Therefore, robust and sensitive process monitoring with a simultaneous autonomous adjustment of the process parameters is required. One parameter that is particularly affected by different material properties is the process force. However, in most cases, precise information on process forces is not available in a machine tool. To date, researchers focused on existing approaches to model process forces by virtual machining [3], by extracting them from control signals [4,5] or by measuring them with external sensors [6,7]. Each of these approaches is subjected to its own limitations. For simulation or determination of forces from control signals, extensive modelling efforts are necessary in order to consider structural dynamic effects. In addition, the simulation cannot consider thermal disturbances or tool wear in real time. Using external sensors often result in high acquisition costs, limited flexibility or is restricted by installation space [8]. Denkena et al. have researched the technology of structure integrated strain gauges in machine components to realize "feeling" milling machines [9]. This technology provides process force information independently of the applied tool and without reducing the available working space.

In this paper, the investigation of disturbance variables, which influence the structure integrated force measurement in machine tools and their compensation is presented for the first time. In this context, a turret has been equipped with structure integrated strain gauges and its suitability for process force reconstruction within a feeling lathe has been investigated. Individual disturbances, which lead to constraint forces in the system and affect strain measurements are presented. This includes the coolant flow through the turret and deviations, which are caused by manufacturing and assembly errors of the turret. Based on the sensory abilities, the application of process monitoring by using the feeling machine is shown in Section 5. A material-specific online parameter adaptation has been explored in order to optimize the machining with regard to the process force difference in the case of material change.

2. Design of feeling turret

In a lathe, the turret is suitable for the integration of sensors close to the process because, in contrast to the workpiece spindle, it does not rotate during machining. Due to this, the turret is a suitable component for implementing structure integrated sensors. However, this component is characterized by high stiffness due to the high demands on machining accuracy and process stability. As a result, only low mechanical strains occur when an external force is applied to the system. To support the identification of suitable locations for strain gauge sensors, a finite element analysis (FEA) was conducted as shown in Fig. 1(a). The analysis of an external force on the turret disc of 1 kN, which was considered individually in all three axes, shows a maximum strain of less than 4 μm/m on the accessible

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surfaces. These small strains result in a high signal-to-noise ratio when strain gauges are used. Thus, this is a major challenge for structure integrated force measurement. For this reason, the structure of previous feeling machines was locally modified by incorporating notches to locally increase the mechanical loads [10]. However, the turret is equipped with a large number of bores for the cooling oil, hydraulic oil and compressed air flow. This restricts the design and location of notches in the component. However, based on the simulation, suitable locations were identified and symmetrical notches with a flat notch ground were applied. A subsequent FEA simulation, depicted in Fig. 1(b), shows how this approach increases the measured mechanical strain. Depending on the sensor position and force direction, the strain at the notch ground increases from 2.3 μm/m to 10 μm/m. The change in the static

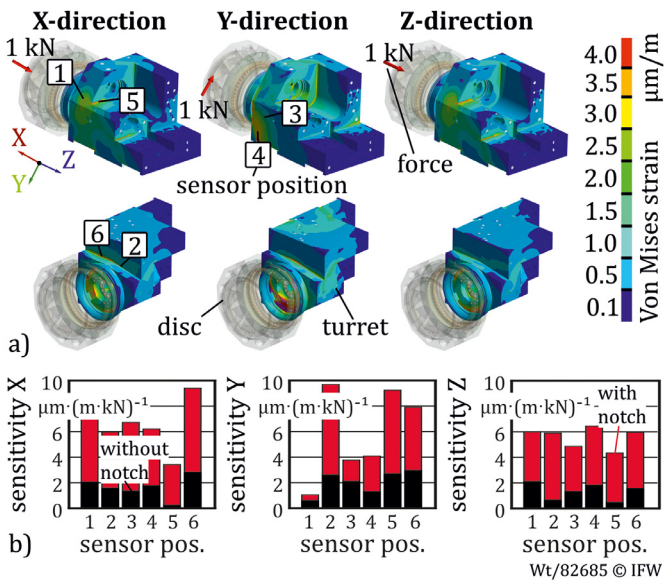

Fig. 1. Strain state in turret structure.

stiffness of the turret caused by the notches is minor due to the small dimensions of the notches. Here, the initial stiffness was reduced by a maximum of 4%.

Based on the simulation results, the turret was manufactured. The strain gauges were set up as a Wheatstone-bridge and attached to electronic devices for signal processing. The electronic device filters, amplifies, samples and finally transfers the strain signals to an industrial PC via CAN-BUS. Depending on the CAN-BUS configuration, signal-sampling rates of up to 1500 Hz are feasible.

3. Calibration of the turret forces

The aim of the calibration is to determine matrices to transform the signals of the strain gauges (SG) into force signals. The calibration matrices were calculated by Moore-Penrose inverse using reference force signals of a dynamometer and by considering all strain signals from the turret. Since each integrated strain gauge is sensitive in all three directions, the quality of the force calibration depends on the type of force excitation. Denkena et al. have shown that static forces are not sufficient to calibrate the system. Therefore in-process calibration is necessary [9]. In the context of in-process calibration, the signals were measured during the cylindrical turning process of 20MnCr5 by varying feed f, cutting speed v_c and depth of cut a_p in order to cover different occurring process forces regarding amplitude and force direction. The reference forces were measured using a dynamometer. The measured forces by the feeling turret after calibration are shown in Fig. 2.

The resolution was determined by the standard deviation of the signal in the unloaded state and the square sum of the distance between the measured force of the dynamometer and the feeling turret. The force resolution in X-direction is 64 N, 43 N in Y-direction and

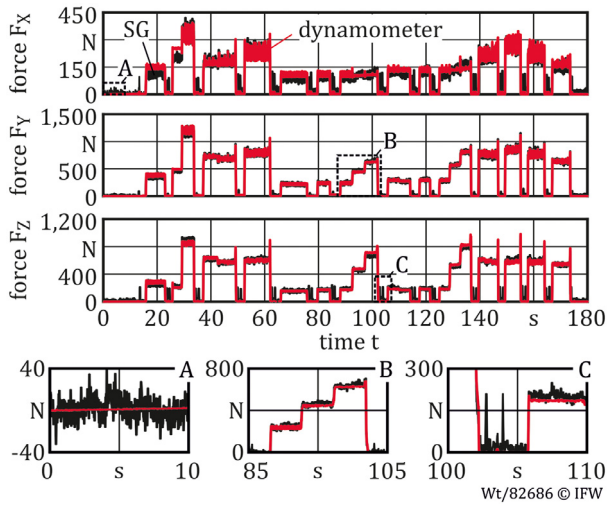

Fig. 2. Calibration of the turret forces using process signals.

44 N in Z-direction. The deviation from the reference measurement is shown in Fig. 2 (section A). Here, the signal from the sensors of the feeling turret shows higher noises. Nevertheless, the noise of the dynamometer $F_{Y,\mathrm{dyn}}$ is negligibly low, compared to the standard deviation of the force of the feeling turret which is $F_{Y,SG}$ = 20 N. In addition, there are qualitative deviations between the reference forces and the forces of the feeling turret. This is shown in section B in Fig. 2, which depicts the machining process for different depths of cut. In this section, the mean deviation between both forces amounts 4.5%. Section 3 shows the force measured during the retraction movement of the turret. The rapid motion result in a significant acceleration response the component. This leads to an amplitude of the determined force of the feeling turret, which increases up to 150 N. Indeed, these inertia effects are negligible since no machining took place during a rapid traverse.

4. Analysis of process influences

Compared to the investigated previously feeling machines, the turret is affected by further disturbance variables, which influence the force determination. These result from the fluids passing through the housing, variation in loading as well as tolerances from manufacturing and assembly that influence each feeling component to a different extent.

An electric drive is installed in the turret disc to drive the rotating tools. To cool the electric motor, the drive is connected to the cooling circuit of the machine tool. A compressor cooler is used, which is operated with a two-point control. The cooling temperature is set to 293 K and the switching hysteresis is 2 K. The coolant is fed through bores in the turret to the drive and back, as shown in Fig. 3(a). In a long-term measurement, the coolant flowing back has a periodic difference of 1.1 K with a periodic duration of 307 s. The resulting temperature fluctuations in the bores influence the measured strains on the turret. Especially at measuring position 3, the variation of the measured strain correlates with the temperature of the returning coolant, as shown in Fig. 3(b). This is due to the close distance of the sensor to one of the bores. This effect was also observed at other measuring positions although these effects were less significant and had a phase shift. Thus, the fluctuating cooling temperature influences the determined process forces, as shown in Fig. 3(c). For a cooling temperature change of 1.1 K, the measured forces vary by ±75 N. Additional investigations are required to investigate further temperature sources and their influence. Subsequently, the behaviour can be modelled and an observer can be used to reduce the temperature influence on the force determination. To limit the influence of the temperature in the following investigations, the subsequent measurements were conducted only during linear increase of temperature.

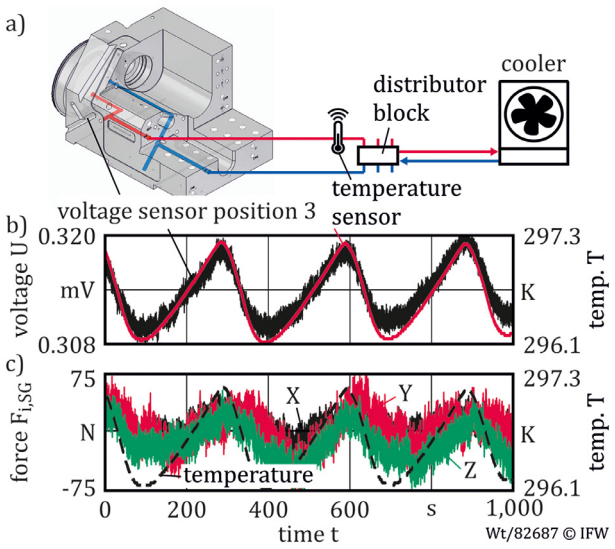

Fig. 3. Influence of the motor cooling on the measuring positions and the calculated process forces.

The resulting effect was considered during the calculation of force signals by subtracting the linear trend.

It was further examined whether the signals change when the turret moves alternately in three axial directions. For all movements, the feed was set to v_f = 575 mm/min. The movement range was 60 mm in the *X*-direction, 50 mm in the *Y*-direction and 120 mm in the *Z*-direction. For a movement in *X*- and *Z*-direction, no significant influence on the strain gauge signals was determined, as shown in Fig. 4. In contrast, movement in the Y-direction causes a significant variation in the measured strains and thus errors in the predicted forces. These errors are characterized by a position-dependant component and by a step in the signal while changing the direction of movement. This behaviour leads to a maximum error of 385 N for the measurement of $F_{Y,SG}$, while the error in the other two directions is approximately half as high.

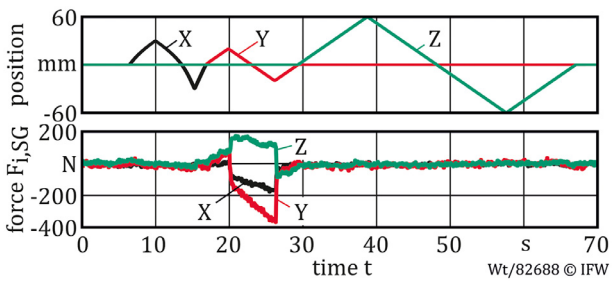

Fig. 4. Influence of the travel motion in *X*-, *Y*-, and *Z*-direction on the calculated process forces.

These errors occur from manufacturing and assembly inaccuracies of the linear guides, which cause constraint stresses in the system due to movement. As the guide carriages are mounted directly under the turret, they transfer the resulting forces to the system, which in turn affects the strain measurement. The step in the measurement appears due to the change of direction probably related to the arrangement of the balls inside the guide carriage [11]. Since the carriages do not have a ball chain, the distance between the balls is not constant. By changing the direction, the balls are re-sorted and forces are applied to the turret. To investigate the predictability of the impact of ball sorting, a driving profile was selected representing a regular change of direction over a range of 40 mm with v_f = 320 mm/min, as shown in Fig. 5. The average increase and decrease of the signal for each change of direction was determined. For $F_{Y,SG}$, an average signal change of 260 N was measured with a standard deviation of 26 N. A similar ratio was also determined for the other two force directions. Based on these results, the average signal step was subtracted from the synchronously measured forces in case of a direction change. After considering the offset, the occurring error could be significantly reduced. Only the position-dependant proportion of the error remained. However, there is a latency between the beginning of the direction change and the resulting force error. Since the latency varies by a few milliseconds, force peaks still occur in some cases when the direction of movement changes. Further studies have shown that for the considered range for finishing parameters of v_f = 192 mm/min to v_f = 575 mm/min, the feed rate has no significant influence on the force amplitude.

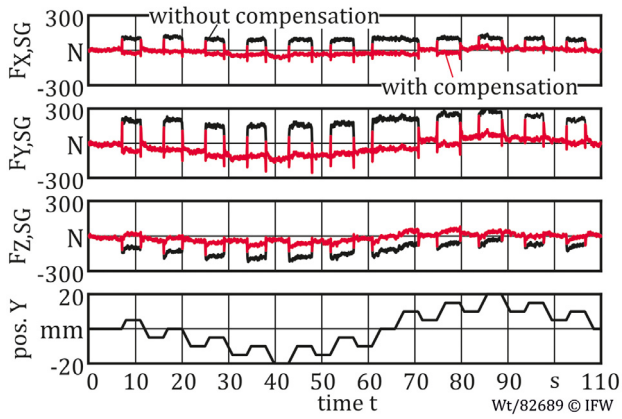

Fig. 5. Calculated process forces during *Y*-axis movement with and without compensation.

The influence of the tool change on the force measurement is discussed below. During tool change, the coupling is released via the hydraulics so that the turret disc is still able to rotate. Due to different hydraulic pressure in the bores of the turret and the resulting movement of the clutch, constraining forces occur. However, these forces decrease to their initial value when the clutch is engaged. Therefore, the coupling process has no influence on the subsequent force measurement during machining.

The selected tool stations were sequentially changed clockwise and counterclockwise to examine their influence. Initially, no tools were mounted on the turret. The measurement was started at the first tool station, which served as a reference for further evaluation. After each tool position change, the position was maintained for three seconds. Each measurement was performed three times. The determined forces after each tool station change are shown in Fig. 6(a). Despite the rotational symmetry of the turret disk, the forces vary with each change. This can be explained by constraining forces in the system due to assembly and manufacturing influences. The largest difference results for the force $F_{Z,SG}$ and is up to 150 N. The double standard deviation is 30 N for $F_{Z,SG}$. Therefore, a correction coefficient, which provides a force offset for each station, can be calculated. Afterwards, tool station 1 was equipped with a tool with a mass of 6 kg. The previous measurement cycle

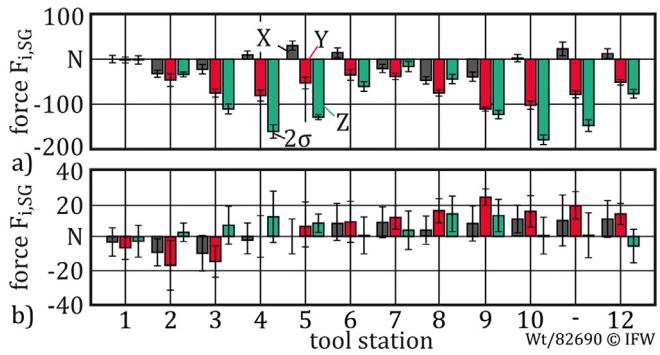

Fig. 6. (a) Influence of tool station on the calculated process forces with offset compensation (b) and asymmetrical loading.

was repeated and the determined offsets were considered, as depicted in Fig 6(b). The influence of asymmetric loading is significantly lower than the effects caused by changing the axis positions. For $F_{Y,SG}$, deviations of up to 22 N were measured. The deviations were mainly smaller than twice the standard deviation determined for a rotation of the turret disc without equipped tool. The influence must only be considered, if the weight on the turret disc is significantly unevenly distributed. One possibility is to use the measured forces after the tool change for online offset generation. In this case, the time for offset determination during the tool change cycle has to be taken into account.

5. Examination of the potential for material monitoring

Lastly, the applicability of structure integrated sensor technology for the implementation of material-specific machining was investigated. For this reason, the forces for different materials and depths of cut were measured with the feeling turret and the dynamometer. Cylindrical turning operations with process parameters of v_c = 300 m/min, f = 0.2 mm and a_p = 0.5–2 mm were conducted. In these experimental turning investigations, aluminium (EN AW-6082) and three different alloyed steels (20MnCr5, C22.8 and 41Cr4) were machined. These materials were chosen because they cover a relevant area of industrial production. The cutting tool was kept constant. The determined cutting forces of the feeling turret and the dynamometer show a high correlation, depicted in Fig. 7(a). Due to these measurements, it can be stated that the structure integrated process force measurement allows to optimize the cutting process e.g. with regard to the maximum cutting force during machining a hybrid shaft with different materials.

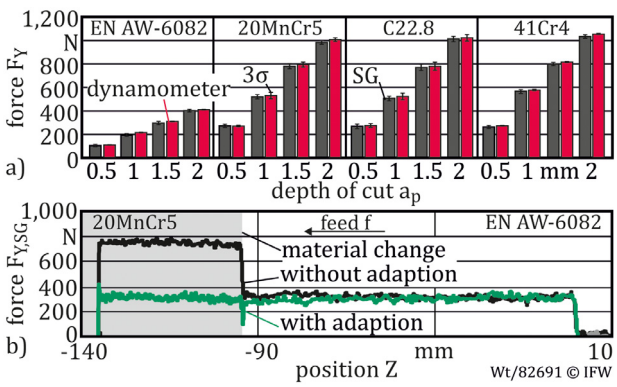

Fig. 7. (a) Cutting forces during machining different materials with various depth of cut (b) and machining of a hybrid shaft with and without adaptation of process parameters.

Therefore, a material specific process parameter adaption based on structure integrated sensors was done according to the approach of Denkena et al. [12]. Based on this, feed and cutting speed were automatically reduced from f = 0.3 mm by 66% and v_c = 300 m/min by 17% during turning a hybrid shaft of steel and aluminium (Fig. 7(b)). Simultaneously the cutting force difference in the material transition could be reduced by 334 N (Fig. 7(b)). Further, a reduction of the geometry error in the material transition can be achieved [13].

6. Conclusion

This paper presents an approach for structure integrated process force measurement in turning machines based on strain measurement. With this feeling turret, a process force resolution of 43 N could achieved. This high process force resolution could be achieved by compensation of machine-specific disturbances based on characteristic diagrams and a lookup table. For different materials and process parameters, the application of this technology for process force measurement was demonstrated. Furthermore, it was shown that an autonomous material-specific adaption of process parameters can be performed using the feeling turret. In further steps, the ability of the feeling turret to detect tool wear and process errors will be researched. In addition, the compensation of temperature influences will be investigated.

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