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# Influence of the cutting tool compliance on the workpiece surface shape in face milling of workpiece compounds

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**Abstract**

A currently common method to design high-performance workpieces is to combine two or more materials to one compound. In this way, workpieces can be composed of the most qualified materials according to local loads. When machining high-performance workpiece compounds high quality requirements concerning the accuracy of dimension and shape as well as surface roughness must be fulfilled. However, in case of parallel machining, where the cutting edge moves from one material into the other within one cutting tool revolution, unequal cutting properties have a significant negative influence on tool wear and surface quality. Shape deviations of the surface occur, which are not detected when machining the single materials. The four most significant shape deviations that affect the workpiece quality are the material height deviation, transition deviation at the material joint as well as surface roughness deviation. This paper contains new approaches on the prediction of the surface shape that is generated by a face milling process. The focus is on the transition deviation at the material joint. It arises from a force impulse that is applied on the cutting tool and creates a wavy surface on the workpiece. This shape is predicted via cutting force prediction as well as frequency response analysis of the cutting tool and workpiece in relation to different tool holders. Furthermore, deviations between calculated surface shapes and measured surface shapes subsequent to machining tests are evaluated.



*Keywords:* Workpiece compound, Surface analysis, Milling

## 1. Machining of workpiece compounds

The mass reduction of components is one of the most effective ways to reduce fuel consumption and emissions in the automotive and aircraft industry. A lightweight strategy used for highly loaded components is the combination of different materials to workpiece compounds. In this way, components can be designed depending on the local load using the most qualified material.

An example for a workpiece compound is an engine block. Here, most of the compound consists of a lightweight material like aluminum. The crank shaft bearing, bedplate and cylinder tread can be enforced with cast iron or steel [1].

A process strategy to machine workpiece compounds is to machine one material after the other sequentially. In this way, process parameters and, if necessary, the cutting tool can be adjusted to the cutting characteristics of the single material.

Brinksmeier and Janssen, for instance, machined Aluminum-CFRP-Titanium stacks in a drilling process. By using a tailored drilling tool and minimum quantity lubrication the diameter deviation as well as the roughness between the machined materials could be reduced [2]. Kramer developed an in-process monitoring system to detect the materials by acoustic emission signals. In this way, process parameters can be adjusted automatically depending on the currently machined material. By using this adaptive feed regulation the height deviation between the machined materials could be reduced from $\Delta s = 5.2$ µm to unverifiable deviations [3, 4]. A diameter compensation strategy for the circular milling process that is based on the process forces was developed by Dege [5]. With his model he could reduce occurring radius deviations of $\Delta DB = 0.49$ mm to $\Delta DB = 0.03$ mm when machining CFRP-Titanium stacks. With these approaches and models the basis for a good


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surface finish in the sequential machining of workpiece compounds is explored.

In contrast, the parallel machining process of workpiece compounds is not yet explored. In this process strategy the materials are cut alternatingly during one revolution of the workpiece or cutting tool, respectively. The cutting edge moves from one material into the other within a split second. Therefore, the process parameters cannot be adjusted. The process has to be designed for the machining of the specific workpiece compound.

In case of parallel machining, unequal cutting properties have a significant negative influence on tool wear and surface quality. Boehnke describes occurring effects in a turning process of workpiece compounds in [6]. He empirically describes influences of the process parameters and cutting tool geometry on the shape of the component as well as cutting edge. Furthermore, he states actions to be taken for a workpiece quality oriented process design.

For the more complex face milling process of parallel machined workpiece compounds there is not enough knowledge of the actual occurring effects, yet, and there are no analytical models available describing the surface shape.

The following paper shows on the one hand challenges when machining workpiece compounds and on the other hand modeling approaches and results for the prediction of the surface shape in parallel machining. The aim is to predict the surface shape defects so that the machined surface quality can be optimized.

## 2. Experimental setup

Experimental tests were carried out on a 4-axis machining center H5000 manufactured by Heller. The cutting tool was a face mill F2233 by Walter AG with a diameter of d = 32 mm and four teeth. The used indexable inserts consisted of TiCN + $Al_2O_3$ coated cemented carbide. To vary the dynamic properties of the cutting tool tip, three different tool holders were used. Fig. 1 displays the shrink fits InduTherm by Gewefa with the lengths 120 mm, 160 mm and 200 mm, respectively. In the following, they are abbreviated as thl120, thl160 and thl200.


Fig. 1. Used tool holders and cutting tool

The specimens consisted of the three materials aluminum EN-AW2030, cast iron EN-GJS600-3 and polyurethane Obomodulan®1400. Aluminum and cast iron have been chosen due to the application in the industry, where engine blocks made of aluminum and cast iron are machined parallel. The compound polyurethane and cast iron has been chosen to increase the difference of the material properties, especially with regard to hardness and tensile strength, so that the resulting surface defects are visible. Basic physical properties of the materials have been provided by the material manufacturers Obo-Werke GmbH & Co. KG (Obomodulan®1400), Eural Gnutti S.p.A. (aluminum EN-AW2030) as well as Gießerei Heunisch GmbH (EN-GJS600-3). They are listed in Table 1.

Table 1. Material properties.

| | Ob®1400 | AW2030 | GJS600 |
|---|---|---|---|
| density [$g/cm^3$] | 1.2 | 2.8 | 7.2 |
| hardness | 83-85 Shore-D | 110 HBW | 212 HB30 |
| tensile strength [$N/mm^2$] | 94 (compressive strength) | 420 | 749 |
| Young's modulus [GPa] | < 1 | 73 | 174 |
| thermal expansion coefficient [$10^{-6}$ $K^{-1}$] | 76.0 | 23.0 | 12.5 |
| thermal conductivity [W/mK] | < 1 | 135 | 35 |

The specimens were fixed to each other by screws and alignment pins to ensure fixation. Subsequently, the specimens were machined in five full slot machining operations without cooling. One set of experiments is displayed in Fig. 2. The three single materials were cut in the first, third and fifth cutting operation and the workpiece compound in the second and fourth cutting operation. When machining the workpiece compound, the cutting edge moves from the low strength into the high strength material with a material ratio of 50:50.

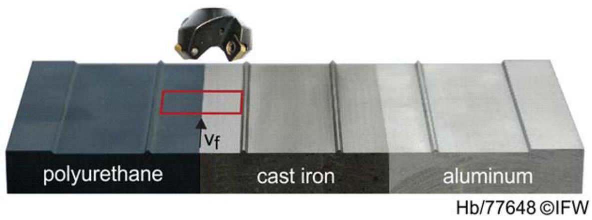


Fig.2: Experimental setup

When machining the opposite way from the high strength material into the low strength material, scratches may occur on the surface of the low strength material. In this case, chips or material segments of the high strength material are transported in front of the cutting edge and damage the low strength material.

Three further shape deviations of the surface occur during parallel machining of workpiece compounds, which are not detected when machining the single materials. The most significant shape deviations that affect the workpiece quality are the

- material height deviation
- transition deviation at material joint
- surface roughness deviation

These shape deviations are described in [7]. Here, the focus is on the cutting tool vibration caused by the transition deviation at the material joint. This effect is significant in particular when machining materials with very different material properties, e.g. polyurethane and cast iron.

### 3. Surface finish when machining polyurethane-cast iron

Fig. 3 displays the surface finish of the workpiece compound polyurethane Obomodulan®1400 and cast iron GJS600 in dependence of the tool holders thl120, thl160 and thl200. The three-dimensional height profiles were measured with an optical profilometer type µScan® by NanoFocus AG. Here, the cutting edge moved from the low strength material into the high strength material. The motion sequence of the cutting tool is displayed by the blue plane. The used process parameters are cutting speed $v_c = 200$ m/min, feed per tooth $f_z = 0.1$ mm, axial depth of cut $a_p = 1.0$ mm, width of cut $a_e = 32$ mm and number of teeth $z = 1$. Three of the four cutting edges have been removed by grinding, so that only one cutting edge generates the surface finish. In this way, the centrifugal force is less than 1 N and can be neglected. Furthermore, the vibration of one cutting edge can be analyzed from the surface finish.

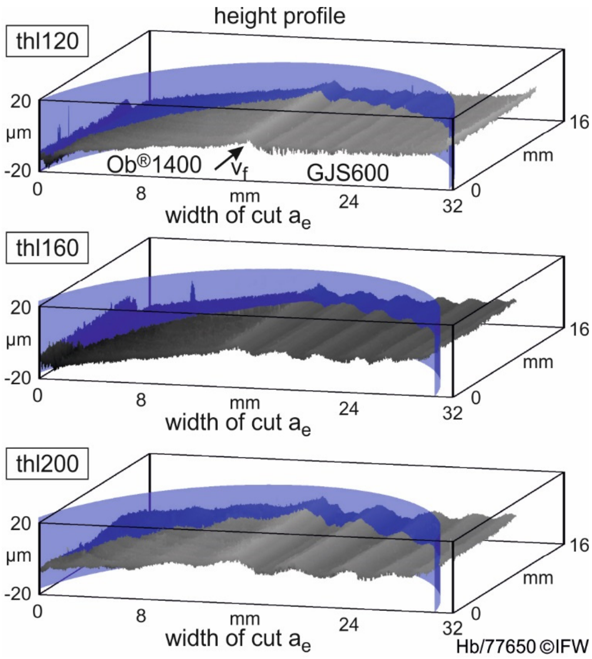


Fig. 3. Measured surface finishes

At the material joint a force impulse is applied on the cutting tool which leads to an excitation of the tool. This creates a wavy surface on the workpiece. A comparison of the three cast iron surfaces displays, as expected, that the tool holder length has a significant influence on the waviness and therefore the surface finish.

To extract the vibration characteristics in cast iron, the motion sequence of the cutting tool (blue plane) is calculated from the measurement data via a cubic interpolation. To extract the wavy surface profile, the cast iron data is aligned via linear regression and a polynomial of the order 2. The result is displayed in Fig. 4. It compares the wavy profiles in cast iron when machining with the three tool holders thl120, thl160 and thl200.

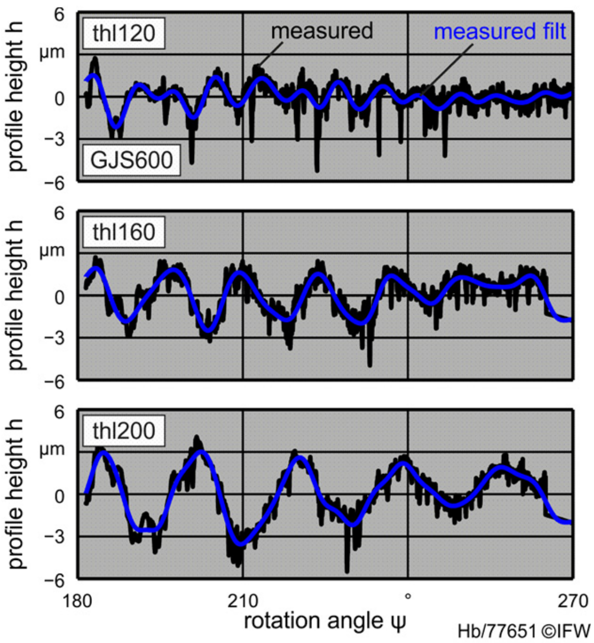


Fig. 4. Measured waviness in cast iron

As expected, the surface measurements show, that the amplitude increases and the frequency decreases with an increase of the tool holder length. A fast Fourier transformation (FFT) of the signals determine the dominant frequencies. Furthermore, the maximum amplitudes are extracted, and listed in Table 2.

Table 2. Dominant modes.

| | frequency [Hz] | max amplitude [µm] |
|---|---|---|
| thl120 | 1069 | + 1.51 / -2.16 |
| thl160 | 875 | + 1.93 / -2.50 |
| thl200 | 680 | + 3.00 / -3.56 |

### 4. Prediction of surface finish

The surface finish is calculated with two single degree of freedom (SDOF) systems in X- and Y-direction, respectively (see Fig. 5). The motion of the system is described by equation (1). $M$ is the local mass matrix, $D$ the damping matrix and $K$ the stiffness matrix.

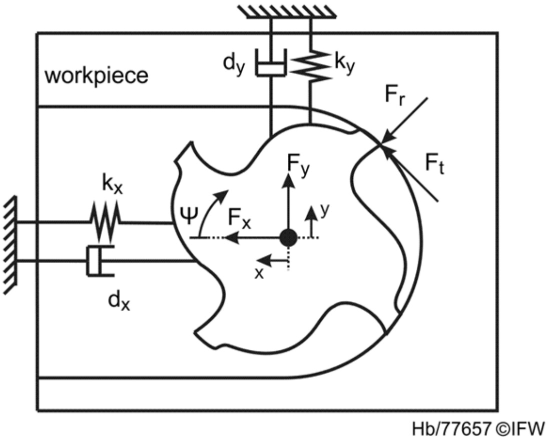


Fig. 5. Two SDOF systems

$$[M]\begin{bmatrix}\ddot{x}(t)\\ \ddot{y}(t)\end{bmatrix}+[D]\begin{bmatrix}\dot{x}(t)\\ \dot{y}(t)\end{bmatrix}+[K]\begin{bmatrix}x(t)\\ y(t)\end{bmatrix}=\begin{bmatrix}F_x(t)\\ F_y(t)\end{bmatrix} \quad (1)$$

$$M=\begin{bmatrix}m_x & 0\\ 0 & m_y\end{bmatrix} \quad (2)$$

$$D=\begin{bmatrix}d_x & 0\\ 0 & d_y\end{bmatrix} \quad (3)$$

$$K=\begin{bmatrix}k_x & 0\\ 0 & k_y\end{bmatrix} \quad (4)$$

The matrices $M$, $D$ and $K$ are determined via a frequency response analysis (see chapter 4.2.). Primarily, the process forces $F_x(t)$ and $F_y(t)$ are predicted in the following section.

### *4.1. Calculation of the process forces*

When machining workpiece compounds the process forces can be calculated via an adaption of the average cutting coefficient model based on average force measurements [8]. Therefore, the single materials are machined to determine the cutting force coefficients $K_{rc}$, $K_{tc}$, $K_{ac}$ as well as the edge coefficients $K_{re}$, $K_{te}$, $K_{ae}$. The results are listed in Table 2 for the three materials AW2030, GJS600 as well as Obomodulan®1400.

Table 2. Cutting force and edge coefficients

| | | AW2030 | GJS600 | Ob®1400 |
|---|---|---|---|---|
| cutting force coefficients [N/mm²] | Krc | 486 | 632 | 164 |
| | Ktc | 1021 | 1487 | 288 |
| | Kac | 282 | 250 | 95 |
| edge coefficients [N/mm] | Kre | 10 | 118 | 8 |
| | Kte | 11 | 123 | 7 |
| | Kae | 23 | 160 | 20 |

Subsequently, the coefficients are implemented in the following force model equations (5). Here, $l$ is the edge contact length and $h(\psi)$ is the instantaneous chip thickness.

$$F_i(\psi)=[K_{ic}\, l\, h(\psi)+K_{ie}\, l]_{Ob}+[K_{ic}\, l\, h(\psi)+K_{ie}\, l]_{GJS}$$
$$for \quad i=tangential, radial, axial \quad (5)$$

When machining workpiece compounds with one cutting edge with a given material ratio, the cutting forces can be calculated. Fig. 6 displays the predicted process forces for one cutting tool revolution in the parallel machining process of polyurethane Obomodulan®1400 and cast iron GJS600. For comparison reason, the measured process forces with the tool holders thl120, thl160 and thl200 are displayed as well. The process parameters are $v_c = 200$ m/min, $f_z = 0.1$ mm, $a_p = 1.0$ mm, $a_e = 32$ mm and z = 1.

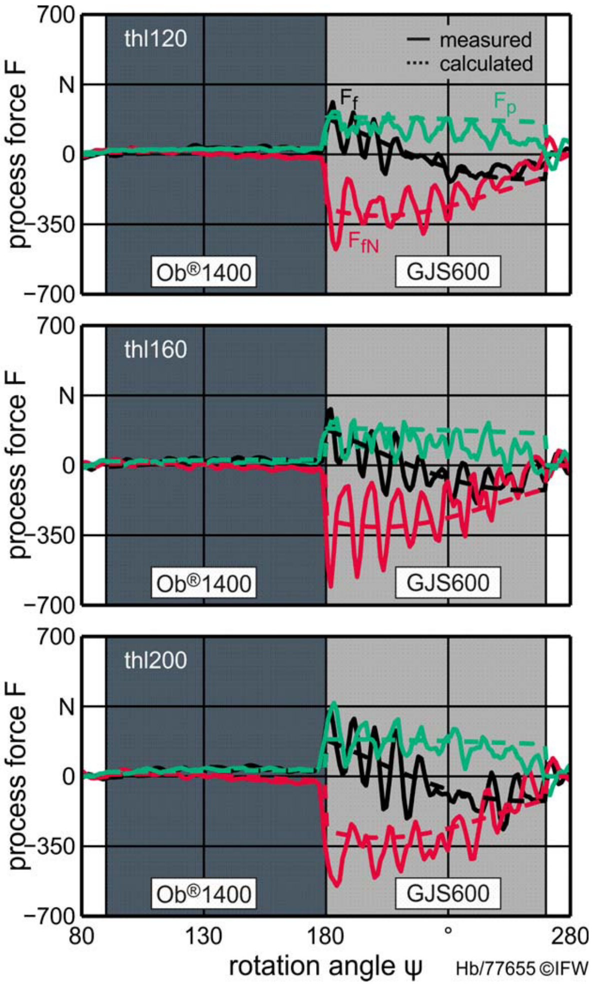


Fig. 6. Measured and calculated process forces (workpiece)

When examining the measured process forces, the force impulse at the material joint with the excitation of the cutting tool is clearly visible in the signals of the feed, feed normal and passive force. This dynamic behavior is not considered in the calculated forces, yet, therefore the signals do not overlap. However, the trend between the measured and predicted process forces correlates well.

### *4.2. Frequency response analysis*

The frequency response tests have been conducted via an impulse hammer and accelerometer as well as the software “LMS TestlabRev. 11A” developed by LMS Testlab. Fig. 7 displays the compliance of the cutting tool tip in relation to the frequency for the three different tool holders in X- and Y-direction.

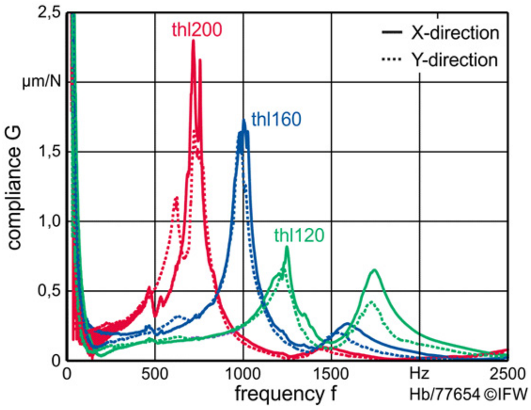


Fig. 7. Frequency response function of cutting tool tips in X- and Y-direction

From the frequency response functions the damped eigenfrequency, compliance as well as the damping ratio of the dominant modes can be extracted. The results are listed in Table 3.

Table 3. Dominant modes.

| | | damped eigenfrequency $f_d$ [Hz] | compliance G [µm/N] | damping ratio D [-] |
|---|---|---|---|---|
| thl120 | X-direction | 1161 | 0.82 | 0.0409 |
| | Y-direction | 1148 | 0.67 | 0.0422 |
| thl160 | X-direction | 941 | 1.73 | 0.0441 |
| | Y-direction | 932 | 1.65 | 0.0338 |
| thl200 | X-direction | 696 | 2.30 | 0.0274 |
| | Y-direction | 704 | 1.66 | 0.0526 |

With the determination of the damped eigenfrequency, compliance and damping ratio, the local mass m [kg], damping d [Ns/m] and stiffness k [N/m] can be calculated via the equations (6-10) and inserted in the equation of motion (1) [9,10]. With the equation of motion and the process forces, the time response of the dynamic system (here: x(t) and y(t) for the cutting tool center point) can be calculated.

$$\omega_d = 2 \cdot \pi \cdot f_d \tag{6}$$

$$\omega_d = \omega_n \cdot \sqrt{1 - D^2} \tag{7}$$

$$k = \frac{1}{G} \cdot \frac{1}{2 \cdot D \cdot \sqrt{1 - D^2}} \tag{8}$$

$$d = 2 \cdot D \cdot \sqrt{k \cdot m} \tag{9}$$

$$m = \frac{k}{\omega_n^2} \tag{10}$$

### *4.3. Surface calculation*

For the prediction of the surface finish, the movement of the cutting edge has to be determined. Therefore, the geometry of the cutting tool as well as the vibration of the cutting tool center point (TCP) are used to calculate the movement of the cutting edge in relation to the rotation angle. Fig. 8 shows the calculation of the cutting edge height in dependence of the radial force $F_r(t)$.

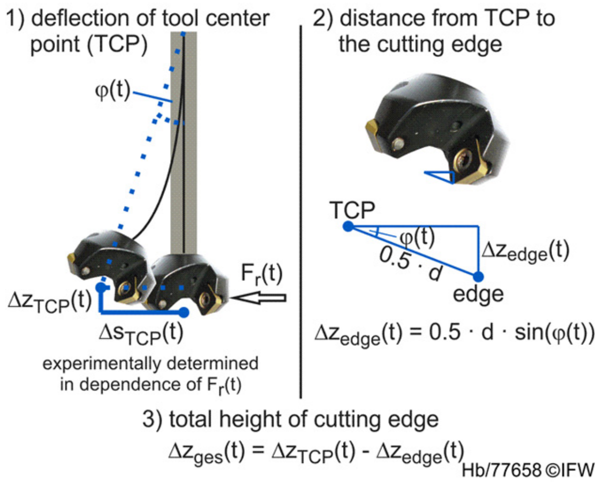


Fig. 8. Calculation of cutting edge height in dependence of radial force

The calculated surface is displayed in Fig. 9. Here, 160 revolutions are calculated with the software Matlab developed by MathWorks on a standard desktop PC within seconds. Comparing the predicted surfaces with the measured surfaces in Fig. 3 shows that the trends of the surface finishes in polyurethane as well as the waviness in cast iron correlate well.

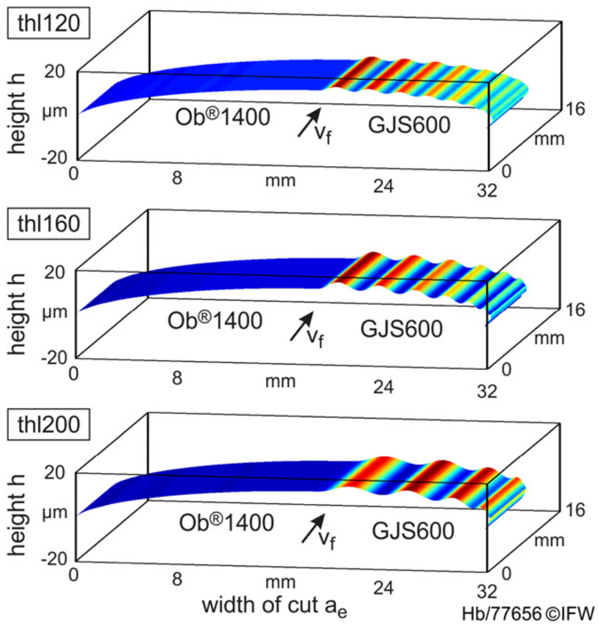


Fig. 9. Calculated surface finishes

Fig. 10 compares the calculated surface profiles with the measured profiles in cast iron GJS600 according to Fig. 4. When machining with the tool holder thl120, the prediction is not satisfying. Especially, the frequency does not correlate with the measured result. This is due to the used SDOF system. As displayed in Fig.7, the frequency response function exhibits two peaks. Therefore, at least a 2DOF system has to be used to increase the accordance with the measured results.

A good correlation is reached with the measured surface finish when machining with the tool holder thl160. The frequency and the compliance can be predicted well.

When machining with the tool holder thl200, the frequency of the wavy surface finish is f = 680 Hz, the calculated frequency is approximately f = 699 Hz (compare Table 2 and Table 3). The difference of calculated and measured frequency is 19 Hz or approximately 3 %.

In general, the results show that the surface finish can be calculated with the used modeling approach. However, a 2DOF system will improve accuracy of the surface finish prediction.

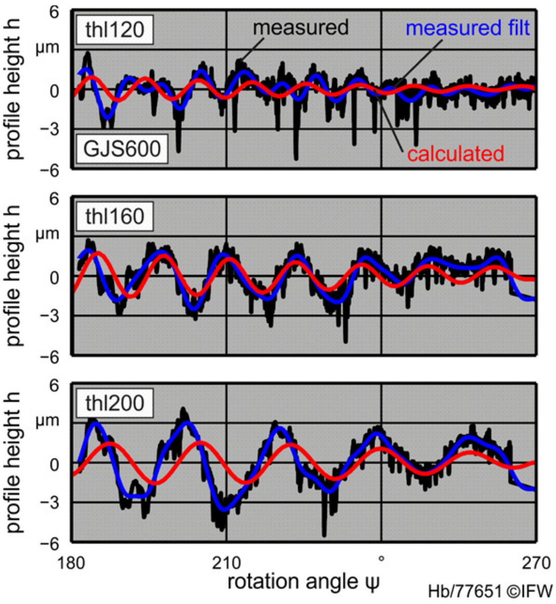


Fig. 10. Comparison of measured and filtered surface profile

## 5. Conclusions

The transition deviation at the material joint as well as the surface waviness are examined via experimentally conducted machining tests. As expected, the tool holder length has a significant influence on the surface shape.

A modeling approach to predict the surface finish when machining workpiece compounds is presented in this paper. It includes the consideration of the cutting tool kinematics, process forces as well as process dynamics. The model provides a good prediction of the surface finish and can be adjusted easily to other workpiece compound - cutting tool - machining center combinations.

## 6. Outlook

Future research at the Institute of Production Engineering and Machine Tools in Hannover will focus on the improvement of this model. The aim is to increase the precision of the predicted process forces, also when machining with four cutting edges. The response of the dynamic system will be calculated more accurate using a multiple degree of freedom system. Furthermore, the material specific chip formation mechanisms of the single materials will be considered to improve the prediction of the surface finish. This may include the implementation of a suitable material model.

## Acknowledgements

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