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Modeling of workpiece shape deviations in face milling of parallel workpiece compounds

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Abstract

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 that way components can be designed depending on the local load using the most qualified material.

For the production of high-performance workpiece compounds high quality requirements concerning the accuracy of dimension and shape as well as surface roughness must be fulfilled. However, machining of workpiece compounds leads to unfavorable changes of the workpiece quality in comparison to machining of the single materials. Significant shape deviations occur when different materials are machined alternately in one cutting operation. This is due to unequal material properties, cutting characteristics, chip formation mechanisms as well as characteristic interactions between the single components.

This paper describes the causes of the three main criteria material height deviation, transition deviation and surface roughness deviation that significantly influence the surface quality in parallel machining. The focus is on the process understanding as well as modeling of the surface defects. The approaches and results show that the characteristic shape deviations can be predicted. With the knowledge of the causes that lead to the surface defects in parallel machining it is possible to optimize the process setup for a surface quality oriented machining process of a workpiece compound.

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Keywords: workpiece compound; surface topography; face milling

1. Introduction

Conventional lightweight constructions based on high specific strength materials cannot cope with the increasing requirements on workpiece performance behavior. Thermo mechanical loads as well as required physical properties become more advanced and are often beyond the capability of single materials. 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.

An example for a metallic compound component is an engine block. Here, most of the workpiece consists of a lightweight material like aluminum. The crank shaft bearing, bedplate and cylinder tread can be enforced with cast iron or steel [1]. 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. The aim is to allow the prediction of occurring surface shape defects so that the parallel machined surface quality can be optimized.

2. Process strategy

A process strategy to machine workpiece compounds is to machine one material after the other sequentially. In this way process parameters and eventually 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

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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 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. Fig. 1 displays examples of sequential and parallel machining.

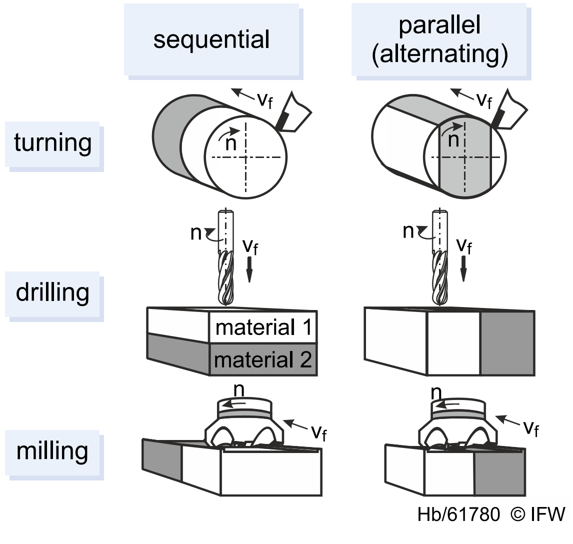

Fig. 1: Examples of sequential and parallel machining strategies.

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 and 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.

3. Experimental setup

Experimental tests have been carried out on a 4-axis machining center MCi16 by Heller. The cutting tool is a face mill with a diameter of d = 32 mm with four indexable inserts made of cemented carbide HW-K15. The specimens consisted of the three materials aluminum AlSi9Cu3, cast iron GJS600 and polyurethane Obomodulan®500, which were fixed to each other by screws and alignment pins to ensure fixation. Basic properties of the materials are listed in Table 1.

Table 1. Material properties

	AlSi9Cu3	GJS600	Ob®500
density [g/cm^3]	2.8	7.2	0.5
hardness	80 HB	169 HB	55 Shore-D
tensile strength [MPa]	240	600	< 0.001
Young's modulus [GPa]	71	174	< 0.001
thermal expansion coefficient [10^{-6} K^{-1}]	23.0	12.5	36.0
thermal conductivity [W/mK]	220	39	0.03

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 are 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. The material ratio during parallel machining is 50:50.

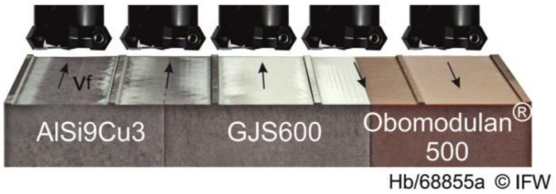

Fig. 2. Experimental setup.

During parallel machining of workpiece compounds shape deviations of the surface occur, which are not detected when machining the single materials. The three most significant shape deviations that affect the workpiece quality are the following three criteria.

4. Shape deviations

4.1. Material height deviation

The shape deviation that affects the surface quality the most in parallel machining is the material height difference. Fig. 3 displays the height profile of a machined specimen. The process parameters used were $v_c = 400$ m/min, $f_z = 0.1$ mm and $a_p = 0.5$ mm. The height profile has been measured by an optical profilometer µScan$^{\circledR}$ manufactured by NanoFocus AG.

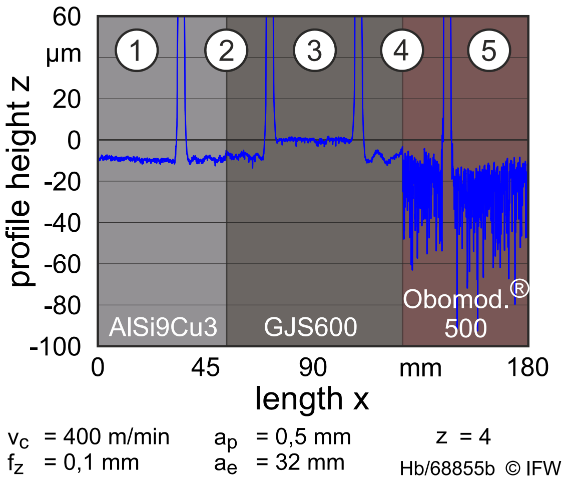

Fig. 3. Height profile in relation to the machined material.

GJS600 is the reference profile. Therefore its average height is $z = 0$ µm. AlSi9Cu3 has an average height profile of $z = -10$ µm and Obomodulan$^{\circledR}$500 a height of $z = -26$ µm. These profiles are significantly caused by the occurring process forces, particularly passive forces, resulting from the material properties. Here, the relation between the maximum passive force and profile height can be described by a polynomial of the 2nd degree (see Fig. 4). The measured maximum passive forces for Obomodulan$^{\circledR}$500, AlSi9Cu3 and GJS600 are $F_p = 5$ N, $F_{p,Al} = 54$ N and $F_{p,GJS} = 111$ N. The higher the process forces, the more dislocates the cutting tool as a function of its compliance and the higher is the profile height.

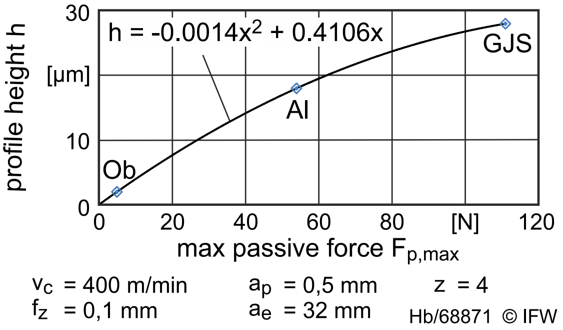

Fig. 4. Profile height as a function of the maximum passive force.

Whereas in single material machining the cutting tool bends primarily in feed direction, the cutting tool in parallel machining also bends in feed normal direction (see Fig. 5). This leads to inclining or declining profiles in relation to the reference profile and is caused by the different passive forces.

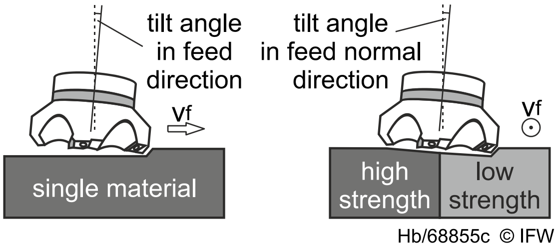

Fig. 5. Tilt angle in feed and feed normal direction.

In contrast to the tilt angle in feed direction, the tilt angle in feed normal direction varies as a function of the cutting tool rotation angle and the number of cutting edges engaged, since the passive forces vary during one revolution. This unequal loading on the upmilling and downmilling side of the cutting tool causes a dynamic variation of the tilt angle in feed normal direction and leads to a local radial and axial runout that can be detected on the machined surface. A profile of a parallel machined AlSi9Cu3-GJS600 specimen is displayed in Fig. 6. Here, the workpiece compound has been machined with one cutting edge. In each material the inclination has a different angle. The material height difference Δs is evaluated by determining the geometric center for each profile. In relation to the reference profile the material height difference can be determined.

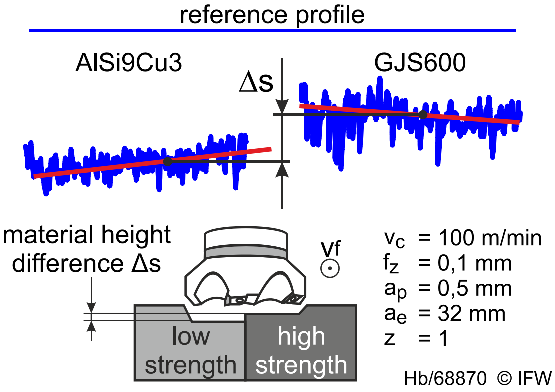

Fig. 6. Profile height: AlSi9Cu3-GJS600.

The process forces can be used to explain and predict these profiles. Here, the process force model by Altintas [7] has been adopted for calculating the process forces in parallel machining. This was done by experimentally determining the cutting force coefficients for the single materials (see Table 2) and implementing them in the force model.

Table 2. Cutting force and edge coefficients.

		AlSi9Cu3	GJS600	Ob®500
cutting force coefficients [N/mm²]	K_{rc}	-883	-1853	30
	K_{tc}	272	519	-7
	K_{ac}	556	868	-3
edge coefficients [N/mm]	K_{re}	-3	-51	3
	K_{te}	4	30	0
	K_{ae}	4	13	4

By the superposition of an upmilling process of Al and downmilling process of GJS the cutting forces for a parallel machining process can be calculated. Fig. 7 displays the predicted process forces for one cutting tool revolution in the parallel machining process of AlSi9Cu3-GJS600 with four cutting edges and the process parameters: $v_c = 100$ m/min, $f_z = 0.2$ mm and $a_p = 0.5$ mm. Higher cutting speeds lead to vibrations close to or above the resonance frequency of the measurement platform. In that case the process forces cannot be measured accurately.

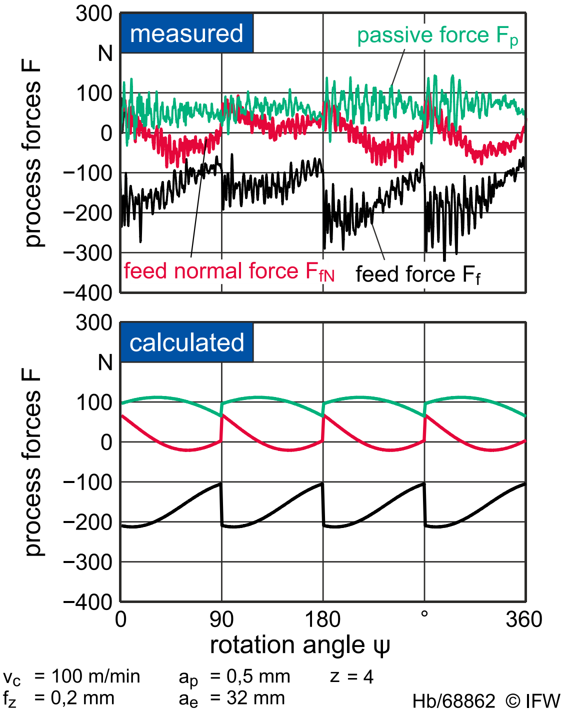

Fig. 7. Measured and calculated process forces (no. of teeth: z = 4).

Good correlations between the trend of the predicted and measured process forces have been reached. However, the influence of the process forces on the surface profile is not directly visible since the process forces of two engaged cutting edges overlap. Therefore Fig. 8 displays the calculated process forces of a face milling process with one cutting edge engaged. Here, the trend of the passive forces is similar to that of the surface profile (compare with Fig. 6). Therefore the influence of the passive force on the surface profile is directly visible.

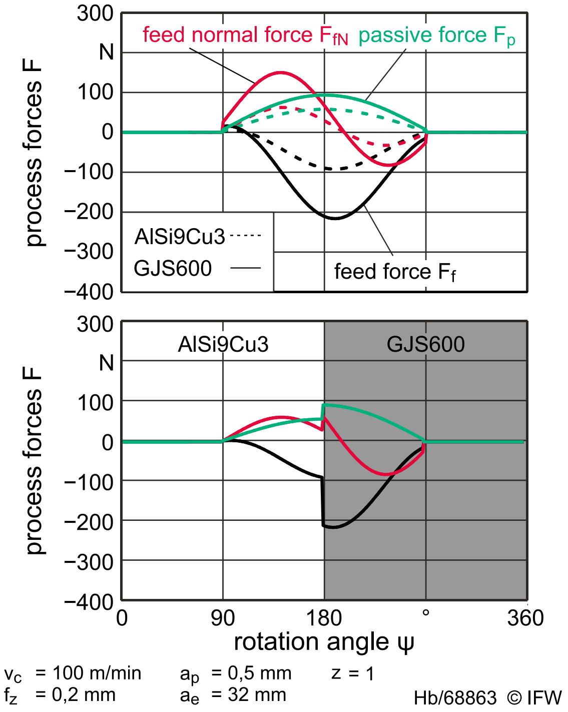

Fig. 8. Calculated process forces (no. of teeth: z = 1).

4.2. Transition deviation at material joint

The second significant surface quality criterion is the transition deviation. It arises from a force impulse that is applied on the cutting tool at the material joint. This impulse leads to an excitation of the cutting tool and creates a wavy surface on the workpiece (see Fig. 9).

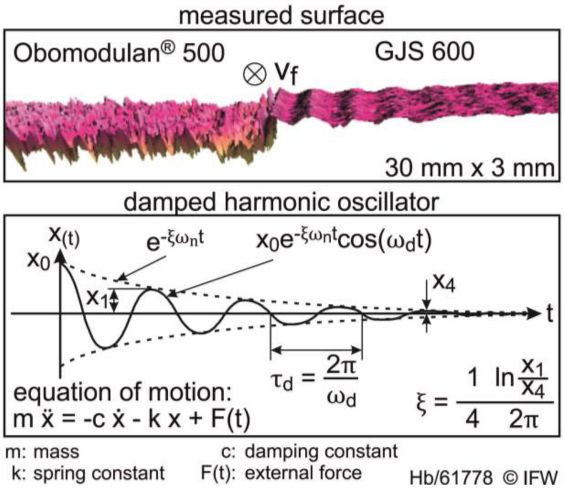

Fig. 9. Transition deviation – oscillation.

Here, the cutting edge moved from the low strength material Obomodulan®500 into the high strength material GJS600. The oscillation on the surface of GJS600 can be compared with a damped harmonic oscillator. The vibration characteristics are significantly influenced by the experimental setup, particularly the vibration characteristics of the cutting tool tip.

When the cutting edge moves from the low strength into the high strength material, the cutting tool displacement instantly increases and the axial depth of cut decreases. Contrariwise from the high strength into the low strength material, the cutting tool displacement decreases at the material joint and the axial depth of cut increases. For a deeper analysis of the transition deviation at the material joint FEM simulations have been conducted. A two dimensional model for the orthogonal cutting process of aluminum and cast iron using the FE Software Deform 2D has been generated.

Here, the material properties of aluminum Al2030Sn and cast iron GJS400 are used. Their properties have been experimentally determined by the Split-Hopkinson Bar method. These materials can be used to display the general behavior of the materials at the interface.

The closest approximation to the measured behavior of Al2030Sn can be described by the Khan-Liang material model. The Zerilli-Armstrong material model had the closest approximation to the measured behavior of GJS400. Fig. 10 displays the FEM calculation at the transition deviation in relation to the cutting direction. Here, the process parameters $v_c = 400$ m/min, b = 1 mm, and h = 0.07 mm have been used.

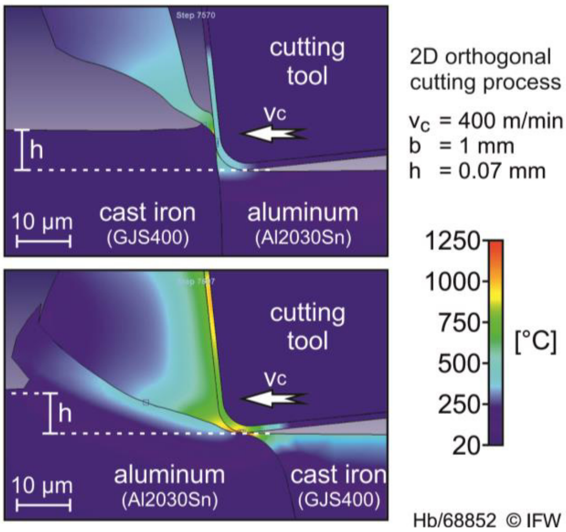

Fig. 10. Transition deviation – material movement and temperature distribution.

The simulation shows that the cutting direction significantly influences the chip formation and material deformation at the material joint. When the cutting edge moves from the low strength into the high strength material, the low strength material is pressed against the projecting edge of the less compliable high strength material. High pressure and high temperatures between the rake face of the cutting tool and the high strength material are the consequences until an impact leads to a deviation and higher loading of the cutting tool.

In the other direction from high strength into low strength material, the low strength material is drawn back by the cutting edge and high strength material until the cutting edge passes the material joint. Afterwards the cutting tool is released and continues cutting with a higher axial depth of cut.

4.3. Surface Roughness deviation

In addition to the material height difference and transition deviation a surface roughness difference occurs in parallel machining. This is on the one hand due to the different chip formation mechanisms of the materials, which influence the workpiece surface shape (see Fig. 11). On the other hand, process dynamics as mentioned before influence the kinematic engagement conditions. Therefore, the surface roughnesses in parallel machining differ more in comparison to the surface roughnesses of single materials. This is underlined by [8] and [9].

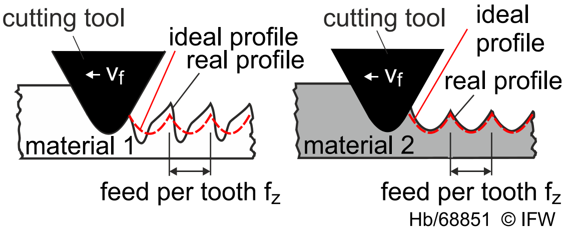

Fig. 11. Influence of chip formation on the workpiece shape.

Both, the chip formation mechanisms as well as the kinematic engagement in parallel machining, are influenced by the process parameters. Therefore, the adaption of the process parameters reduces the surface roughness difference and improves the surface quality of the machined workpiece compound.

5. Modeling approach for the prediction of the surface shape

With the knowledge of the described effects it is possible to generate a comprehensive model for parallel machining of workpiece compounds, which enables the prediction of the machined workpiece shape. Hereby, a quality oriented process can be designed in relation to the cutting tool geometry and process parameters.

The modeling approach includes the consideration of the cutting tool kinematics, process forces, compliance in feed and feed normal direction as well as process dynamics and material specific chip formation mechanisms (see Fig. 12). Its input parameters are the tool geometry, process parameters, material data as well as static and dynamic tool properties of the machine tool. After generating the calculated surface shape, a comparison with a measured surface shape can be conducted. Stochastic deviations like scratches or cavities may occur on the surface due to adhesions, built-up edges, tribochemical reactions or wear. These effects may cause surface damages and therefore a deviation of the calculated and measured surface shape.

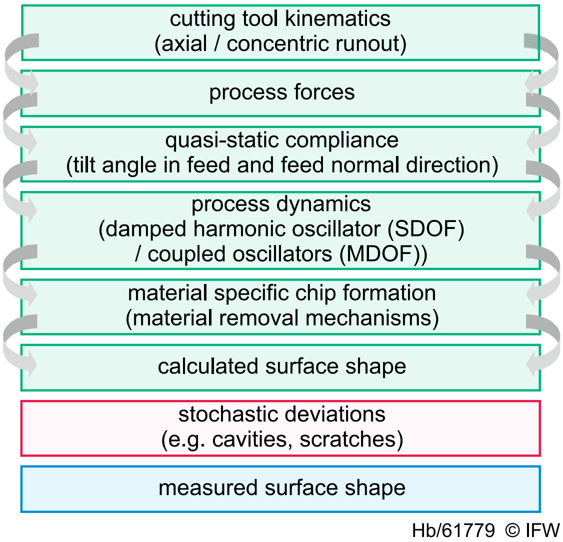

Fig. 12. Modeling approach for the prediction of a parallel machined workpiece surface.

6. Conclusion

The presented results describe the effects occurring during the parallel machining process of workpiece compounds. With the knowledge of the three characteristic surface deviations and their causes a model of the complete shape of a parallel machined surface is possible. Future research at the Institute of Production Engineering and Machine Tools in Hannover will focus on the implementation of this model.

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