Modelling of Scaling Effects during the Scaling of the Chipping Process of a W-Cu-Particle Compound Material

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Experimental preliminary analyses must be carried out on the relevant process parameter ranges to analytically examine the non-linear scaling effects of W-Cu-particle compound materials during micro cutting with milling tools to improve the quality of the workpiece and efficiency of the cutting process. This paper examines the process forces developing during milling with a three-edge mill with the help of a dynanometer and the speed profiles with a laser vibrometer. The used material is a compound material with 80 % tungsten and 20 % copper and an average tungsten particle diameter of 15 µm.

1 Properties and application of W-Cu-particle compound materials

The objective of the research is to examine the scaling effects in the contact zone of the cutting edge in the macroscopic and microscopic range in a process model. W-Cu-particle compounds are multiphase materials, which, in contrast to pure refractory metals such as molybdenum or tungsten, are produced by liquid phase sintering or high temperature infiltration. The W-Cu-material specifications vary in terms of grain size and grain size distribution of the tungsten and of the fraction of the metallic copper binder phase. **Figure 1.1** shows the cross section polish of a W-Cu-particle compound material with an 80 % tungsten- and 20 % copper-fraction. The average tungsten particle diameter is 15 µm.

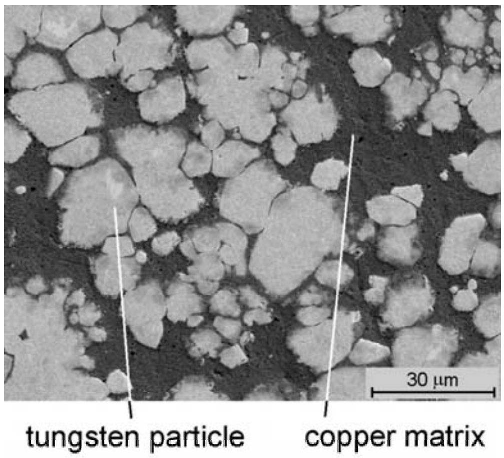

Figure 1.1: Micro structure of the W-Cu-particle compound material 80/20

Tungsten has a higher melting point (T_s = 3407 °C) and a higher E-modulus (E = 401000 N/mm^2) than copper (T_s = 1083 °C, E = 123000 N/mm^2). The combination of the two materials allows generating a multifunction material, which, due to its especially adapted mechanical, thermal, and material technological properties, is used in electrical engineering, microelectronics, and as electrode materials in tool and die making. Examples of application are structured electrodes for die sinking and contacts for circuit and vacuum breakers. In the case of these applications, the high burnout strength, welding resistance, and the low contact resistance are to be highlighted. The lack of manufacturing strategies and the specific process modelling, however, represent a problem for the machining of this material group.

2 Cutting of W-Cu-particle compound materials

Due to its hardness (*HRC* = 62 - 70), tungsten causes extreme mechanical and thermal stress at the tool cutting edge during cutting. The life cycle of tungsten carbide tools is below that of the soft machining of steels [1]. The machining of copper as soft metal binder phase requires a high cutting speed causing high temperature stresses in the contact zone [5, 6, 7]. Due to the multiphase structure of the W-Cu-particle compound material, the thermal conduction behaviour in the material cannot be constantly described. It rather depends on the thermal properties and the material structure of the composite partners. As a result, residual stresses can be induced in the particle compound material during machining, which, in turn may lead to deformation or compound failure.
Experimental investigations are presented in [2] and [3] for the cutting of W-Cu-particle compound materials with small end mills (d < 3 mm). The materials handled in research reports on cutting with geometrically defined cutting edge published so far are mainly non-ferrous metals and steels up to HRC 59 [9, 11].

3 Experimental Investigations

Analyses were carried out on a GAMMA 303 PERFORMANCE 5-axis milling machine by WISSNER, Göttingen, Germany, to quantify the scaling effects for the scaling of cutting processes of the above-mentioned materials with three-edge (micro) end mills (d = 0.5 mm; 1 mm; 2 mm; 3 mm). The cutting speed (v_S = 80 m/min), the tooth feed (f_z = 5 µm), and the depth cut of (a_p = 1/5*d) are defined as process parameters. Grooves of a length of 15 mm and a width equal to the tool diameter d are continuously milled in the main cut. During the machining process, the x and y process forces (orthogonally and along the direction of milling) are recorded with a dynamometer (type: KISTLER MiniDyn) and the speed profile in milling direction with a laser vibrometer (type: Polytec OFV - 353) with a measurement application developed at the IWF based on the commercial software „LABVIEW" with a sample rate of 25 kHz/s per measurement channel. The tools are fixed with a clamping length of 25 mm. **Figure 3.1** shows the process force spectrum in x-direction within the time range (left) and the transformed spectrum via fft (fast fourier transformation) in the fourier space (right) for a tool with a diameter of 0.5 mm. In the fourier space, the amplitude-peaks to be examined have to be multiplied with a correction factor of $\sqrt{2 \cdot \pi}$ to be able to qualitatively compare them in the time range [13]. A Hamming correction filter is

Process Parameters:	Tool :	Compound Material:
v_c = 80 m/min f_z = 5 µm a_c = 1/5*d	Three Edge End Mill , d = 500 µm	80/20 Tungsten-Copper-Compound Material, milled in the main cut

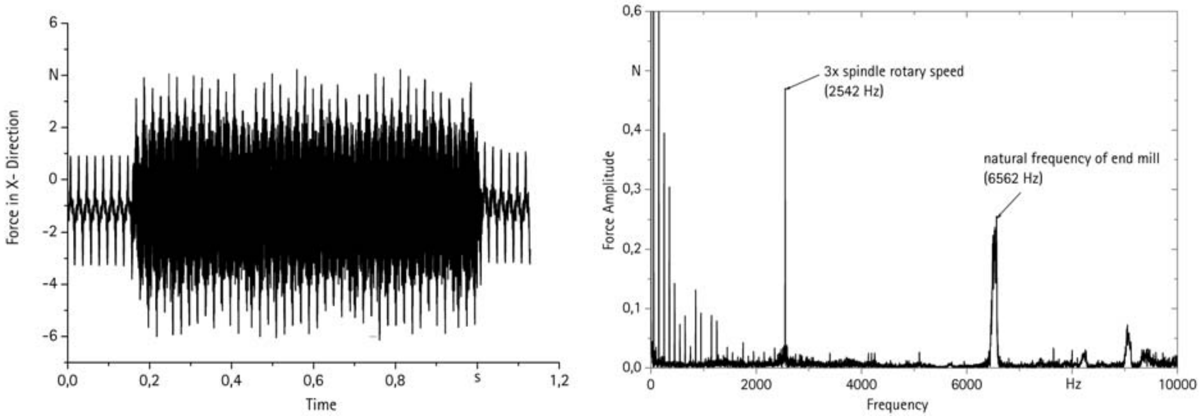

Figure 3.1: Measured force spectrum orthogonally to cutting direction (left) and the fast fourier transformed spectrum (right)

used to smooth the settling and decay processes at the boundaries of the spectrum to be considered in the time range. The spindle rotary speed of the above-described tool and process parameters is 50928 $min^{-1} \equiv$ 848.8 Hz. The first natural frequencies of the dynamometer are 5.1 kHz in x and y direction and 5,6 in z direction. In order to quantify the speed and force amplitude peak at 3x spindle rotary speed (< 2542 Hz) of the end mills the natural frequencies of the dynamometer are twice this speed. In the range of 0.18 s – 1.00 s, the milling process of Figure 3.1 can be seen. The idle run is depicted in the range of 0 s – 0.18 s and of 1.00 s - 1.20 s. The "peak to valley" value is 9.8 N. A representative, theoretically calculated static process average value is introduced for the comparison of the recorded ranges. It is calculated as follows:

$$f_{average} = \frac{1}{t_l - t_0} \sum_{m=0}^{m=l} \left| \int_{t_m}^{t_{m+1}} f(x)dx \right|$$

The index 0 stands for the starting point, *l* the for ending point, and *m* for the number of zero passages of the function *f(x)*. This process average value is representative for an equivalent static value, which describes the spectrum. The process average value for the configuration above is 3.4 N. Figure 3.2 shows that significant deflections can be observed in the frequency range of 0 Hz – 2000 Hz, which result from the natural frequencys of the machine tool and its machine components and are not further examined. An amplitude peak of 0.47 N at a frequency of 2542 Hz, which is the triple of the spindle frequency within an error of 0.002 %, results from the three-edge tool. The range of 6000 Hz – 10000 Hz is a result of the natural frequency of the tool and of the workpiece. Analytical and experimental examinations of the natural frequency of the tools during milling are compared in 3.2.

Figure 3.2 shows the measured speed spectrum of the above-mentioned tool in the time range (left) and the transformed milling spectrum in the fourier range (right).

Process Parameters:	Tool :	Compound Material:
v_c = 80 m/min f_z = 5 μm a_c = 1/5**d*	Three Edge End Mill , *d* = 500 μm	80/20 Tungsten-Copper-Compound Material, milled in the main cut

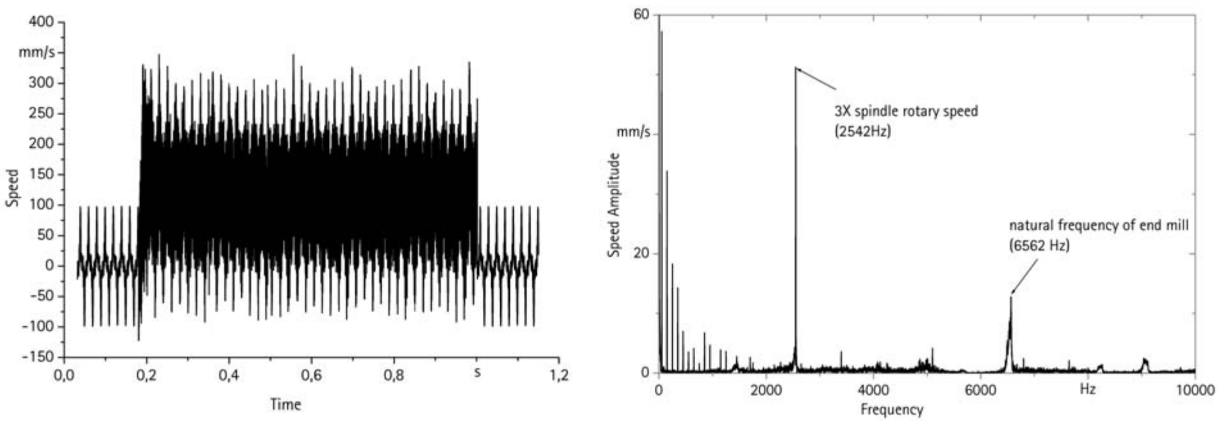

Figure 3.2: Measured speed spectrum orthogonally to cutting direction (left) and fast fourier transformed spectrum (right)

It shows also the idle run and the milling process range. (see also figure 3.1 left). The "peak to valley" – process speed value is 420 mm/s and the theoretically calculated static average speed value is 112 mm/s. Figure 3.2 (right) shows the fourier transformed speed spectrum of the milling process in the range of 0.18 s – 1.00 s. The triple of the spindle rotary speed (2542 Hz) and the natural frequency of the tool (6562 Hz) can be clearly seen. The speed amplitude peak at 2542 Hz is 51.4 mm/s and is significant in contrast to the other amplitude peak in the range of 1 kHz – 10 KHz.

Figure 3.3 shows the transformed path amplitude spectrum of figure 3.2. In the transformation it is assumed that the temporal speed spectrum oscillates stationary, i. e. settling and decay processes are neglected (see figure 3.3). In the transformation, each value has to be divided by the respective angular frequency in the fourier transformed speed spectrum.

If the natural frequency of the machine and of its components is neglected in the range of 0 kHz – 1 kHz, the maximum drift peak is significant at the triple spindle rotary speed and to be recognized with a peak of 1.2 µm. The total drift of the tool in milling direction during engagement results in 7.9 µm from the addition of the single amplitude peaks of the fourier spectrum in figure 3.4 and under consideration of the phase.

Process Parameters:	Tool :	Compound Material:
v_c = 80 m/min f_z = 5 µm a_c = 1/5*d	Three Edge End Mill , d = 500 µm	80/20 Tungsten-Copper-Compound Material, milled in the main cut

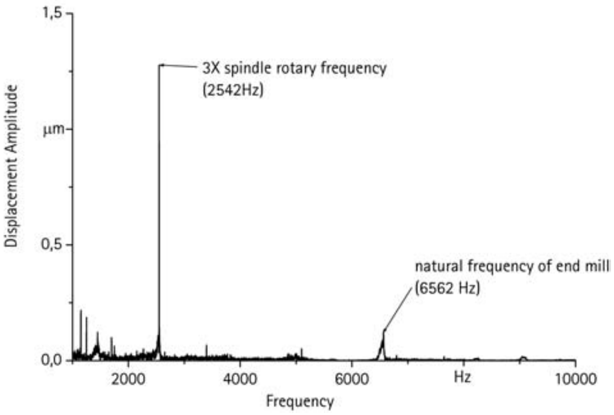

Figure 3.3: Vibration displacement amplitude of end mill with 0,5 mm diameter

3.1 Results (force, speed, tool drift)

Figure 3.4 a) shows the "peak to valley"- and average process values for the measured forces. The "peak to valley"- and the average process values in x and y direction show a qualitatively similar course. In the case of the tools of diameters of 1 mm – 3 mm, a linear course of the average process values can be recognized. The tool with a diameter of 0.5 mm has an average process value of 3.4 N and that of a diameter of 3 mm 55 N. The "peak to valley" measured process force values show a linear course for the tools with diameters of 1 mm – 3 mm. The respective force values are 19 N and 279 N. The "peak to valley" process value of the tool with a diameter of 0.5 mm is 9.8 N for the values measured in x direction, and 10.1 N for those measured in y direction. **Figure 3.4 b)** shows the force amplitude peak in x and y direction at the spindle rotary speed of the respective tool. The values in x and y direction describe a similar course in qualitative as well as quantitative terms. In the case of tools with diameters of 0.5 mm – 3 mm, the force amplitude peaks are 0.47 N and 4.34 N in x direction, and 0.35 N and 4.03 N in y direction. **Figure 3.4 c)** shows the average and "peak-to-valley" process values for speeds and speed amplitude peaks at the spindle rotary speed in milling direction according to the diameter of the tools to be examined. The "peak-to-valley" speed values increase in a disproportionate way in case of a tool with a diameter of 0.5 mm to 420 mm/s and to 1424 mm/s in the case of a diameter of 3 mm. The average process speeds constantly increase with a growing diameter. In the case of a tool of a diameter of 0.5 mm, it is 112 mm/s, in the case of 3 mm 291 mm/s. The speed amplitude peaks, which occur at the spindle rotary speed, are convergent with a growing tool diameter. In case of a tool diameter of 0.5 mm, the amplitude peak is 51 mm/s, in case of a tool diameter of 2 mm, it is 87 mm/s, and in case of a diameter of 3 mm, it is 92 mm/s. **Figure 3.4 d)** shows the total mill drift and the drift amplitude peak of the tool at the respective spindle rotary speed. Analogously to figure 3.8, the mill drift amplitude peaks are convergent at the spindle rotary speed. In case of a tool with a diameter of 0.5 mm, the drift is

3.25 µm, in case of a diameter of 2 mm, it is 26.6 µm, and in case of 3 mm, it is 30.8 µm.

Process Parameters:	Tool :	Compound Material:
v_c = 80 m/min f_z = 5 µm a_c = 1/5*d	Three Edge End Mill , d = var	80/20 Tungsten-Copper-Compound Material, milled in the main cut

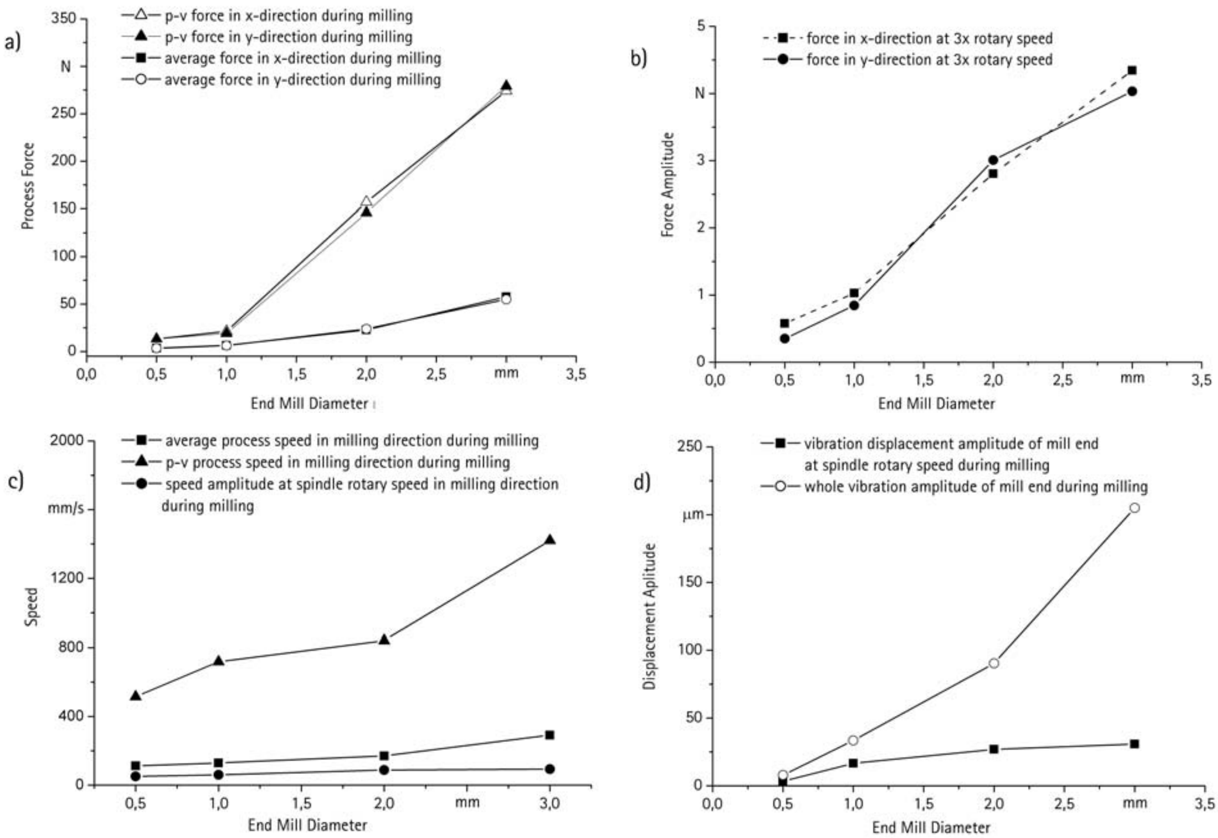

Figure 3.4: a) Peak to valley and theoretically average determined process forces depending on end mill diameter; b) Force amplitude peak at 3x spindle rotary speed of end mill depending on end mill diameter; c) Peak to valley and average determined process speeds depending on end mill diameter; d) Displacement amplitude at 3x rotary spindle speed and whole displacement amplitude peak of end mill depending on end mill diameter

3.2 Natural frequencies of the tool

To detect further relations between the force, the speed, and the surface quality of the workpiece, the first bending natural frequency of the tools has to be characterised in the fourier spectrum. Thereby, the tool geometry (lengths and diameters) is measured. The geometry of the end mills is not proportional to each other except the cutting diameter. The density of the tool is experimentally calculated and is in average 13800 kg/m^3. The E-modulus is assumed 6.9*10^{11} N/m^3 [4] and the Poisson's ratio 0.22. A Rayleigh-Ritz-method [14] is chosen for the frequency calculation. The Bernoulli's bending line is used as initial function. The transition from cutting edge to the shaft is assumed a truncated cone and the cutting edge with a groove approximated as a cylinder. The results are numerically verified with the „Ansys" software and compared with the experimental results of the fourier-transformed speed and force spectra.

Process Parameters:	Tool :	Compound Material:
v_c = 80 m/min f_z = 5 µm $a_c = 1/5^*d$	Three Edge End Mill , d = var	80/20 Tungsten-Copper-Compound Material, milled in the main cut

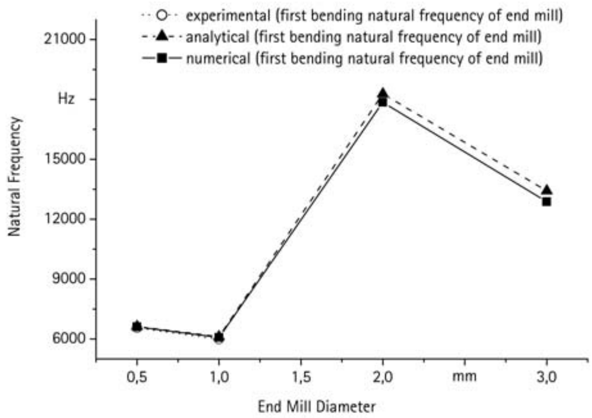

Figure 3.5: First bending natural frequency of end mills

Figure 3.5 shows the first bending natural frequency of the tools depending on the diameter. In the case of tools with a diameter of 0.5 mm and 1 mm, the experimentally measured first bending natural frequency is 6562 Hz and 5997 Hz. Within an error of 1 %, these results correspond to the numerical and analytical calculations and provide satisfactory results. The calculative values of the natural frequencies and their amplitude peaks in case of tool diameters of 2 mm and 3 mm are 18279 Hz and 13422 Hz, and cannot be offhand measured at a scan rate of 25 kHz/s by the test setup used here due to the non-compliance with the Shannon Theorem [12].

3.3 Surface roughness

The results of the surface roughness measurements of the 15 mm milled grooves according to tool diameter for R_{zDIN} and R_a are depicted in **Figure 3.6**. The roughness reaches a maximum value of R_{zDIN} = 2.2 µm in case of a tool diameter of 2 mm and R_a = 0.225 µm. The minimum is reached at R_{zDIN} = 0.95 µm at a tool diameter of 1 mm for and R_a = 0.08 µm.

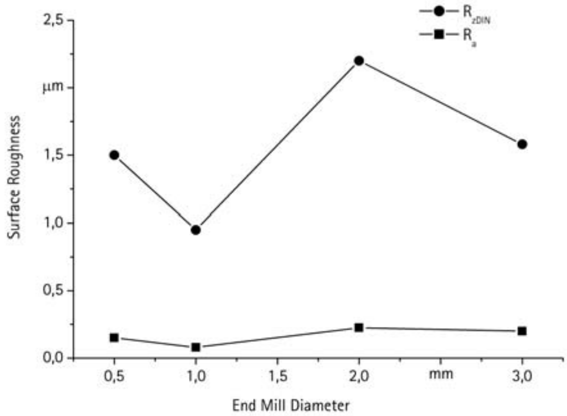

Figure 3.6: Surface roughness of milled grooves

4 Discussion

The force spectra in x and y directions (orthogonally and along the milling direction) and the speed spectra in milling direction are recorded for tool diameters of 0.5 mm, 1 mm, 2 mm, and 3 mm, the cutting speed (v_s = 80 m/min) and the tooth feed (f_z = 5 µm) as well as the depth of cut (1/5*d) remaining constant during the entire measurement cycle. In the evaluation, the average "peak to valley" and static process values from the temporal spectra and the amplitude peaks from the fast fourier transformed temporal spectra at the spindle rotary speed are compared. The result is that the "peak to valley" forces have a linear course for tool diameters of 1 mm – 3 mm. A nearly linear relation can be stated for the average process forces in x and y direction for about all examined tools. The tool with a diameter of 0.5 mm departs from the linear behaviour with a value of 13.3 N. In case of the force amplitude peaks, too, there is a linear relation between the amplitude peaks for tool diameters of 1 mm – 3 mm. With 0.58 N and 0.35 N, the tool with a diameter of 0.5 mm has higher values than expected in a linear relation. The examination of the measured speed values shows a disproportionate increase of the "peak to valley" values in case of tools with increasing diameters. The average speed values show a linear behaviour in case of tool diameters of 1 mm – 2 mm. With a value of 291 mm/s, the tool with a diameter of 3 mm departs from this value. The speed amplitude peaks at the spindle rotary speed converge with an increasing diameter. The "peak to valley" speed value for a tool diameter of 3 mm is 92 mm/s. The amplitude peak in case of a tool diameter of 3 mm is 51 mm/s. Analogously to the speed amplitude peak, the drift amplitude peak is proportional for this tool and tends to a value of 30.7 µm. As far as the forces are considered it can be stated that in case of tool diameters of 1 mm – 3 mm, there is a linear behavior for all three examined physical values as anticipated by Kienzle upon the measurement of process parameters in the macroscopic cutting theory [8]. The speed and drift behaviour cannot yet be predicted in a deterministic way. Machine natural frequencies, natural frequencies of the workpiece and of the environment cannot yet be characterized and must be verified more accurately for further investigations. Based on preliminary considerations, the first bending natural frequencys of tools with diameters of 0.5 mm and 1 mm can be derived from measured values. A higher sample rate must be achieved for measurements in order to determine the natural frequency of tools with diameters of 2 mm and 3 mm. The result of the investigations is that the spindle rotary speed proportionately grows with a decreasing tool diameter at constant cutting speed. The natural frequency, however, rises. Consequently, the development of chatter marks can be emerged with smaller tools. The surface quality along the 15 mm long groove is derived from these considerations with the help of R_{zDIN} and R_a. The results show that the maximum roughness is 2.33 µm in case of a tool diameter of 2 mm for the R_{zDIN}-value. The minimum value is 0.95 µm for a tool diameter of 1 mm and a R_{zDIN}-value. This surface examination shows that a surface quality cannot be merely characterized by the natural frequency and the spindle rotary speed of the machine tool, but influences such as tool structure and machine natural frequencies must be considered, too.

5 Summary and Outlook

The analyses have shown that process forces of tools with diameters of 1 mm – 3 mm have a linear interrelation in cutting during the milling of a W-Cu-particle compound material (consisting of 80 % tungsten and 20 % copper with an average grain diameter of 15 µm). This proportionality does not apply to micro cutting with tool diameters of 0.5 mm. In the further progress of work, the scaling effects will therefore be examined by means of non-linear FEM-calculations in cooperation with the LFM-Aachen (Prof. El-Magd) for the description of the process forces in case of different material specifications during micro milling (d < 0.5 mm). The LFM examines the material behaviour of the W-Cu-particle compound material with the help of upset experiments and creates flow curves on the basis of these experiments [10]. In a first approximation the flow curves should be used for the description of material behaviour during chipping in micro milling in order to transfer a current macroscopic method to a microscopic one.

6 References

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