Prod. Eng. Res. Devel. (2011) 5:175–181
DOI 10.1007/s11740-010-0296-4

PRODUCTION PROCESS

Influences on specific cutting forces and their impact on the stability behaviour of milling processes

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Received: 22 October 2010 / Accepted: 30 December 2010 / Published online: 27 January 2011

Abstract To withstand global competition, nowadays it is essential for companies to assure high productivity and high quality. To reach this aim permanent technical innovation and further developments are necessary. In machining industry and especially in the field of milling the development of possibilities to increase chip removal is the major goal. The optimisation of the cutting process is one way to achieve this aim. Here, the use of stability prediction models is essential to reduce the effort in time and costs. To implement a stability prediction tool with a high accuracy in representing reality, all relevant influencing parameters and their interactions within the cutting process have to be analysed. This article describes one possibility for the experimental identification of instable milling processes. Furthermore, the influences of spindle speed and temperature on specific cutting forces and the temperature influence on the stability behaviour in milling processes are shown.

Keywords Machine tools · Process analysis · Stability prediction

1 Introduction

Due to steadily growing competitive pressure a continuing enhancement in productivity of manufacturing processes is necessary. Based on these conditions high speed cutting was developed, which gives the possibility to realise a higher material removal rate in the field of machining. These high speed processes are differentiated by cutting speed [1]. A lower surface roughness and smaller machining forces are the fundamental advantages of high speed cutting besides higher material removal [2]. In addition, higher cutting speeds lead to rising temperatures within the cutting zone. While this fact is leading to a reduction of the occurring frictional forces between tool and work piece, a change in chip formation and chip flow arises [3]. Thus, cutting forces decline effectively. As a consequence cutting forces are depending on cutting speed and therewith on cutting temperatures which has a considerable effect on the stability behaviour of milling processes.

The stability behaviour of machining processes has a wide influence on process productivity and the workpiece quality. To increase productivity and product quality, it is inevitable to determine optimised process parameters. For this purpose, time-consuming and cost-intensive experiments for each specific machine tool have to be performed [4]. One way to reduce this effort in time and costs is the use of stability prediction models. Here, it is essential to get a better understanding of the influences of process and machine tool behaviour on the productivity and product quality in order to implement a stability prediction tool with a high accuracy in representing reality. This leads to an analysis of all influencing variables on the behaviour of the process and machine structure. Moreover, the analysis of interdependencies of such influencing variables and the interaction between process and structure is important as well. This displays the only way for the development of precise prediction models for the interaction between process, machine structure and the resulting stability behaviour [5].

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In this context, first a measurement set-up is presented, which allows the verification of the influence of cutting speed on the specific cutting forces. The same set-up is used for an analysis of the dependency of specific cutting forces on the temperature and the influence on stability behaviour of milling processes. Afterwards, a method for identification of unstable milling processes will be described. Finally, the temperature dependency of the specific cutting forces and the resulting impact on the stability behaviour of high speed cutting processes will be presented.

2 Experimental analysis of specific cutting forces and process stability

2.1 Measurement set-up

All machining tests were performed at a five-axis machining centre type MAP LPZ 500. The machine tool features linear drives for the linear axes and is able to realise feed speeds of up to $v_f = 120$ m/min. The analysed machining process was peripheral end milling. Workpieces with different preheating conditions were used to analyse the influence of temperature on specific cutting forces.

According to [6] a commonly used measurement set-up for milling experiments was implemented to measure the specific cutting forces and analyse the process behaviour. This set-up was adjusted to analyse the temperature effect on stability behaviour and cutting forces. Machining tests were carried out using a one-edge end mill cutter of High-Speed Steel (HSS) according to DIN 6535 HA with a diameter of $D_t = 8$ mm and a side rake angle of $\gamma_f = 23°$. The tool was shrunken in a HSK A63 chuck according to DIN 69882-8. The utilised material is the aluminium alloy EN AW-7075 which is frequently used in aircraft industry. The workpiece was mounted on a 3-component-dynamometer type Kistler 9257A. The dynamometer was connected to three voltage amplifiers type Kistler 5011. For measurement data acquisition a measuring board of National Instruments which features a maximum sample rate of 500 kHz and a resolution of 16 bit was applied. The preheating of the workpiece was realised with a heating plate by Horst GmbH with three heating cartridges and a heater power of $P = 300$ W. Thus, temperatures up to $T = 200°C$ could be realised. The plate was triggered by a temperature regulator device type HT MC1. Figure 1 schematically displays the measurement set-up.

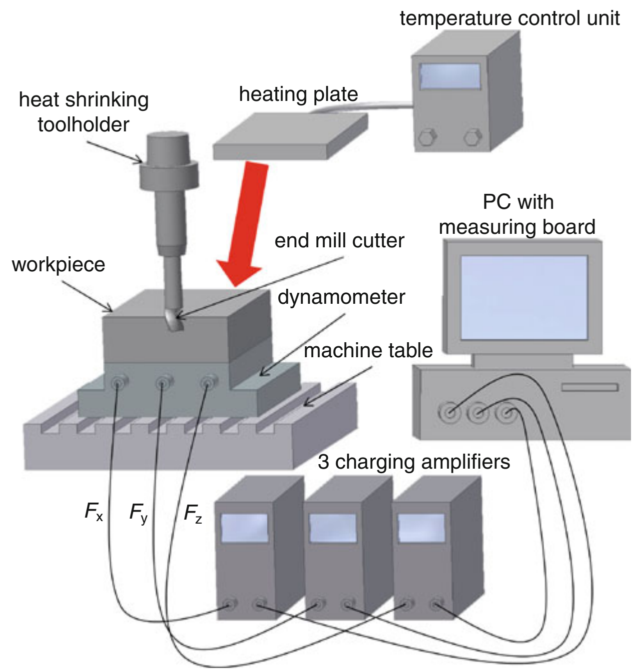

Fig. 1 Measurement set-up for machining tests

Table 1 Process parameter for machining tests

Process parameter	
Feed-rate-per-tooth	$f_z = 0.2$ (mm)
Spindle speed	$n = 4{,}000.....19{,}800$ (rpm)
Cutting speed	$v_c = 100.....500$ (m/min)
Cutting depth	$a_p = 0.5.....5.0$ (mm)
Cutting width	$a_e = 8$ (mm)
Number of teeth	$z = 1$
Workpiece temperature	$T_{ws} = 25–100$ (°C)

2.2 Experimental procedure

For the determination of the dependencies of cutting speed and temperature on specific cutting forces, machining tests with different process parameter combinations were carried out (Table 1).

Flutes were milled into the workpiece with full immersion of the cutter $a_e = 8$ mm. During the process the cutting force components F_x, F_y, and F_z according to the machine coordinate system were measured at the workpiece using the three-component-dynamometer. For data acquisition a sample rate of 50 kHz was used. To analyse the temperature influence the workpiece was warmed-up before machining using the heating plate. The workpiece was preheated upside down to temperatures between $T_{WP1} = 25°C$ and $T_{WP2} = 100°C$. In order to ensure homogeneous heating conditions during the machining tests, thermocouples type K were fixed on the sides of the workpiece to control the local workpiece temperature. In addition, the temperature was monitored using a thermal imaging camera type Infratronics IR600. By this approach it was possible to execute cutting tests with defined and homogeneous heating conditions ($\Delta T = 1$ K) of the workpiece. At the same time, the process stability behaviour could be analysed by the determination of stability charts. Thus, process parameters like cutting speed v_c and cutting depth a_p were varied with a fixed feed-rate-per-tooth of $f_z = 0.2$ mm to generate stable and unstable process conditions.

2.3 Temperature influence on accuracy of the measurement results

The force platform is a piezoelectric sensor. To avoid possible errors in the measurement results the temperature dependency of the three-component-dynamometer was analysed. For this purpose the dynamometer was heated gradually to different temperatures from $T_{WS1} = 25°C$ to $T_{WS2} = 100°C$. Here, force measurements were executed using defined force signals. First, the dynamometer was loaded with defined masses in a static way and the arising differences between the measured force signals of the platform and normal forces were identified. In a second step an impact hammer was used for excitation of the dynamometer. This approach was used for different temperatures as well. Due to the load cell, which is integrated in the impact hammer, the amplitudes and lengths of the force impulse signals could be recorded and subsequently be compared with the measured signals of the dynamometer. Due to the temporally short contact between platform and impact hammer, the warming of the hammer can be neglected.

As a result of this approaches only a small measurement inaccuracy of the dynamometer of about 1% for the static case and 0.5% for the dynamic case could be identified. Thus, a thermal decoupling between dynamometer and workpiece was not required. However, the variance was considered later in the analysis.

3 Influences of cutting speed and temperature on specific cutting forces

3.1 Analysis of the of cutting speed on specific cutting forces

The cutting force model of Weck Eq. 1 points out, that variations in the cutting forces are either caused by a variation of the chip cross-section or varying specific cutting force coefficients [7].

$$F = ha_p \begin{bmatrix} K_c \\ K_f \\ K_p \end{bmatrix} \tag{1}$$

While the chip thickness h and cutting depth a_p are to be considered as constant the only possibility for a variation of

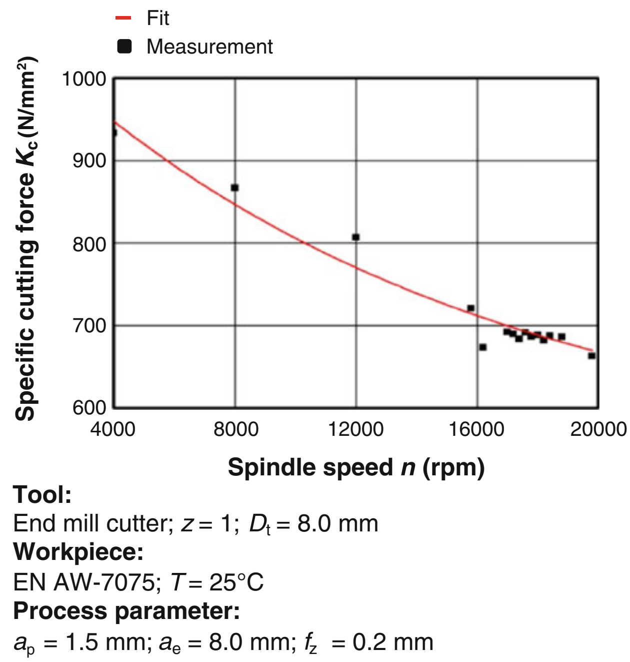

Fig. 2 Dependency of the specific cutting force K_c on the spindle speed

cutting forces is the variation of the specific cutting force coefficients. In Eq. 1 the parameters in the brackets K_c, K_f K_p represent specific cutting forces in the three spatial directions. To determine the dependency of specific cutting forces on cutting speeds a stable cutting process was analysed. Therefore, a cutting depth of $a_p = 1.5$ mm and a feed-rate-per-tooth of $f_z = 0.2$ mm was chosen (see Figs. 2 and 3). Thus, the specific cutting forces depend on ideal chip cross-sections. So, the results are not affected by high variations in the cutting forces or the chip thickness, which is very common for instable process states. The specific cutting force K_c was calculated after [8, 9]. Figure 2 shows the interdependency between the specific cutting force K_c and the cutting speed v_c.

Figure 2 reveals an almost linear correlation between the specific cutting force and the spindle speed. It shows that with increasing spindle speed the specific cutting force coefficient decreases and therewith the measured cutting forces. It can be assumed that higher spindle speeds lead to higher temperatures in the cutting zone. Therefore, reduced cutting forces due to melting of the workpiece material and a change in chip formation and chip flow arises.

3.2 Analysis of the temperature dependency of specific cutting forces

With the same procedure described above the influence of different pre-heating states of the workpiece on the specific cutting force coefficients were analysed Fig. 3.

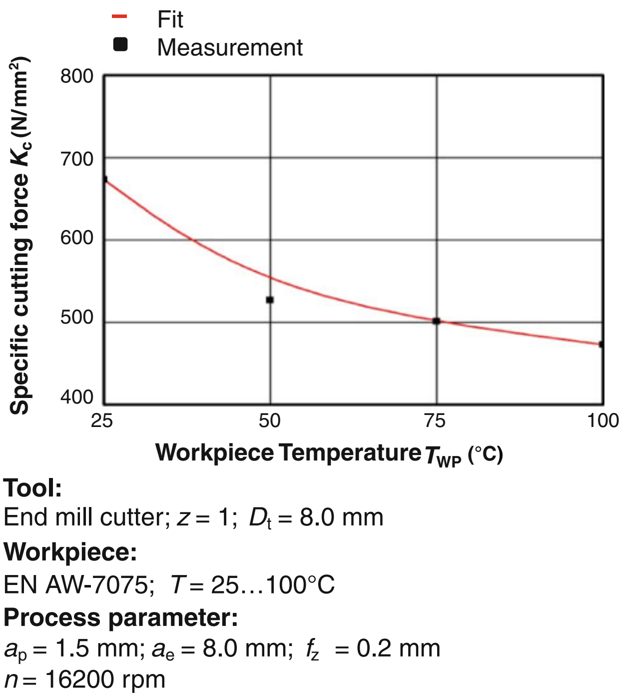

Fig. 3 Dependency of the specific cutting force K_c to the preheating of the component part

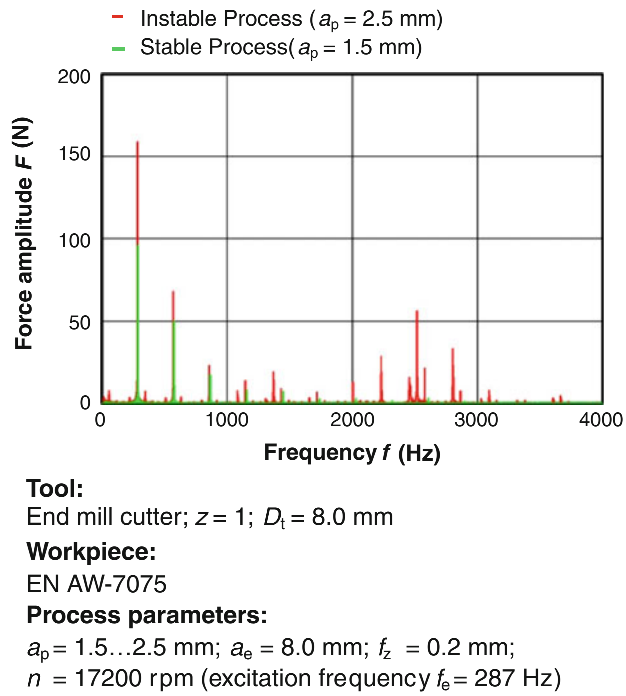

Fig. 4 FFT of stable and instable cutting processes

Figure 3 shows the result for different workpiece temperatures between $T_{WP1} = 25°C$ and $T_{WP2} = 100°C$, a cutting depth of $a_p = 1.5$ mm, a feed-rate-per-tooth of $f_z = 0.2$ mm and a spindle speed of $n = 16{,}200$ rpm. A non-linear relationship between the workpiece temperature and the specific cutting force can be determined. With an increasing workpiece temperature the specific cutting force decreases. In a temperature range of $T = 25°C$ and $T = 50°C$ the decline is about 16 %. This characteristic reduces within the remaining temperature range. Thus, the graph has a decreasing negative slope. An approach like Eq. 2 can be used to describe this characteristic.

$$F = ha_p \begin{bmatrix} K_c \\ K_f \\ K_p \end{bmatrix} (cT)^{-b} \text{ in which } \quad c, b > 0 \tag{2}$$

Here, c and b are free parameters to describe the gradient of the graph. In summary, just like before higher temperatures in the cutting zone lead to decreasing specific cutting forces and therewith smaller cutting forces due to reduced friction.

4 Influence of the workpiece temperature on stability behaviour

4.1 Identification of instable milling processes

To analyse the stability behaviour of cutting processes a method to differentiate stable and instable process states has to be defined. One possibility to identify instable milling processes is the evaluation of cutting force signals (in x-, y- and z-direction) in the time domain. For this purpose, the recorded signals can be transformed into frequency domain using Fast-Fourier-Transformation (FFT) [10–12]. A plot of these signals in the frequency domain allows the identification of all contained frequencies and their related amplitudes. Figure 4 shows the force signals of a stable and an instable milling process with use of a one-edge end mill cutter for an excitation frequency of $f = 287$ Hz.

In a stable process the significant force amplitudes (highest peaks) solely relating to the excitation frequency and its harmonics. Besides these peaks other dominating frequencies can be identified in an instable process state. The regenerative effect is the main reason for stable cutting processes to become instable. Varying cutting forces lead to self-excited vibrations and an additional relative shift between tool and workpiece. These dislocations create a characteristic waviness on the workpiece surface. Every following cut results in a chip-thickness modulation which is amplified by the machine vibrations [11, 13–16]. This effect makes it possible to identify process instabilities considering force signals in the frequency domain. The so called chatter frequencies are located in general next to the eigenfrequencies of the considered machine structure. Chatter leads to a worse product quality because of additional self-excited vibrations. So, it is necessary to define a stability criterion to

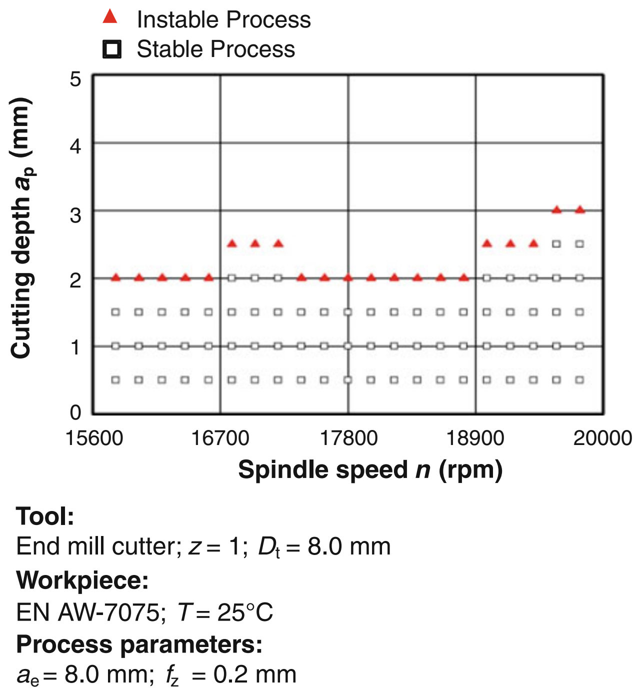

Fig. 5 Stability plot at $T = 25°C$

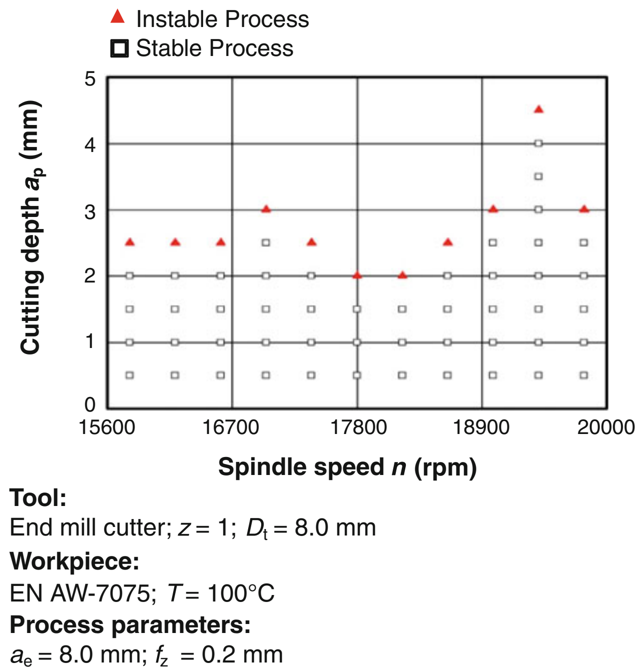

Fig. 6 Stability plot at $T = 100°C$

identify instable milling processes to maintain a good product quality.

For the evaluation of the stability limits in the lower stability plots, the ratio between the absolute value of the largest force amplitude, which can be allocated to the excitation frequency, and the largest force amplitude of the occurring chatter frequency was determined according to Sims [17]. If the ratio exceeds a value of 10%, the corresponding process is classified as instable. In addition, to determine process stability the resulting surface roughness, the occurrence of chatter marks and noise during the machining process can also be taken into account [6].

4.2 Results of the stability analysis for different workpiece temperatures

To create stability plots the cutting depth was incrementally increased for several cutting speeds (see Table 1). In order to reduce the measurement effort a closer spindle speed range between $n = 15{,}800$ rpm and $n = 19{,}800$ rpm was regarded. For the determination of stability limits the measured cutting force signals were analysed. With use of the measurement set up in chapter 2.1 and the illustrated method for the identification of instable cutting processes, stability plots in dependency of the workpiece temperature were determined. Figure 5 shows the result for a workpiece temperature of $T = 25°C$.

Within the figured range of spindle speed the plot reveals only a small variation in the stability limit. The maximum stability limit in the stability plot above is $a_p = 2.5$ mm at spindle speeds around $n = 19{,}700$ rpm. At spindle speeds around $n = 19{,}200$ rpm and $n = 17{,}000$ rpm the stability limit has a value of $a_p = 2.0$ mm. For other spindle speeds the value of the stability limit is $a_p = 1.5$ mm.

Figure 6 illustrates the same speed band against the cutting depth. In this case the workpiece was pre-heated to a temperature of $T = 100°C$.

Due to pre-heating of the workpiece an increase of stability limits of at least $\Delta a_p = 0.5$ mm in the whole rpm-range with a maximum of $\Delta a_p = 2$ mm at $n = 19{,}400$ rpm can be determined. Only at spindle speeds between $n = 17{,}400$ rpm and $n = 18{,}600$ rpm no rise in the stability limits exists. As a result it can be found out that higher workpiece temperatures have a stabilising effect on the process behavior (Fig. 7).

With the pre-heating higher temperatures in the cutting zone arise. Thus, the workpiece material softens and the part of the cutting force related to plastic deformation decrease. Partially the temperatures can reach such high levels that melting of the machined aluminum can be observed. The viscous interface between chip and tool improves the chip flow which results in decreasing cutting forces [1, 18–20]. This leads to increasing stability limits. It is also observed that in certain ranges of the spindle speed the increase of the stability limit is significantly larger than at other spindle speeds. It can be assumed that the pre-heating of the workpiece has an influence on the process damping. A decreased process damping leads to a

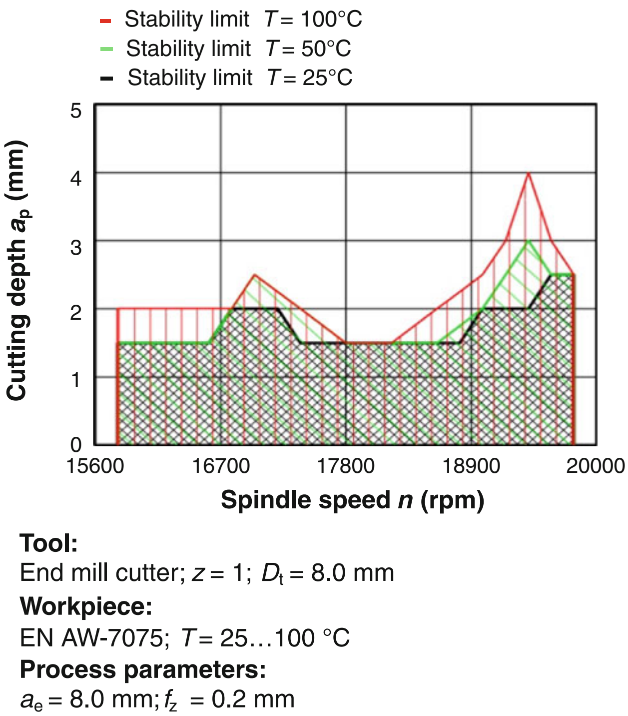

Fig. 7 Stability limits dependency on the temperature

higher and slender peak characteristic of the stability limit course. At the same time the amplitude values in the valleys of the stability limit would decrease. Here, it is possible that a decreasing valley characteristic cannot be observed because of the resolution of the measurement.

5 Summary and conclusions

This paper deals with problems of increasing the productivity in milling processes. One possibility to reach this aim is the increase of the material removal rate and the product quality. By use of stability prediction optimised process parameters can be determined. In order to reach a higher accuracy in representing reality the paper shows the dependency of specific cutting forces on cutting speed and temperatures. First, a measurement set-up for the experimental determination of stability limits and specific cutting force coefficients is presented. Then, the dependency of specific cutting forces on spindle speed and workpiece temperatures are illustrated and discussed. Afterwards a procedure for the identification of instable milling processes is described. Finally, the article reveals the influence of different process parameters and their interaction on stability behaviour. Mainly, the dependency on temperature and the positive effect of higher cutting temperatures on stability limits are shown.

As a result it is shown that specific cutting force coefficients are dependent on spindle speed and therewith the cutting temperature. First, higher spindle speeds cause higher friction in the cutting zone which leads to higher cutting zone temperatures. These higher temperatures soften the workpiece material. Therefore, the part of the cutting force related to plastic deformation decreases and partially melting of the machined aluminium arises. Therefore, the cutting force coefficients also decrease. This assumption is verified by the second measurement which reveals the decline of cutting forces as a result of increasing workpiece temperatures. In addition, this behaviour leads also to higher stability limits due to lower self-excitation of the machine tool. So, existing cutting force models should integrate these influences to improve current tools for stability calculation. Therefore, future stability prediction tools could represent reality in a better way.

The aim of further work is the implementation of a precise stability prediction tool. It is planned to analyse the temperature influence at lower spindle speeds to extend the observed spindle speed range in the stability analysis. Moreover, current research deals with the analysis of the influence of the workpiece geometry on process stability. In addition, it is planned to analyse and model the damping effects in joints of the machine tool structure, because these comprise the main part of the system damping [14]. The desired knowledge will be used in a machine model for stability prediction which can also be used for weak point analysis and structural optimisation.

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