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Evaluation of the influence of different clamping chuck types on energy consumption, tool wear and surface qualities in milling operations

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Abstract

The energy consumption of milling operations is influenced by several interacting parameters. To increase productivity and energy efficiency of related machining tasks, different methods like optimization of machining parameters, new machining strategies and innovative cutting edge geometries for tools are already available. Regarding clamping chucks, only limited information is available on how different chucks influence sustainability of the machining process. Hence, this paper examines the influence of different clamping chucks on the parameters energy consumption, tool wear as well as surface qualities and thereby focusses on important sustainability indicators in machining operations. Therefore, a collet chuck, a Weldon chuck and a precision chuck were evaluated during individual machining tests. Based on the analysis of the gained data, a systematic description of the different influence of each chuck type was carried out and discussed in context of sustainable manufacturing.

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Keywords: milling; clamping chuck; energy efficiency; tool wear; surface quality;

1. Introduction

Cost savings are an important topic in all economic sectors. The so called Life-Cycle-Costing (LCC) is a process of economic analysis that assesses the total cost of investment over the product lifetime [1]. Especially for small and medium-sized enterprises (SME) the purchase of modern and expensive technologies often does not seem profitable if only calculated with amortization. However, regarding the whole life cycle, the high investment costs are mostly faster amortized.

To ensure competitiveness of the enterprises, precise manufacturing in a short time with high surface qualities is required. For these reasons high investments in modern technologies should not be seen as a burden but as a chance to enhance future competitiveness. The operational costs of machine tools have an annual average of 23 % of the electrical energy [2]. Furthermore, a standard milling machine emits as much CO_2 as ten medium-sized cars each year [3]. Due to these facts, an approach like mentioned before is also useful for milling operations. Besides high

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invests for a modern milling machine, operational costs, especially for energy and tools, are a challenge for many SME. Optimized factors in all fields are necessary to keep the costs as low as possible. Different possibilities to increase the overall efficiency of milling operations exist:

- Optimized process parameters, e.g. infeed optimization and computer aided machining strategies [4,5]
- Optimized cutting edge geometry of the tool, e.g. cutting edge preparation [6] or differential helix angle [7]
- Type of chuck [8,9]

All these factors lead to a reduction of the needed cutting power, whereby considerable energy savings are possible. This does not only reduce the energy consumption, it also has an effect on the wear development. Especially a suitable clamping chuck for the current machining operation can increase tool and machine spindle life, which contributes to sustainable machining operations and leads to cost savings in manufacturing processes.

In this paper the behavior of different clamping chuck types while side milling is examined. The test series include a collet chuck (type ER), a Weldon chuck and a precision chuck. Moreover, solid end mills were used for the test series, because up to 80 % of small and medium-sized metal-cutting companies use this type of tool [10].

2. State of the Art

A huge development in the field of milling machines for higher productivity and precision has taken place in the last decades. For example higher rotation speed, multi-axis milling, Computerized Numerical Control (CNC), Computer Aided Manufacturing (CAM) as well as High Speed Cutting (HSC) were implemented. [11,12]

The necessity for increased productivity, precise manufacturing, high surface qualities and a long tool and machine life is increasing. Besides the choice of the cutting material, a precise radial accuracy increased by the use of an optimized clamping chuck is needed. Clamping chucks hold the cutting tools in the machine spindle [13]. The listed requirements only can be fulfilled by safe and precise clamping, which has a huge importance, especially for HSC.

A lot of different clamping systems exist on the market, e.g. collet chucks, Weldon chucks or whistle-notch chucks, the shrink technology or a hydraulic expanding chucks are often used. By using new types of precision chucks and innovative technologies, increasing demands on the clamping technology can be fulfilled.

Currently, manufacturers try to reduce the disadvantages by combining the positive characteristics of the different clamping chuck types, e.g. a precision collet and a hydraulic expanding chuck are combined [13].

With highly precise chucks it is possible to reach a long tool life and better surface qualities. Furthermore, cost savings can be achieved. Therefore, manufacturers promote their chucks with slight radial deviations. Studies have shown, that by using a precision chuck instead of a Weldon chuck savings up to one third of the costs per order assuming an order size of 1,000 workpieces are possible, involving all cost factors. In contrast, the direct costs are nine times higher than the one for a Weldon chuck. [14]

Furthermore, it was found that constructive generated damping and overall stiffness as well as a precise radial accuracy of the precision chuck can lead to a one and a half times longer tool life in comparison to shrink chucks [15].

The used toolhoders in this paper, namely a collet chuck (type ER, a), a Weldon chuck (b) and a precision chuck (c), are shown in figure 1.
The collet chuck consists of a front socket, a collet, and a locknut. Weldon chucks have a higher radial stiffness but are less versatile than collet chucks. The standard Weldon chuck has one side-mounted clamping screw. [13] In a precision chuck, the cutting tool is clamped by a worm gear connected to a clamping sleeve [16].

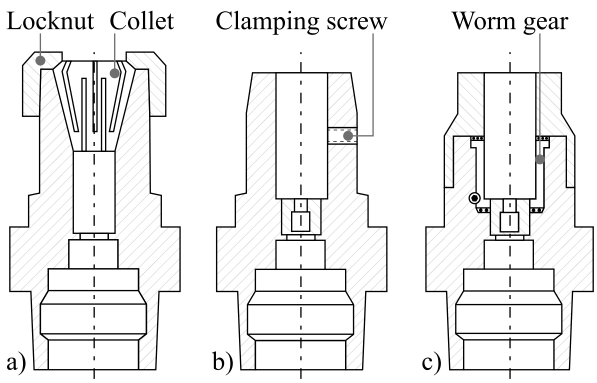

Fig. 1: Considered clamping chucks, based on [9]

3. Approach and Experimental Details

The static and dynamic radial deviation at the tool shaft were measured because of the significant influence of the chuck on the concentricity of the clamped tool, the tool life as well as the dimensional accuracy of the workpiece [17]. With this approach it is possible to generate a holistic interpretation of the results by including the determined radial deviation in later evaluations.

In order to assess the energy consumption, the electrical cutting power of spindle and drive motors were measured by the power analyzer *Chauvin Arnoux C.A 8335 QualiSTAR+* during the milling test series.

To inspect the wear development, the chuck including the solid end mill was removed in regular intervals. Every single cutting edge was inspected at specified positions with an optical microscope. The microscopic images were made with a 40-fold enlargement by the *Lynx Stereo Dynascope Microscopes* created by *Vision-Engineering*. All four cutting edges of the solid end mill were aligned in defined positions to guarantee the same viewing angle on each edge. By using the microscopy software *uEye Cockpit*, it was possible to measure the width of flank wear lands directly. This process was repeated until the solid end mill could no longer be used because of high wear.

For evaluation of surface qualities of the manufactured workpieces roughness measurements were conducted after the milling tests. Therefore, a surface measuring instrument with skid touch probe of the type *Perthometer S2* by the *Mahr GmbH* was used. The measuring instrument has a measuring range of $\pm 250\ \mu m$, a sensitivity variation of < 5 % as well as a maximum linearizing action deviation of < 1 % [18]. In regards to the achievable average surface roughness R_z of $6-30\ \mu m$ in milling operations [12], the measuring instrument has a sufficient measurement accuracy.

Furthermore, all test series were carried out on the five-axis milling machine *Deckel Maho DMG 50 eVolution* using down-milling. The measuring of the static and dynamic radial deviation at the tool shaft was conducted by an digital dial gauge with a stylus tip created by *Mitutoyo*. The measured values are 2.5 μm for the collet chuck, 6.0 μm for the Weldon chuck and 5.0 μm for the precision chuck.

For the test series four tooth TiAIN coated solid end mills with a tool diameter of $d = 16\ mm$ and a helix angle of 30° were used. The dimensions of the tested workpiece, made out of steel C60E (1064 (SAE)), were 200 x 200 x 30 mm, see figure 2.

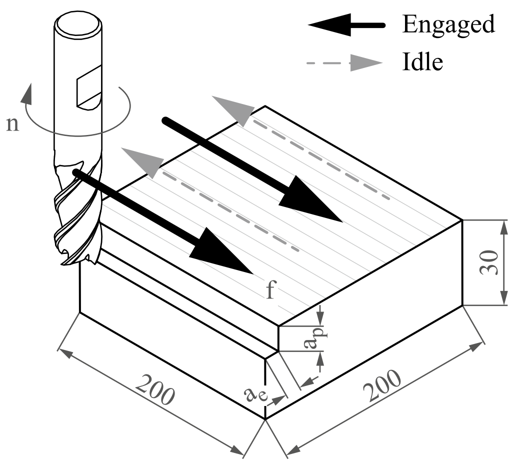

Fig. 2: Tested workpiece

Table 1: Machining parameters for the test series

Parameter		Value	Unit
cutting speed	v_c	55	[m/min]
feed velocity	v_f	320	[mm/min]
number of rotation	n	1096	[min^{-1}]
feed per tooth	f_z	0.073	[mm/z]
depth of cut	a_p	10	[mm]
width of cut	a_e	4	[mm]

For the setup of the NC-program, table 1 indicates the machining parameters which were used for the milling tests within this research work. With the chosen machining parameters it was possible to mill 50 lanes per tested workpiece. This corresponds to a cutting distance of 10 m.

4. Results and discussion

4.1. Effective power and cutting power

The development of the effective power is used to show the effect of the increasing wear. The cutting power is the required electrical energy for the performance of the mechanical work, in this case chipping [19]. Hence, air cuts for each chuck were made and the idle load power was measured. The idle load power is the electrical energy for the relative movement between the tool and the workpiece [19]. The values of table 2 arise from averaging the measured idle load power of three milled lanes for each type of chuck.

Table 2: Idle load powers of the different chuck types

	Collet chuck	Weldon chuck	Precision chuck
Idle load power [W]	1381.94	1382.78	1380.79

The small deviations show that possible differences in weight and type of chuck have a negligible influence on the idle load power. Differences occuring due to measurement inaccuracies are limited to less than 1 % [20].

In figure 3 the effective power for engaged solid end mills is shown. One milled lane corresponds to 0.2 m cutting distance. The resolution of the effective power is one value per second.

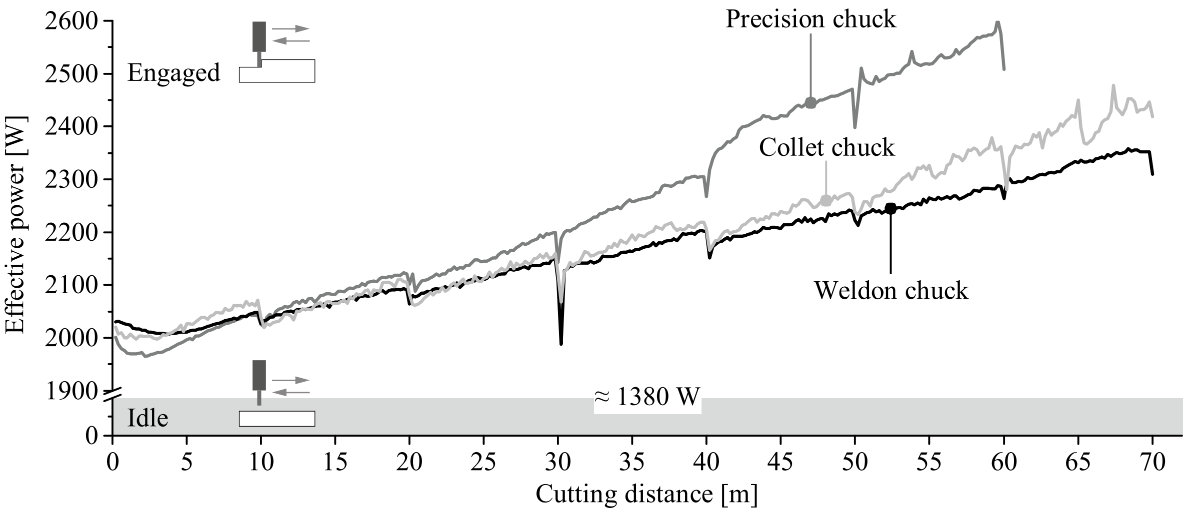

Fig. 3: Comparison of the effective power of the different clamping chuck types

Due to the high wear of the solid end mills clamped in the precision chuck and the risk of damaging the milling machine the experiments could only be conducted until a cutting distance of 60 m, whereas the solid end mills clamped in the Weldon chuck and the collet chuck were used until a cutting distance of 70 m.

The particular cutting power result after subtraction of the idle load power (see table 2) from the effective power. The comparison of the cutting power shows that the precision chuck has the lowest power consumption at the beginning. From about 10 m cutting distance, the power consumption exceeds the one of the collet chuck and the Weldon chuck. Furthermore, the power consumption of the precision chuck at about 40 m cutting distance is almost equal to the level that the collet chuck and the Weldon chuck have reached after 70 m. The effective power of the precision chuck is doubling during the test, from about 600 W to 1200 W, whereas the collet chuck only has an increase from about 630 W to 1050 W and the Weldon chuck from about 640 W to 970 W.

With an idle load power for the considered chuck types in the range between 1381 W and 1383 W a constant level is reached. In the following the respective idle load power is subtracted from the effective power. Thus, focus is set on the cutting power. In table 3 average values of the cutting power of each milled plate, i.e. 50 lanes, were formed to receive the percentage increases. This was made to compensate statistical outliers and achieve a systematic comparability between the different clamping chuck types.

Table 3: Average values and percentage increases of the cutting power for increasing cutting distance

Cutting distance [m]	Collet chuck Avg. cutting power [W]	Collet chuck Increase [%]	Weldon chuck Avg. cutting power [W]	Weldon chuck Increase [%]	Precision chuck Avg. cutting power [W]	Precision chuck Increase [%]
0 - 10	645.98	-	639.83	-	619.79	-
10 - 20	686.38	6.25	683.60	6.84	703.76	13.55
20 - 30	733.30	6.84	727.81	6.47	768.10	9.14
30 - 40	799.92	9.08	780.65	7.26	875.64	14.00
40 - 50	851.80	6.49	827.04	5.94	1036.73	18.40
50 - 60	931.38	9.34	875.73	5.89	1145.53	10.49
60 - 70	1017.76	9.27	944.39	7.84	-	-

As the power consumption of the precision chuck amounts to 619.79 W for the first 10 m of cutting distance, it is lower than the one of the collet (645.98 W) and the Weldon chuck (639.83 W). Furthermore, the precision chuck has the highest variation of the percentage increases of the cutting power. With 84.83 % the precision chuck has the highest relative increase of the cutting power over the whole cutting distance. In comparison, the cutting power of the collet chuck increases by 44.18 % and by 36.87 % of the Weldon chuck, which was the lowest increase. Hence, a comparison of the average cutting power for the last milled plate shows that the precision chuck has the highest value (1145.53 W), although one plate less was milled.

To sum up, the Weldon chuck has the lowest energy consumption as well as variation of the percentage increases of the cutting power. The collet chuck has a slightly higher energy consumption and the precision chuck is the most energy-intensive of the tested clamping chucks.

4.2. *Tool wear*

The width of flank wear lands of each cutting edge was analyzed with an optical microscope at four different measurement points (MP 1 - 4) after milling of one plate. The distances between the different measurement points and the cutting edge are shown in figure 4. Afterwards, the measurement points of the four cutting edges were averaged to compensate breakaways.

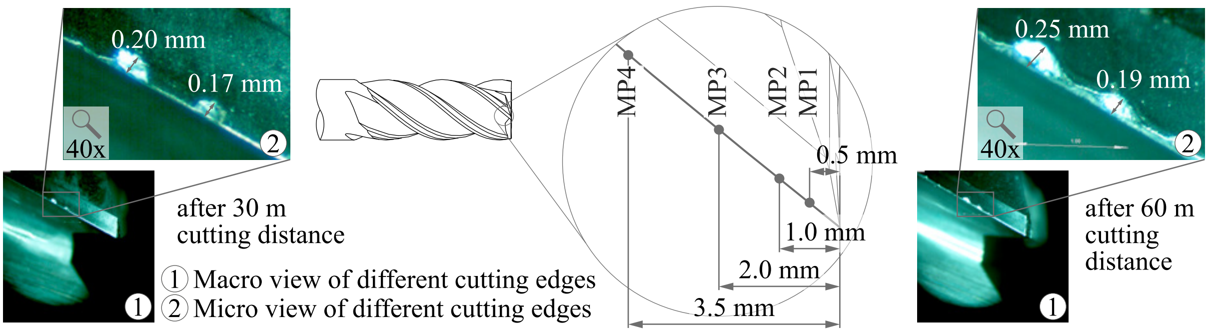

Fig. 4: Distance between the different measurement points and the cutting edge

According to *Taylor*, the curved increase of the tool life over the cutting distance depends on the cutting speed [21]. Furthermore, a linear development between the measurement points of the width of flank wear lands cannot be assumed. For this reason, the width of flank wear lands averaged over all measurement points is shown in a scatter diagram [22], see figure 5.
All clamping chucks have in common that the width of flank wear lands increases with the cutting distance.
Until a cutting distance of 20 m the width of flank wear lands of the different chuck types are similar. After a cutting distance of 30 m, the values of the width of flank wear lands of the precision chuck are the highest. A difference between the width of flank wear lands of the Weldon chuck and the collet chuck is visible after a cutting distance of 50 m. Overall, the Weldon chuck shows the lowest width of flank wear lands.

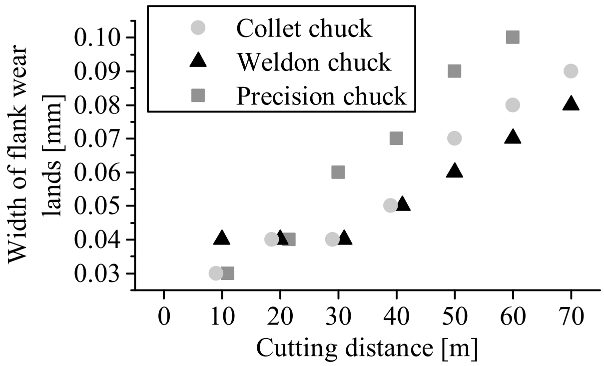

Fig. 5: Development of wear lands averaged over all measurement points

A correlation between the results of the energy consumption measurements and the width of flank wear lands, analyzed with microscopic images, can be identified.

4.3. Surface qualities

According to *Sohner*, the width of flank wear lands influences the surface qualities significantly [23]. To identify the influence of the increasing wear of the solid end mills on the surface qualities of the workpieces, roughness measurements were implemented. The average surface roughness R_z was measured. The results are shown in figure 6.

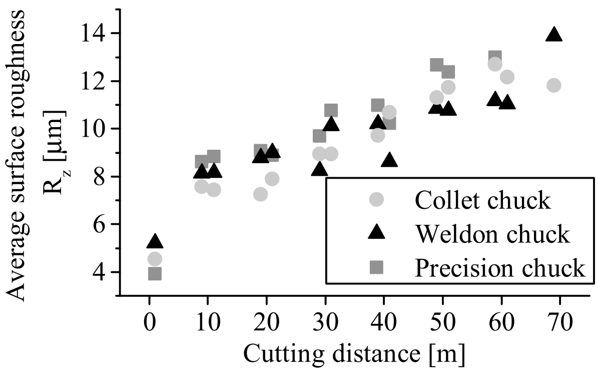

Fig. 6: Average surface roughness R_z

Figure 6 shows that at the beginning of the milling operation the workpiece processed with the precision chuck has the lowest surface roughness. The average surface roughness R_z is 3.912 μm. In contrast, the average surface roughness R_z of the collet chuck is 4.532 μm and 5.204 μm of the Weldon chuck.
Until a cutting distance of 39 m, the workpieces processed with the collet chuck show the best surface qualities, except at the measurement points of 1 m and 29 m cutting distance. The workpieces processed with the Weldon chuck, except the last measurement point, show the second best surface qualities in this range. From a cutting distance of 29 m the workpieces processed with the precision chuck have the worst surface qualities, except the measurement point at 41 m cutting distance.

To sum up, the precision chuck shows the highest surface roughness R_z with increasing cutting distance. Only at the beginning of the cutting operation, after 1 m cutting distance, the surface qualities were the best. The surface qualities of the Weldon chuck had the best values after a cutting distance of 29 m, except the measured values at the cutting distance of 41 m and 69 m. The values remained almost constant over the cutting distance.

A comparison between the increases of the cutting power and the width of flank wear lands indicate a proportional correlation. Also, the involvement of the average surface roughness R_z showed that the flank wear probably has a significant influence on the surface qualities. Despite the shorter tool life when using the precision chuck, it showed the best results concerning energy consumption and surface qualities at the beginning of the machining process.

4.4. Environmental aspects

Regarding the environmental aspects of the different clamping chuck types, conclusions may be drawn from the average cutting power shown in table 3. The carbon dioxide (CO_2) emission per kWh in 2015 equals 587 g/kWh in Germany [24]. In figure 7, the CO_2-emissions of the different clamping chuck types are shown over the cutting distance. The values are analog to figure 3. This is caused by the average cutting power as calculation basis.

The CO_2-emissions referred to the cutting distance enables a comparison to the width of flank wear lands, shown in figure 8. Therefore, CO_2-emissions were divided by the cutting distance. The cutting power of the regarded clamping chucks assigned to the width of flank wear lands were averaged subsequently. The increases of the CO_2-emissions are also shown in figure 8. As a result, an average increase of 8.91 % of carbon dioxide emissions per meter per $\frac{1}{100}$ *mm* width of flank wear lands was determined.

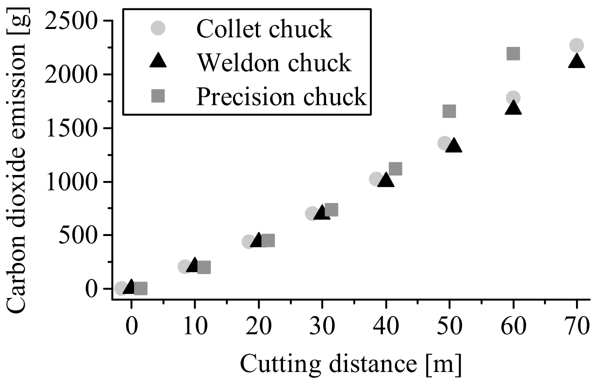

Fig. 7: CO_2-emissions of the different clamping chucks

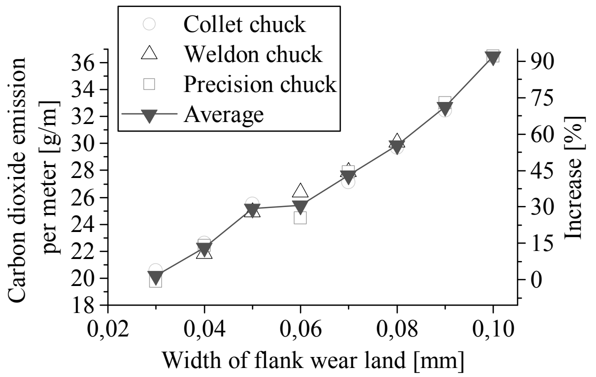

Fig. 8: CO_2-emissions per meter as function of the width of flank wear lands

5. Conclusion and Outlook

Summarizing, this paper describes the influence of three different clamping chucks, namely a collet chuck (type ER), a Weldon chuck and a precision chuck, on energy consumption, tool life and particularly surface qualities for machining test workpieces. For implementing the tests, the multipass milling of a workpiece made out of steel C60E (1064 (SAE)) was chosen.

The test series showed that the Weldon chuck had the lowest average cutting power demand followed by the collet chuck and the precision chuck, see table 3. By comparing the increases of the effective power and the width of flank wear lands, a similar development of the measurement results can be recognized.

Additionally, the increase of the average surface roughness and the width of flank wear lands are showing a certain similarity. Therefore, it can be stated that the flank wear significantly affects the energy consumption, but also has an effect on the surface qualities.

Furthermore, a link between the wear of the solid end mills and the radial accuracy of the different clamping chuck types can not be proven. The solid end mill clamped in the Weldon chuck, which had the highest radial deviation, showed the lowest width of flank wear lands, see section 3. In practice external influence factors and random chip behavior are often important. This relationship has to be verified by repeated test series.

Finally, a correlation between the carbon dioxide emissions per meter and the width of flank wear lands was found. An average increase of 8.91 % of carbon dioxide emissions per meter per $\frac{1}{100}$ *mm* width of flank wear lands was determined.

For validation of the effective power demand depending on cutting distance, the width of flank wear lands and surface qualities further test series need to be conducted. Furthermore, machining parameters, for example cutting speed, feed velocity etc., will be varied and interaction will be examined using detailed design of experiments. The behavior due to a variation of the material was not considered. Furthermore, the test series were limited to multipass milling of the workpiece. It needs to be evaluated if more complex milling operations, i.e. grooves or pockets, are influencing cutting power. To improve comparability additional clamping chucks will be taken into account aiming at the derivation of requirements for an energy efficient and low-wear chuck construction.

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