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Application of spindle speed increaser as sustainable solution to upgrade machine tools

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Abstract

Due to varying machine operations, cutting material and feed motion of the respective milling machine, a wide range of spindle speed is required. Modern machine tools are therefore occasionally equipped with two spindles to cover a wider application scope. Especially while increasing the cutting removal rates for soft materials like aluminium alloys, outdated machine tools fail to provide high spindle speed. Spindle speed increasers (SSI) are possible solutions in order to flexibly increase the cutting removal rates of milling machines. In this paper, the state of the art of SSI is investigated regarding its application in different milling machines and with respect to resource and energy efficiency. Therefore, based on the respective machining operations, spindle input and milling machine, a selection methodology is provided to prove the feasibility of the application of existing SSI. This allows estimating the sustainable benefit on theoretical basis.

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1. Introduction

In order to develop a resource efficient way of upgrading conventional outdated milling machines the authors propose an approach of applying add-ons within the Collaborative Research Centre (CRC) 1026 B5 project. This approach is aiming at enhancing specific functions of the respective machine tool in a flexible manner. Fig. 1 shows

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an accuracy increasing add-on as sustainable solution to compensate the positioning deviations of a Deckel FP4NC milling machine (thereafter: FP4) in x- and y-plane [1].

Fig. 1. Deckel FP4NC milling machine (a) accuracy increasing add-on; (b) productivity increasing add-on

High Speed Machining (HSM) plays a vital role in automotive, aircraft and mould industry. By increasing the spindle speed a reduction of the specific cutting forces and temperature has been experimentally observed [2]. The achievable cutting removal rates range mainly between $Q_w = 150 - 1{,}500\ cm^3$ and cutting velocities v_c up to $10{,}000\ min^{-1}$ are reached [2]. Cutting conditions play a major role to reduce the energy consumption and thus increase the machining efficiency. Kianinejad et al. compared the energy consumption of an outdated FP4 and a newer DMG DMU50 milling machine under varying cutting conditions. The objective was to identify the factors, which limit the achievable removal rate for different tools, processes and materials. The results obtained show that, especially for finishing processes, the maximum possible spindle speed was the bottleneck for the maximum achievable removal rate. Altogether, it was found that the outdated machine tool has about 40 % higher specific energy consumption during cutting operation. Due to limited maximum spindle speed and spindle power, the outdated machine tool is not able to reach higher removal rates. The energy efficiency is further limited while machining materials, which allow even higher cutting speeds than offered by FP4 such as aluminium alloy [3].

Nomenclature

a_e	cutting width
a_p	cutting depth
D	tool diameter
F_{cmz}	average cutting force
f_z	feed per tooth
h_m	average chip thickness
κ	pressure angle
k_c	specific cutting force
K	correction factor (K_V: cutting velocity, K_{Ver}: tool wear, K_γ: chip thickness)
m	slope
n	spindle speed
φ_s	cutting arc angle
Q	cutting removal rate
z	number of teeth

In order to increase the machining productivity several actions took place. Rangarajan and Dornfeld conducted a case study to identify an optimum angle for face milling and roughing [4]. A kinetic energy recovery system (KERS) has been simulated and presented as a worthy solution to enhance the energy efficiency of machine tools. The simulation results have shown that the use of KERS results in 5 - 25 % power reduction [5]. Mori et al. experimentally measured the impact of cutting conditions on the power consumption. By varying cutting speed, feed rate, cutting depth in radial and axial direction the power consumption was reduced about 40 % for end milling [6].

In order to increase the spindle speed of conventional machine tools they can be flexibly upgraded by so called SSI, see Fig.2. These SSI are either driven by the machine tool spindle and work as a mechanical transmission or they are powered by an integrated fluid or electric drive.

In their article Salgado and Alonso described the design process of a mechanical SSI for high-speed machining [7]. The aim was to upgrade a conventional machine tool by means of a multiplier gearbox. In order to increase the spindle speed by a mechanical transmission a four-member planetary gear train (PGT) was used (Fig. 2). Throughout the reduction of the volume and kinetic energy of the respective design solution the authors achieved a speed ratio greater than 1:10.

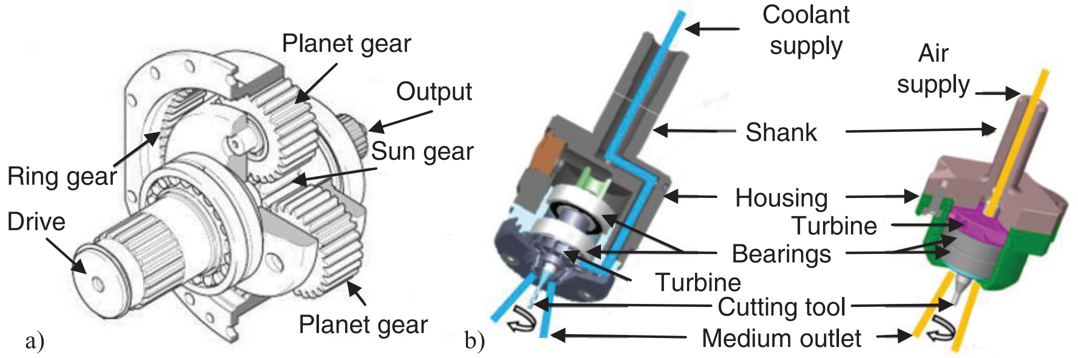

Fig. 2. SSI (a) mechanical transmission; (b) fluid driven (coolant and air) [7,9].

Besides increasing the spindle speed Yamanaka et al. focussed on improving the surface roughness by using a wedge roller traction drive. Moreover, the designed SSI is capable of measuring the cutting force quantitatively by means of a piezofilm [8].

By upgrading large machine tools by fluid-driven spindles the application range can be broadened. Therefore, Schubert et al. proposing a coolant-driven spindle for semi-finishing, finishing and micro milling processes [9]. Particularly for machining dies and moulds the combination of roughing processes requiring high spindle power and finishing operations, where high spindle speeds are necessary, is possible by means of a coolant-driven spindle. For an exemplarily turbine part the results show that the manufacturing time could be reduced by around 75 %.

2. Application Scope

As discussed earlier the application of SSI is limited by the required cutting power. Therefore, different sets of cutting parameters (tool diameter, workpiece material and cutting velocity) were considered in order to estimate the required cutting force, power and the achievable cutting removal rates. All values were estimated through calculation and haven't been checked in machining tests. The values for a process without or with a mechanical SSI are dependent on the used machine. That means the results are valid for the FP4 milling machine only. It has a maximum spindle speed of $n = 3{,}150\ min^{-1}$ and is taken representative example of an outdated conventional milling machine. Three models of SSI were put in focus: a mechanical, an air-driven and a coolant-driven SSI. For each type one example has been chosen for comparison. The mechanical one has a gear ratio of 5. The air-driven spindle provides a number of revolutions of $n = 40{,}000\ min^{-1}$ and the coolant-driven of $n = 30{,}000\ min^{-1}$. The number of revolutions of both of them is dependent on the air- and coolant-pressure and flow rate, respectively.

In order to calculate the average cutting force of a milling process the equation of KIENZLE is used [10]. Therefore the average chip thickness h_m is needed and can be obtained by following equations:

$$h_m = \frac{114{,}6°}{\varphi_s} \cdot f_z \cdot \frac{a_e}{D} \tag{1}$$

and

$$\cos\varphi_s = \left(1 - \frac{2a_e}{D}\right) \tag{2}$$

In equations (1) and (2), φ_S represents the cutting arc angle [°], f_z the feed per tooth [mm], a_e the cutting width [mm] and D the tool diameter [mm]. Furthermore the specific cutting force k_c is required and can be estimated with the following equation:

$$k_c = \frac{k_{c1}}{h_m^m} \tag{3}$$

In equation (3), k_{c1} represents the principal value of specific cutting force [N/mm^2] and m the slope. With these equations the average cutting force F_{cmz} can be calculated:

$$F_{cmz} = \frac{a_p}{\sin\kappa} \cdot h_m \cdot k_c \cdot K_\gamma \cdot K_v \cdot K_{Ver} \tag{4}$$

In equation (4), κ is the pressure angle and a_p the cutting depth. K_γ, K_v and K_{Ver} represent correction factors for chip thickness, cutting velocity and wear of the tool. The average cutting forces for different tool diameters were estimated and compared with the forces the spindles can provide at their highest speed. As long as the cutting force is smaller than the spindle force, the tool diameter can be used. For the highest possible tool diameters, the removal rates Q were calculated using equation (5):

$$Q = a_e \cdot a_p \cdot f_z \cdot z \cdot n \tag{5}$$

In equation (5), z is the number of teeth and n the number of revolutions [1/min]. For this example milling cutters were used which have a recommended cutting width of

$$a_e = 0.1 \cdot D \tag{6}$$

and a recommended cutting depth of

$$a_p = 1.5 \cdot D. \tag{7}$$

Table 1 and Table 2 give an overview about the removal rates of the different SSI for various tool diameters at the maximum number of revolutions. Entries marked with a star (*) are only theoretical values and not achievable by the FP4 milling machine as the calculated cutting forces exceed the provided torque. The limitation of tool diameter, cutting width and cutting depth, respectively, due to the dynamic behavior of the FP4 has not been considered. The tables show the application scopes of the SSI. It is clearly visible that high tool diameters are only usable without a SSI. For processes where small tool diameters are required the air- and coolant-driven SSI have an advantage, especially when milling aluminium. Cutting forces are relatively small and due to the high cutting speed coolant-driven SSI can reach higher removal rates than with a mechanical or without SSI.

Table 1. Comparison of removal rate Q [cm^3/min] for steel milling.

Tool diameter [mm]	0.5	1	2	4	6	8	10	12	16
Without	0.002	0.015	0.121	0.968	3.674	7.620	13.608	21.773*	43.062*
Mechanical	0.010	0.076	0.605	4.838	18.371	38.102*	68.040*	108.864*	215.309*
Air-driven	0.024	0.192	1.536	12.288*	46.656*	96.768*	172.800*	276.480*	546.816*
Coolant-driven	0.018	0.144	1.152	9.216*	34.992*	72.576*	129.600*	207.360*	410.112*

*theoretical value

Table 2. Comparison of removal rate Q [cm^3/min] for aluminium milling.

Tool diameter [mm]	0.5	1	2	4	6	8	10	12	16
Without	0.001	0.011	0.081	0.726	2.109	5.685	11.907	21.501	48.868*
Mechanical	0.007	0.057	0.454	3.629	10.546	28.426	59.535*	107.503*	244.339*
Air-driven	0.018	0.144	1.152	9.216*	26.784*	72.192*	151.200*	273.024*	620.544*
Coolant-driven	0.014	0.108	0.864	6.912	20.088*	54.144*	113.400*	204.768*	465.408*

*theoretical value

Table 3 andTable 4 show removal rates of different spindle speed increasers with it highest possible tool diameter. Because of the low power provided, the air- and the coolant-driven spindles are not able to provide a torque which allows the use of high tool diameters. Despite the high spindle speed, the fluid-driven SSI reach relatively low removal rates. This leads to reduced processing time in comparison to the FP4 milling machine without SSI. In contrast to that, the mechanical model increases the cutting removal rates by around 30 %, which leads to a time profit and thereby higher productivity. Higher tool diameters could be used when milling with smaller cutting width a_e and cutting depth a_p.

Table 3. Removal rate for steel milling with highest possible tool diameter.

Spindle speed increaser	Without	Mechanical	Air-driven	Coolant-driven
Highest possible tool diameter D [mm]	10	6	2	2
Cutting width a_e [mm]	1	0.6	0.2	0.2
Cutting depth a_p [mm]	15	9	3	3
Feed per tooth f_z [mm]	0.072	0.054	0.016	0.016
Number of teeth	4	4	4	4
Number of revolutions n [min^{-1}]	3,150	15,750	40,000	30,000
Removal rate Q [cm^3/min]	13.608	18.371	1.536	1.152

Table 4. Removal rate for aluminium milling with highest possible tool diameter.

Spindle speed increaser	Without	Mechanical	Air-driven	Coolant-driven
Highest possible tool diameter D [mm]	12	8	2	4
Cutting width a_e [mm]	1.2	0.8	0.2	0.4
Cutting depth a_p [mm]	18	12	3	6
Feed per tooth f_z [mm]	0.079	0.047	0.012	0.024
Number of teeth	4	4	4	4
Number of revolutions n [min^{-1}]	3,150	15,750	40,000	30,000
Removal rate Q [cm^3/min]	21.501	28.426	1.152	6.912

3. Conclusion

The application of SSI as add-on is a promising measure in order to increase the productivity of the outdated FP4 milling machine, especially by increasing the removal rate. For roughing operations with high tool diameters the mechanical SSI can help to increase the removal rates and thereby to save machining time. It is suitable for steel and aluminum milling up to a tool diameter of 8 mm. For operations, which require small tool diameters, cutting removal rates are massively higher with the use of air- and coolant-driven spindles than the FP4 machine can reach without or with the mechanical SSI due to the higher cutting speed. Air- and coolant-driven SSI can handle tool diameters up to 4 mm depending on workpiece material. Higher tool diameters are possible by decreasing the cutting width a_e and cutting depth a_p because of smaller cutting forces.

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