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Substitution of coolant by using a closed internally cooled milling tool

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Abstract

The saving of raw materials plays a major role in industry and is becoming increasingly important. In the field of cutting technology, the aim is to maximise practices such as the substitution of coolant and the steady increase of tool life in order to make an effective contribution towards environmental protection. Concerning the saving of coolant and to enhance the performance in dry machining a milling tool with a closed internally cooled system was developed. Heatpipes are applied which ensure improved heat dissipation from the cutting edge because of their excellent thermal conductivity. The dissipated heat is subsequently delivered to the surroundings via a heat sink. This contribution describes how the performance of a standard tool can be enhanced by the integration of a closed internally cooled system. Simulations of the heat distribution in the tool have been conducted to design and optimise the prototype. Hence, milling tests on duplex steel and temperature measurements in the cutting process have been carried out to verify and further optimise these simulation results.

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Keywords: Milling; internal cooled; heatpipe; dry machining; duplex steel; sustainable manufacturing

1. Introduction

The process of dry machining is becoming increasingly important due to rising requirements regarding the economic, technological as well as environmental aspects of Life Cycle Engineering. The presented tool system makes an important contribution to this. Consequently, by using the closed internally cooled milling tool productivity can be increased, cost and waste can be reduced.

A specific case of application is the production of functional surfaces, where dried coolant residues have to be removed for further manufacturing steps. An additional energy- and resource-intensive cleaning process is unavoidable. Another reason to avoid the use of cooling lubricants is the occurrence of thermal shocks. When processing difficult to machine materials the cold coolant leads, in combination with the high cutting temperatures, to high thermal loads on the tool. Especially in milling, due to the continuous entry and exit of the tool, recurring heating and cooling phases occur. This thermal shock is additionally reinforced by the use of cooling lubricants and can cause cracking and premature failure of the tool [1].

Compared to conventional wet processing the average cutting temperatures are higher in dry machining at the same process parameters. This increase in temperature leads to a greater thermal stress of the cutting material and the wear protection layer. If the same process parameters of wet processing are transferred to dry processing, above all the thermally induced tool wear rises [2]. This includes especially the tribochemical wear, which can be subdivided into diffusion and oxidation wear. High process temperatures also favor the abrasive wear. This wear mechanism is intensified by the softening of the cutting material at high temperatures [3].

An alternative to wet processing and dry machining is the use of a closed internal cooling system. Until now, turning tools with a closed internal cooling system have mainly been developed and scientifically studied. One approach is the dissipation of the heat through a fluid. Therefore, the tool has cooling channels and the fluid transports the heat from the cutting zone. Various scientists have already investigated this

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cooling strategy. In all studies, a reduction of the cutting temperatures and increasing of tool life could be detected [4-9]. A further possibility for the heat dissipation from the working zone is the use of heatpipes. The decisive advantage of heatpipes is the low thermal resistance in a small space. This principle of heat conduction has been investigated in turning and drilling tools [10-12]. In drilling of cast iron the tool life, compared to dry processing, could be increased by 125 %.

The aim of the presented work was to develop a more economical way to substitute coolant instead of using conventional dry cutting processes. Therefore, a milling tool using heatpipes for heat dissipation was realised. Simulative analyses of the heat distribution, milling tests to verify the tool performance and temperature measurements were carried out.

Nomenclature

a_e	Radial depth of cut
a_p	Axial depth of cut
f	Feed
f_z	Feed per tooth
l_c	Cutting length
PVD	Physical vapour deposition
Q	Heat generation rate
$Q_{transient}$	Heat generation rate for transient simulation
Q_w	Material removal rate
t_c	Cutting time
$t_{cooling}$	Cooling time
$t_{cutting\text{-}edge}$	Cutting time per edge
t_{diff}	Temperature difference in transient simulation
t_{global}	Global tool temperature
t_{local}	Local Heatpipe temperature
t_{max}	Maximum temperature in transient simulation
$t_{max(1)}$	Maximum temperature of standard tool
$t_{max(2)}$	Maximum temperature of cooled tool
$t_{max(cooled)}$	Maximum temperature of cooled tool measured with thermography camera
$t_{max(pyro)}$	Maximum temperature measured with pyrometer
$t_{max(standard)}$	Maximum temperature of standard tool measured with thermography camera
$t_{max(thermal)}$	Maximum temperature measured with thermography camera
$t_{VB0.3}$	Tool lifetime at VB = 0.3 mm
VB	Width of flank wear land
v_c	Cutting speed
z	Number of cutting edges

2. Experimental setup

2.1. Development of a closed internally cooled milling tool

The aim of the presented work was to develop a closed internally cooled milling tool that enables an extension of the tool life on the one hand, and increases of the process parameters at similar tool wear on the other hand. Moreover, the total cost of application of the closed internally cooled tool compared to wet processing should be kept low, regarding this as an important economic criterion. To achieve this, heatpipes were used to allow the generated heat to dissipate. This also offers the advantage of no additional peripheral equipment for cooling as well as no need for reconstruction of the machine spindle. Heatpipes are a closed two-phase system, which are filled with a working fluid and characterized through a high thermal conductivity. Depending on the application and the temperature range, an appropriate medium has to be selected [13]. For evaluation and comparison of the tool wear, the standard cutting head CoroMill® 390 of Sandvik Coromant with a diameter of 40 mm was used for integrated the internal cooling.

Fig. 1. Closed internally cooled milling tool (a) Model; (b) Tool; (c) Cutting head; (d) Cutter arbor with heat coupling elements

The heatpipes were integrated into a defined angle in the milling cutter. Thus, the impact on the tool stability and the centrifugal force, which affects the functionality of the heatpipes, were reduced. The backflow of the medium is also facilitated. For an even better heat dissipation, a heat sink was used. The fins are oriented in the direction of rotation, so that a maximum amount of air passes the heat sink. The heat transfer from the indexable inserts to the heatpipes and the transfer from the heatpipes to the heat sink is realized by heat coupling elements made of tungsten copper (Fig. 1; a, b, c, d).

2.2. Milling tests

The milling tests were performed on a 5-axis milling machine from MAP Werkzeugmaschinen GmbH, type LPZ 900. To compare the reference tool and the closed internally cooled milling tool in dry cutting, machining tests in face milling, with a down milling feed direction, were carried out.

For the investigations, austenitic-ferritic duplex stainless steel X2CrNiMoN22-5-3 was used. This steel is mainly used because of its outstanding properties with regard to corrosion resistance and ductility in combination with tensile and yield strength.

Cutting inserts R390-11 T3 08M-MM 1040 from Sandvik Coromant were used for milling. This PVD-coated cemented carbide is particularly suitable for austenitic and duplex steel. For analysis of tool wear, the flank wear VB was measured until reaching the defined tool life criterion VB_{max} = 0.3 mm.

The tool wear was constantly measured after a cutting length l_c of 500 mm.

2.3. Simulation of the heat dissipation

The heat dissipation of the standard tool and the closed internally cooled milling tool was analysed with the Computer Aided Engineering program ANSYS 16.0 by ANSYS, Inc. The geometries of the components were simplified and implemented in the simulation model to reduce the computation time for the solution algorithm. For the simulation it is assumed that an ideal connection of the elements exists and no losses in the contact zone occurs. In order to make a more detailed statement about the heat distribution within the indexable inserts, heatpipes and heat coupling elements, these areas were partitioned in the simulation with small control volumes. This allows an even finer gradation of the temperature.

Currently, there is no universally valid calculation basis to determine the generated heat generation rate Q in cutting. To develop a model, the resulting heat generation rate Q of the quantity of heat in the cutting process, was estimated with the aid of Formula 1 [14]. The process parameters cutting depth a_p, feed f and cutting speed v_c were considered. The heat distribution in the standard tool and internally cooled milling tool were simulated based on the calculated amount of heat. The following parameters were assumed for this simulation: v_c = 200 m/min, a_p = 0.5 mm and f = 0.4 mm.

$$Q = 1.68 \cdot a_p \cdot f^{0.15} \cdot v_c^{0.85} \quad (1)$$

2.4. Measurement of temperatures in milling process

The temperatures in the cutting process were determined with non-contact measurement techniques. Using thermography and pyrometry the temperatures, which occur on the tool, were empirically detected and compared with the results of the simulation. With both non-contact measuring methods it is possible to visualize the invisible electromagnetic radiation. The use of a two-color pyrometer allows measurements without knowledge of the emissivity, provided that the object is conducting as a gray body and the emission is independent of wavelength [15, 16].

3. Results

3.1. Milling tests

Figure 2 shows the comparison of achieved tool lifetimes for standard and internally cooled milling tools with different cutting speeds v_c. With increasing cutting speed v_c, the maximum width of wear VB_{max} is reached faster. However, the tool lifetime $t_{VB0.3}$ can be extended with the same parameters up to 50 % by the use of the internally cooled tool. Additionally, the internal cooling concept shows similar wear characteristics and tool lifetime $t_{VB0.3}$ at a cutting speed of v_c = 250 m/min, as the conventional tool at v_c = 200 m/min. Hence, a higher material removal rate Q_w by approximately 125 % can be achieved here. Depending on the cutting speed v_c, different characteristics of wear can be detected. The cutting speed v_c exerts the main influence on temperature in cutting processes, with increasing cutting speed v_c the process temperature rises [17]. Figure 3 illustrates the tool wear depending on the cooling strategy and cutting speed v_c. Using the internally cooled system, the wear on the cutting edge is significantly reduced. It can be assumed that different wear mechanisms are caused by temperature differences (Fig. 3; a, b, c). The abrasive wear is dominant at lower cutting speed v_c when using the internally cooled milling tool. In comparison, the standard tool at lower and the developed tool at higher cutting speed v_c show adhesive wear.

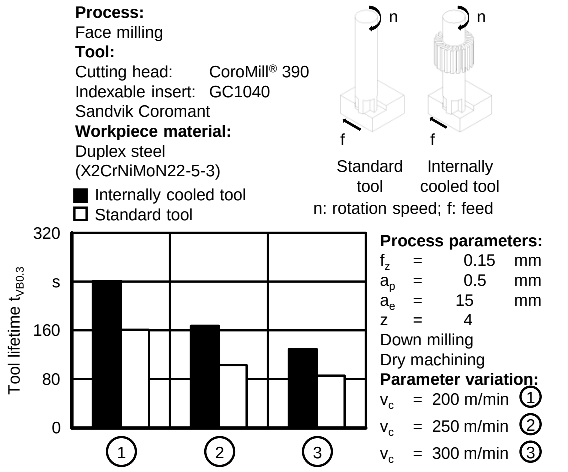

Fig. 2. Comparison of $t_{VB0.3}$ at various cutting speeds between standard and internally cooled milling tool

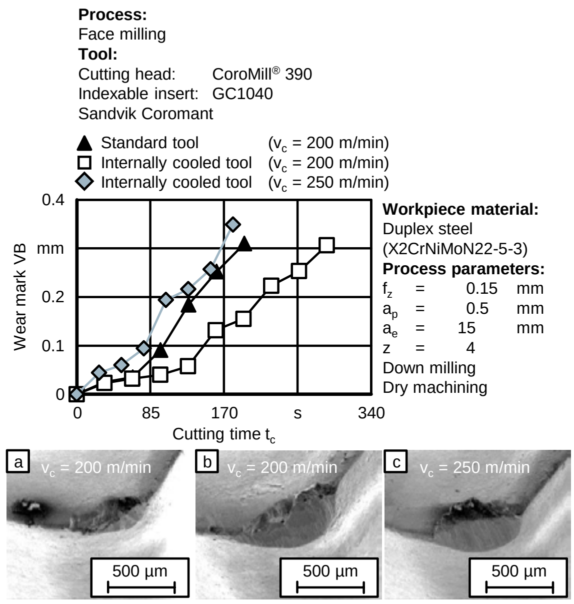

Fig. 3. Wear behavior at different cutting speeds v_c (a) Internally cooled tool after t_c = 129 s; (b) Standard tool after t_c = 129 s; (c) Internally cooled tool after t_c = 155 s

3.2. Comparison of simulated and measured temperatures

Initially, the simulative temperatures at the cutting edge were detected stationary with a constant influence of the calculated heat generation rate Q (Formula 1). Furthermore, the calculated rate has to be evenly distributed on all cutting edges. This results in a heat generation rate Q = 16.5 W per cutting edge. As soon as the simulated model is in thermal equilibrium with the environment, the steady temperature condition is reached. In order to adapt the simulation in more detail, the intervals of cutting have to be considered. The stationary analysis requires a cyclic thermal load of the cutting edges, which is enabled by a transient simulation.

In contrast to the static simulation, the transient simulation is characterised by a cutting period of $t_{cutting\text{-}edge} = 0.01$ s, which is defined by cutting time per revolution and cutting edge, followed by a cooling period of $t_{cooling} = 0.03$ s. A total heat generation rate of $Q_{transient} = 66.1$ W is assumed. For comparability of the simulative values with the empirical temperatures, the moment of temperature detection must be nearly equal. Thus, the cooling process after exit of the tool has been considered for the transient solution. The temperature was detected for one cutting path after a cutting time of $t_c = 16.15$ s. Temperatures of $t_{max(1)} = 267$ °C for the standard tool and $t_{max(2)} = 252$ °C for the cooled tool were determined.

Figure 4 illustrates the maximum temperature in a transient simulation of $t_{max} = 520.45$ °C in the cutting process. The main view (global temperature) shows that after t = 16.15 s there is no heat distribution above the cutting head. However, the internal heat pipes show a temperature gradient (local temperature) of about $t_{local} = 8$ °C, which is an indication that a significant cooling effect can be achieved.

Overall the maximum cutting temperatures are significantly higher in the transient simulation, only the cooling process after tool exit decreases these temperatures. The small temperature difference of $t_{diff} = 15$ °C results from the short simulation time, because the heat-conducting elements have a thermal inertia. A more time-consuming and computationally intensive simulation would clarify the differences between the tool concepts.

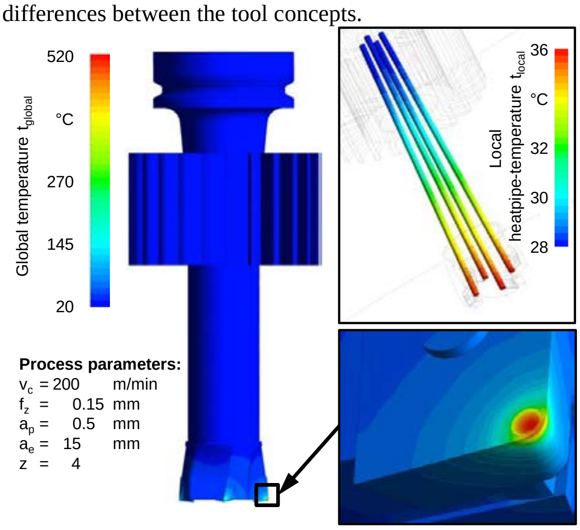

Fig. 4. Simulated heat distribution with ANSYS 16.0

The resulting temperatures that have been recorded by thermography and pyrometry differ. Hence, the maximum detected temperatures shows that the pyrometric measurements on the standard tool of $t_{max\ (pyro)} = 456$ °C are much higher than the recorded thermographic values of $t_{max\ (thermal)} = 356$ °C. This can be attributed to the unknown emissivity of the tool rake face and the measurement position.

However, average temperatures on the standard tool of $t_{max\ (standard)} = 356$ °C and the internally cooled milling tool of $t_{max\ (cooled)} = 302$ °C were measured with thermography. Thus, a reduction of the cutting edge temperature of about 15 % could be verified. As a result, a reduction of tool temperatures is possible by use of the tool with an internally cooled system.

3.3. Evaluation of the Life Cycle impact

The energy and resource efficiency could be proven in trials, where the power consumption of the machining system in dry and wet processing has been analysed. It intends to demonstrate the potential of energy and lubricant savings by using the closed internally cooled tool compared to a conventional flood cooling system. In reference to KUCHENMEISTER an example calculation for a two-shift operation was carried out [18]. Table 1 shows the comparison of the processes in term of costs.

Table 1. Comparison of wet machining and closed internally cooled milling tool [18].

		Wet machining	Internally cooled milling tool
Electricity	[EUR/kWh]	0.15	0.15
Power consumption of machine tool	[kW]	7.5	6.8
Machine hours per year	[h]	4112	4112
Cost of power consumption per year	[EUR]	4626	4194
Cost of cooling lubricant emulsion - 1000 litres per year	[EUR]	500	-
Cost of disposal of cooling lubricant - two times a year	[EUR]	300	-
Total	[EUR]	5426	4194
Savings per year	[EUR]	1232	

It could be determined that without using cooling lubricant, the power consumption of the machine tool could be reduced by 9.4 %. Furthermore, the costs for lubricant and disposal can be saved. Based on a two-shift operation this will result in a saving of about 1232 € per year. The requirement of cutting inserts can also be reduced by 50 % due to the longer tool lifetime $t_{VB0.3}$. However, the high saving potential of the tools depends on the specific application and a calculation has to be adapted.

In conclusion, the closed internally cooled milling tool leads to a decrease of the monetary costs in the production process, to a productivity increase up to 25 % as well as a waste reduction by avoiding the use of cooling lubricants. Furthermore the adverse health effect of the worker is also reduced by the substitution of cooling lubricants.

4. Conclusion

The results of the presented investigations show the benefits of an internally cooled milling tool. Based on machining tests with duplex steel (X2CrNiMoN22-5-3) it was shown that between the dry cutting and the internally cooled process a temperature difference of 15 % is present and an increase in productivity by the use of an internally cooled milling tool is possible. Different sets of parameters were compared and it could be proven, that with the cooled tool an increase in tool life of 50 % is feasible. Additionally, the temperature reduction was detected in milling process and simulative analyses. Hence, the use of the internally cooled milling tool offers an affordable, energy- and resource-saving solution and also allows an increase of the process parameters.

The comparison of dry and wet processes will be focused on in future studies on machining high temperature-resistant materials.

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