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Evaluation of Energy Efficiency in Cutting Aerospace Materials with High-Pressure Cooling Lubricant Supply

Fritz Klocke[1], Dieter Lung[1], Tolga Cayli[1,#], Benjamin Döbbeler[1], and Hubertus Sangermann[1]

1 Laboratory of Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Steinbachstraße 19, 52056 Aachen/Germany
Corresponding Author / E-mail: T.Cayli@wzl.rwth-aachen.de, TEL: +49-241-80-20524, FAX: +49-241-80-22293

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In the field of machining difficult-to-cut materials like titanium or nickel-based alloys, the use of high-pressure cooling lubricant supply (HPCLS) offers huge potential to significantly increase productivity and process stability. Due to enhanced cooling and lubrication of the cutting zone, tool wear can be decreased which allows higher applicable cutting speeds. Furthermore, process stability can be increased through effective chip breaking and evacuation. Increasing energy prices and legislative framework conditions, require energy efficient machine tools and processes. Since additional energy is required to run the high-pressure pump, it has to be determined if the overall process is still energy-efficient due to the increase in productivity resulting in shorter cycle times. In this paper the overall aim is to evaluate the conventional-flood-cooling and HPCLS in terms of economics and energy efficiency. Therefore a case study has been performed in which the energy consumption and production times for machining a rotationally symmetric jet engine part made of Inconel 718 were compared for both conventional and HPCLS. Furthermore, an ecological evaluation has been conducted to determine the advantageousness of the HPCLS. Due to the rising necessity of suppliers to provide a product carbon footprint, a methodology for assessing the footprint has been applied.

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NOMENCLATURE

HPCLS = High-Pressure Cooling Lubricant Supply
CoC = Conventional Cooling
HPP = High-Pressure Pump
HP = High-Pressure
P = Energy consumption [kW]
p = lubricant supply pressure [bar]
Q = lubricant flow rate [l/min]

1. Introduction

Although considerable improvements have been made in the area of tool development, cutting materials and tool coatings, the use of cutting fluid is considered as indispensable when machining difficult-to-cut materials like high alloyed steels, titanium or nickel-based alloys.[1-3] Due to their physical and mechanical properties the machining of these materials is characterised by low applicable cutting speeds due to excessive tool wear, long machining times and thus high manufacturing costs as well as the formation of ribbon and snarled chips. In this context, high-pressure cooling lubricant supply (HPCLS) represents a modern coolant strategy with a great capability to increase the productivity and process stability in machining difficult-to-cut materials. Due to the government requirements for achieving a more sustainable manufacturing especially machine tools and manufacturing processes are analysed to benefit from all these positive effects with minimised overall energy consumption per part.[4] The power consumption of the high-pressure equipment directly depends on the lubricoolant supply pressure and flow rate. Therefore it is essential to carefully adjust setting paramters like supply pressure, flow rate, cutting parameters and tool design. For the use of high-pressure lubrication it is necessary to understand the fundamental acting mechanisms and the impact of the jet setting parameters (e.g. pressure and flow rate) in order to increase its performance and energy efficiency.[5] A profound lack of knowledge exists concerning the energy-efficient use of this technology.

In this paper the energy consumption of a machine tool used with a conventional low-pressure flood cooling is compared to external high-pressure cooling lubricant supply when machining a rotationally symmetric engine part. With reference to the applicable cutting cutting parameters depending on the cooling lubricant supply strategy and setting paramters, the power consumption per part is examined in order to identify the most energy-efficient process design.

2. State of the Art

2.1 Conventional machining of difficult-to-cut materials

The conventional cooling lubricant supply strategy is characterised by flooding the area of chip formation. The consequence of this supply strategy is that the cooling lubricant is impinging preliminary the chip top side and can not penetrate to the cutting edge. So the heat can not lead away from the most thermally stressed areas of the insert in an effective way. Resulting problems during machining of these materials are excessive tool wear, low applicable cutting speeds and thus long machining times and manufacturing costs as well as the formation of ribbon and snarled chips in continuous cutting.[6] Under these conditions the automation of the production process is limited.[7] Therefore it has to be a major task to set up the application of cooling lubricants as effectively as possible.[5,8]

2.2 High-pressure cooling lubricant supply (HPCLS)

2.2.1 Characteristics and advances of HPCLS

First experimental investigations to high-pressure cooling lubricant supply strategy were carried out in the second half of the 20th century.[9] Since then many researchers have demonstrated the huge potential of this coolant supply strategy especially when machining difficult-to-cut materials.[1,8,10-12]

The characteristic of this cooling lubricant supply strategy is that a high-pressure cooling lubricant free jet is focused and directed into the wedge between chip bottom side and tool rake face.[13] This rake-face sided cooling lubricant supply is most widely used in industrial applications. One of the effects of the high-pressure coolant lubrication supply is the reduction of chip-tool contact length respectively friction.[14] As a result the reduction of tool wear enables to increase the cutting parameters, so a significant increase in productivity can be achieved. Furthermore leads the securing chip breakage[15] and controlled chip removal to an increase in process stability.

When machining easy-to-cut materials at low cutting speed it was find out by Sharman that the conventional flood cooling is effective to extend tool life. Due to the fact, that machining difficult-to-cut materials with increased cutting speeds generates higher cutting temperatures,[16] some researchers postulate the vapour barrier theory. According to this theory, high temperature at the cutting zone vaporises the cooling lubricant and generates a vapour barrier. During conventional flood cooling this vapour barrier prevents an effective cooling of the tool in the region of the cutting edge. The supply of the coolant lubrication jet with high-pressure may breake this vapour barrier enabling the cooling lubricant to penetrate closer to the cutting edge, thus leading to enhanced cooling of the tool.[8,14,17,18] The impact of the coolant lubrication jet on the chip underside and the resulting reduction of the upward bending radius of the chip can be influenced by the hydraulic jet force. The most important factors on the hydraulic jet force are cooling lubricant supply pressure p and flow rate Q.[12,13,19-21] In this sense, the coolant lubrication jet acts as a liquid chip former. Consequently the tool chip contact zone is reduced by up to 50% in comparison to the conventional flood cooling.[16,17,22]

Kaminski has shown that the shorter contact length and the reduction of friction also lead to a larger shear plane angle and reduced chip compression. This states that chip formation is significantly influenced by the high-pressure cooling lubricant supply. As a result Kaminski pointed out that a reduction of the tool temperature of about 40% is possible with the use of high-pressure coolant lubrication supply in comparison to the conventional flood cooling.[8]

On the basis of a rake face sided supply of the cooling lubricant, Dahlman investigated the performance of HPCLS in longitudinal external turning of two different steels ((34CrNiMo6 (SS 2541) and 100Cr6 (SS 2258)) and figured out that for materials with a large tool-chip contact length (e.g., 100Cr6) a large flow rate combined with low pressure shows the best cooling effect. He explained it by the fact that a larger tool-chip contact area in which heat is generated needs more flow rate for heat dissipation. Conversely, when cutting materials with a naturally small contact length (e.g., 34CrNiMo6) a larger supply pressure is needed instead of a high flow rate, because less heat is generated. For those materials, low flow rates of cooling lubricants are sufficient for heat dissipation.[17]

Crafoord et al. have carried out detailed investigations about the influence of high-pressure cooling lubricant supply on chip formation in external longitudinal turning of 100Cr6 (SS 2258) with cemented carbide tools. They pointed out that in case of rake-face sided cooling lubricant supply the chip upward bending radius is reduced more efficiently by increasing the flow rate and decreasing the cooling lubricant pressure.[13]

Although many investigations show the positive effects, the scientific relations of the high-pressure cooling lubricant supply are not completely analysed so far. Especially, the understanding of the fundamental mechanisms is necessary to improve the systematic use of the high-pressure cooling lubricant supply and its optimal adjustments against the background of profitability and energy efficiency.[6,15,23] The energy-efficient use of this cooling lubricant supply strategy requires the appropriate adjustment of the setting parameters so that the maximum productivity and process reliability gains are achieved with minimum pump power. For this purpose an appropriate ratio of pressure and flow rate has to be determined and carefully coordinated with the cutting parameters and the tool design.

2.2.2 Necessary technological changes for the use of HPCLS

The use of the HPCLS generally allows an automated manufacturing process of difficult-to-cut materials and leads to an increase in productivity compared to the state of the art.

In most cases the required pressure for ensuring chip breakage is exceeding the maximum permitted pressure of the cooling lubricant supply through the rotary union. In these cases a bypass-solution respectively external supply of the cooling lubricant by means of hydraulic hoses from the high-pressure unit through the tool holder to the cutting edge is applied.

In practise, a high-pressure suitable machine tool has to meet a huge number of requirements. For the application of this cooling lubricant supply strategy the working room in the machine has to be seal. Furthermore, an extraction system for aerosol mist as well as a high-pressure pump with a filter system is necessary. Appropriate high-pressure tool holders with integrated nozzles for the directed and focused cooling lubricant supply are offered from many tool manufacturers.

The cooling lubricant tank in the external high-pressure unit has to be sufficient large for both continuous supply with cooling lubricant due to high flow rates and offering a cooling down period to avoid warming up effects of the cooling lubricant. One more application requirement is the construction of scratch-proof machine parts in the working room especially safety window due to high bombardment with short breaking chips.

3. Experimental Procedure

3.1 Workpiece material

The investigated material was a rotationally symmetric jet engine part made of Inconel 718, which is a very tough, high temperature nickel-based alloy and is resistant to corrosion. This workpiece material belongs to the group of hardenable nickel-based alloys, which gain their strength properties during the heat treatment process (solution annealing followed by artificial ageing) in which intermetallic phases and carbides precipitate from the matrix.[24] The application of hardenable nickel-based alloys is mainly in the aerospace and gas turbine industry. Those parts made of Inconel 718 are exposed to high dynamic mechanical loads during high working temperatures.[2] The tensile strength of Inconel 718 is about 1375 N/mm^2 at room temperature and it decreases only by approximately 20% to 1100 N/mm^2 at 650°C.[25]

Inconel 718 belongs due to its mechanical, thermal and chemical characteristics to the group of difficult-to-cut materials.[2,26,27] In addition to a great high temperature resistance nickel-based alloys have a low thermal conductivity in comparison to steel. As a consequence a very low percentage of the total generated heat during cutting is lead away through the chips. Fig. 1 shows the thermal conductivity of Inconel 718 in comparison to different materials. It is noticeable that the thermal conductivity of Inconel 718 is only little higher than the thermal conductivity of TiAl6V4. Therefore high cutting and especially tool temperatures occur during machining since the heat can not be dissipated fast enough through the workpiece or the chips.[2,16]

Notch wear is one of the common wear forms when machining nickel-based alloys.[28] This wear form is a great problem due to its fast and often unpredictable increase. Segmented chip formation is characteristic during machining of Inconel 718. Furthermore, the high chemical affinity to many cutting tool materials leads to elevated diffusion and adhesion wear. Due to the formation of discontinuous chips the tool is exposed to an alternating mechanical and thermal load.[28] The short tool-chip contact length when machining nickel-based alloys leads to elevated specific load on the cutting edge whereby the risk of tool fracture and/or plastic deformation raises. The tendency to form build up edges and to work hardening as well as the abrasive effect of carbides and intermetallic phases result in extremely high mechanical and thermal loads on the cutting edge during machining.[28] Due to the high ductility of Inconel 718, uncontrolled chip breakage and complicated chip evacuation are one of the main problems. In turning Inconel 718 cemented carbide tools are mostly used at a cutting speed around 20 to 50 m/min. However during semi-roughing and finishing operations an increasing amount of ceramics is used as well as PCBN for finishing operations.[25]

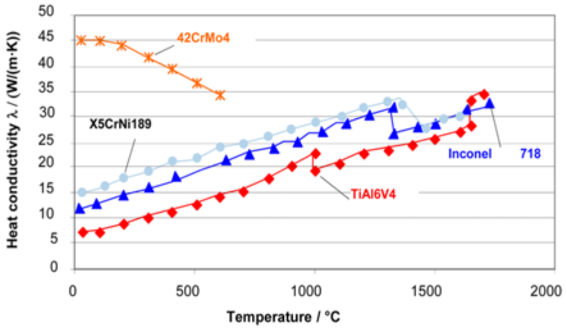

Fig. 1 Heat conductivity of different materials[6]

3.2 Experimental setup

For the evaluation of conventional flood cooling and HPCLS in terms of economics and energy efficiency, the energy consumption and production times for machining a rotationally symmetric jet engine part made of Inconel 718 on a CNC-lathe using cemented carbide cutting inserts were compared for both cooling lubricant supply strategies. The manufacturing of this part requires various turning operations (e.g., grooving, facing, external and internal longitudinal turning), so a broad range of turning techniques were captured in this case study.

The evaluation of the cooling lubricant supply focuses on the required energy consumption correlated to the removed material. When the cooling lubricant was supplied with high-pressure, jets were directed straight onto the rake face of the tool. In the case of HPCLS the power consumption of machine tool and high-pressure unit were investigated during the hole machining operation. The supply of cooling lubricant with high pressure was performed by an external unit with a maximum pressure of 300 bar (continuously adjustable) and a maximum flow rate of 22 l/min. In case of conventional flood cooling the external high-pressure pump was switched off and the cooling lubricant supply was performed by the internal low-pressure pump of the machine tool was used. The tool geometries and feed rates were the same for both process chains. The single most evident change was the increase of cutting speed, which has been more than doubled in comparison to conventional overflood cooling (CoC). The test conditions are summarised in Table 1.

For the evaluation of the turning processes it was essential to collect beside the electrical energy, which is directly consumed by the machine tool, also the electrical energy from the external cooling lubricant supply unit to generate the required energy per part. For this purpose, the power quality analysers Chauvin Arnoux C.A. 8335 are generally used for power quality measurements.

4. Results and Evaluation

In order to evaluate the whole process from an ecological point of

Table 1 Process design with CoC and HPCLS

	CoC	HPCLS
Machine tool	CNC-lathe	
Processes	grooving, facing, longitudinal turning	
Specimen	rotationally symmetric jet engine part	
Material	Inconel 718	
Cutting material	cemented carbide inserts	
Cutting speed vc	20~35 m/min	80~100 m/min
Feed rate f	0,10~0,25 mm	
Coolant supply strategy	flooding (≈ 6 bar)	high-pressure (70~300 bar)
Energy consumption	machine tool	machine tool+ high pressure unit

view it is of big importance to interpret the electrical measurements in the right procedure. This chapter will explain how the basic energy consumptions of the machine tool are distributed on the process, standby times and the high pressure coolant supply pump. For determining these different consumptions within the machine tool it is advisable to apply suitable measurement devices to the single aggregates. In this case a more usable and industrially applicable approach has been pursued. The electrical energy consumption has been measured at the main supply. In order to be able to distinguish between different consumers it was necessary to set the machine tool in different states.

Firstly, the standby energy which includes the basic consumers in a non-productive state of the machine tool was measured. Secondly, the process has been operated without high pressure and without a work piece. Due to this air-cut the necessary energy consumption for machine tool movements and the basic coolant supply could be determined. Thirdly, the whole process with high pressure and without a work piece has been performed in order to determine the power of the high pressure pump. The last step was to machine the work piece and thus determine the average cutting power. These different states, their respective average energy consumption as well as the cutting process can be envisioned in Fig. 2.

For evaluating the processes with or without the high pressure this procedure has been abstracted and the electrical power separated into different parts.

The distribution on standby, variable consumers and the process itself is shown in the following Fig. 3. For each process step of the considered work piece and therefore a bunch of different tools this procedure has been applied in order to determine the average power consumptions of the high pressure pump and the process itself. Due to much higher cutting velocities during the high pressure coolant supplied processes the process times were significantly reduced in both clamping situations.

The reduction of these times is illustrated in Fig. 4. It has to be stated that the process times have been aggregated over all necessary cutting operations. In this case, as mentioned before, a whole set of different operations has to be performed in order to create the final part. Two different clamping situations can be envisioned in the figure above indicated with the enumeration of the conventional coolant (CoC) and the high pressure supply (HP). Due to the higher cutting parameters, in this case basically the increase of the cutting speed by the factor 2 in average, leads to a reduction of cycle times by 63% in the first and by

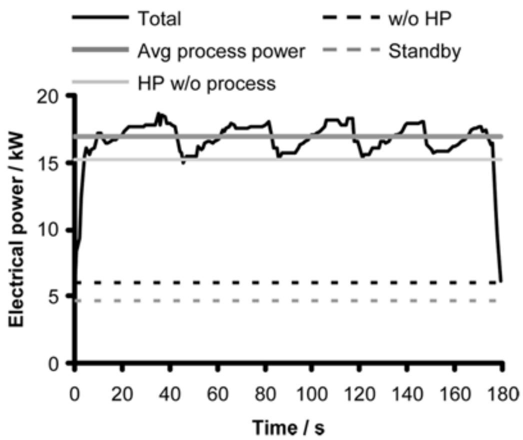

Fig. 2 Power distribution of a typical machine tool during high pressure processes[29]

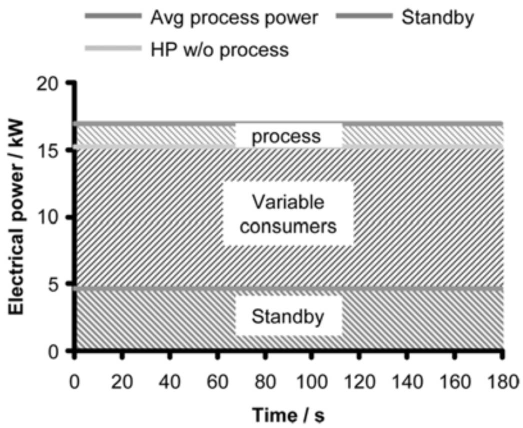

Fig. 3 Electrical power distribution[29]

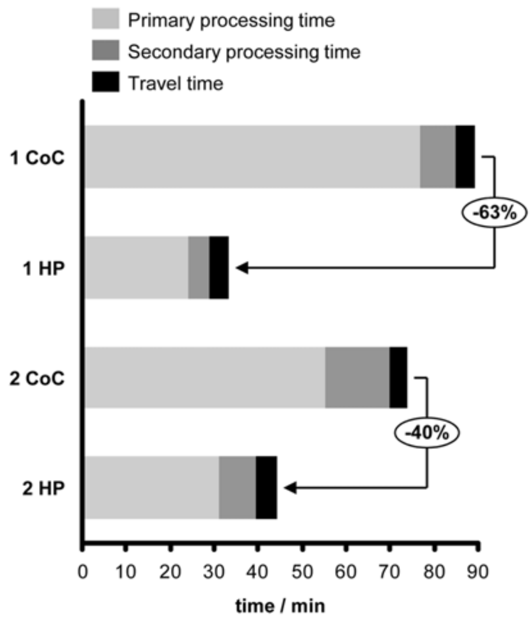

Fig. 4 Process and cycle times of CoC and high pressure cooling[29]

40% in the second clamping situation. Taking in mind the fact that the standby power of machine tools usually is responsible for a significant share of the total energy consumption of a process, it might be assumed that the reduction of process time will obviously reduced as well. Due to the process design which incorporates the high pressure supply, the reduction of the process time has to be balanced against the additionally necessary electrical power consumption of the pump.

In Fig. 5 the shares of the product carbon footprint of both clamping situations as well as the conventional cooling and the high pressure supplied cooling strategy are shown. The underlying methodology of evaluating the electrical energy by the equivalent carbon dioxide emissions has been used in former case studies and was performed by taking corresponding conversion factors from the life cycle assessment software GaBi.[30] The distribution of the total energy consumption over the whole process measurement was conducted on the consumption times and consumption points envisioned in the legend below.

Although the process times in both clamping situations led to significant process time reductions, the product carbon footprint did not decrease in both cases. Regarding the distribution of clamping situation 1 the main consumption origin shifts from the standby energy to the high pressure pump, although in the high pressure supply scenario the internal coolant supply pump was running. This was observed due to not optimized NC-program code which will be adapted in the future. Basically all shares decrease whereas the high pressure pump accounts for the biggest share of the consumption. This behavior can be observed in the second clamping situation as well. In this case the reduction of process times and thus the reduction of the standby share of the energy consumption cannot outweigh the additional consumptions of the high pressure pump. On the other hand, the auxiliary times are highly dependent on the chip breakage and removal. In several of the processes considered within this study the chip removal could not be guaranteed, which was one of the main reasons for the industrial partner to implement the high pressure technology. Times for the additional effort for removing ribbon and snarled chips have not been considered due to their unpredictable occurrence, but it has to be stated that the cycle time and thus the consumed electrical energy has risen significantly by using the former coolant supply technology.

This leads to the conclusion that a break even point of reduced process times and increased required power consumptions due to the high pressure components exists and needs to be evaluated. More detailed process analyses are the basis for this research topic which arise the need to investigate possible process accelerations and their electrical consumption costs at the same time. Furthermore, regarding the total process stability as well as the productivity, from an economic point of view the use of high pressure coolant supply may be highly advisable. Reports from the industrial partner, at which the process data has been acquired, indicate that the process stability itself has been increased significantly due to the use of high pressure coolant supply. Hence, the process change is considered a major step towards higher productivity and stability in respect to lower scrap, non-acceptable parts and reworking after machining.

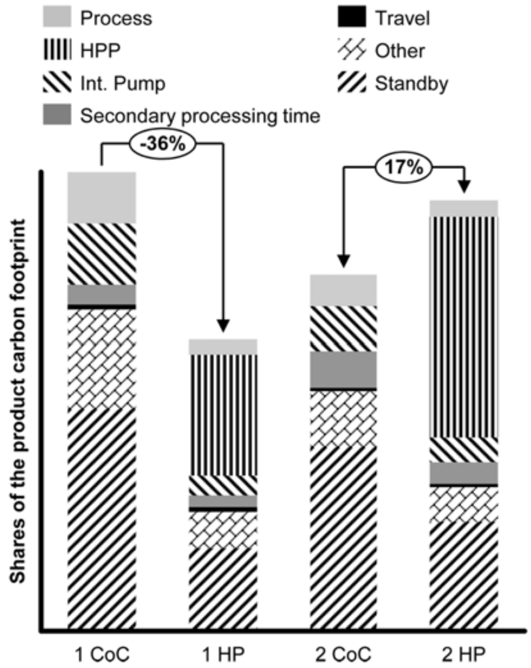

Fig. 5 Primary energy consumption of CoC and HP process design[29]

5. Conclusions

This paper has shown the advantageousness of the high pressure cooling lubricant supply in the industrial application. Due to technological changes of the supply system, single aggregates, the control unit of machine tools and suction systems may have to be adapted in order to ensure process stability and a healthy work environment regarding the lubricant mists. This necessities have been shown in the earlier parts of this paper. Furthermore it is of utmost importance not only to consider chip breakage or increasing cutting speeds in order to evaluate the whole process from an economic and ecological point of view. High pressure pumps cause higher electrical energy power consumptions. But due to higher productivity, especially by applying higher cutting speeds, the technology bears a huge advantage for many work piece materials such as the investigated Inconel 718. Of course not every process step can be enhanced by using HPLCS, but processes where chip breakage is one of the main problems, can significantly profit. Regarding the ecological point of view the results are inconclusive at first. At the second glance further investigations are necessary in order to predict operations which profit from higher cooling lubricant supplies in a obvious manner. When evaluating all non-productive times due to chip removal necessary due to inadequate chip breakage, most high pressure coolant supply scenarios might be favoured when chip breakage is one of the main problems.

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