Modelling of Energy and Resource-Efficient Machining

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Abstract:
The key goal of high performance cutting is to increase the material removal rate and product quality combined with a decrease of the cost of resources and energy. Energy and raw material prices are expected to rise as demand increases in the near future. Thus, the share of energy costs will have a much more significant impact in the overall production costs. The minimisation of energy consumption per unit material removed becomes, therefore, a very important goal in investigations of machining processes.
The present study focuses on the development of an energy balance of the drilling process. It considers the process energy, the efficiency of the machine during the cutting process, and the tool wear with the aim of finding conditions requiring minimum energy and ressource consumption. The influence of removal rate, tool type, and lubrication on the energy and ressource consumption are analyzed using experimental drilling tests on cast iron. During the investigation it was found that the energy efficiency increases with an increase of the removal rate. Machining with high feeds and cutting speeds resulted in lower energy consumption per drilled hole. In the case of dry maching, the machine efficiency could be increased but on the other hand the tool wear and the resulting tool cost rise significantly. The experimentally determined resource and energy balances laid ground for a modelling approach based on 3D Finite Element simulations of the drilling process. The process energy and energy efficiency of drilling on high-strength steel were numerically determined to show the validity of the approach as a process planning tool in the development of resource-efficient metalworking chains.

Keywords: Energy and Resource Efficiency, Drilling, Finite Element Method, Process Machine Interactions

1. Introduction

The increased demand for natural resources in the last years has put significant pressure on the availability and costs of raw materials and primary energy. This has motivated a growing emphasis on energy and resources conservation in policy making and business. Furthermore, the energy efficiency of products has become an important buying criterion among consumers. In the next years, energy efficiency will play a greater role in competitiveness. Of particular interest is the energy and resources efficiency of the manufacturing industry because it is one of the most energy-consuming sectors.
Manufacturing is a wide field and an overarching energy efficiency analysis can only be applied at an abstract level. An energy consumption analysis of individual manufacturing processes is key in the creation of an energy balance of the overall product lifecycle. The main goal is the reduction of resources usage for the creation of the desired degree of value added. In the case of the drilling process, the focus of the present investigation, the main goal is to use the minimum amount of energy necessary to reach a given hole quality. To this end, experimental and numerical analysis of the drilling process have been carried out to gain insights on the main influences on the energy efficiency of the drilling process.

2. On the scope of resource-efficient machining

Investigations have shown that in cutting processes the mechanical energy input is almost exclusively converted into thermal energy[1]. In addition, many prior investigations have shown the material flow and temperature distributions in the chip formation process [2,3]. So far, analyses of the cutting process have focused on the cutter-workpiece interaction, a scope that is far too limited for the prediction of the energy and consumables usage of cutting processes. For the practical use of a resource balance it is necessary to include the influences of the machine tool, byproducts chips and burrs, and time and tool path-dependent aspects such as tool wear.

2.1 Process energy and machining energy efficiency factor

The machining energy efficiency factor is defined as the ratio of the mechanical energy input by the cutting edge to the direct energy from the grid consumed by the machine tool. Back in 1986, in a survey of manufacturing facilities, Degner [4] reported that the average machining energy efficiency factor in metal cutting chains is approximately 19%. However, it was shown that the machining efficiency factor drops considerably when the electricity generation efficiency and energy consumed during machine tool non-productive time and by auxiliaries such as compressed air supply are considered. Clearly, a realistic energy balance would necessarily include the aforementioned influences in addition to the process energy or specific cutting energy. In fact, it was shown that the energy consumed by the machines during non-productive time usually dominates in comparison to the process energy, and, consequently, short cycle times or high material removal rates are most effective in decreasing the energy consumption per operation [4].

2.2 Energy-efficient products and byproducts

In addition to the energy variables, the properties of the finished product and the value-added must be considered in the energy analysis of processes. An increase in the energy efficiency of manufacturing processes can only be successful when the resulting product properties are either unchanged or improved.

The products of the machining process encompass the finished good and the byproducts chips and burrs. The requirements of the workpiece or finished product include dimensional accuracy, surface integrity and material properties. In the case of the byproducts chips and burrs, the goal is to modify or minimize them and thus keep their negative effects during the cutting process, subsequent manufacturing operations, and service life of the finished product to a minimum. Typically, cutting processes are optimized for maximum material removal rates and the generated burrs are removed by subsequent deburring operations. These additional steps in the manufacturing chain incur energy and consumables costs as well as longer lead times. Clearly, deburring operations have a negative effect on the energy balance of machining process chains. The energy-friendly alternative is the application of burr minimization strategies in cutting operations.

Regarding the byproduct chips, their shape and size are the most important parameters in the design of energy-efficient machining process chains. For instance, mid-size chips that are strongly coiled and hence with a low drag surface area are optimal for cleaning of mechanical components using fluids. In contrast, small chips may become trapped in small geometry features and large, loosely coiled chips impair the handling and transport of the workpieces. Likewise to the deburring steps, cleaning operations have a negative impact on the overall energy efficiency of machining process chains.

3. Energy and cost assessment of the drilling process - Experimental investigations

An initial screening is carried out using commercially available drilling tools with different removal rate and wear resistance rating. The purpose is to determine the most promising tools and cutting regimes for energy and cost-effective drilling.

3.1 Experimental design

The experiments were planned to answer the following questions:

- What are the cutting parameters and tools that lead to optimal use of resources?
- Is High Performance Cutting (HPC) energy-efficient?
- Could the higher tool costs for HPC be compensated by its lower energy and machine costs?
- Is dry machining resource-efficient?
- What are the influences of high material removal rates on hole precision, burr formation, and chip geometry, i.e., on the amount of subsequent finishing processes?

Drilling tests were performed on a Heckert CSK400 milling centre with a spindle power of 22 kW and an axis feed with a capacity of 8 kN. A through-hole geometry of Ø7mm and 35 mm depth was selected for all of the experiments. The workpiece material selected was cast iron EN-GJL-250. This material is used extensively for pumps, transmission housings and engine blocks, all of tham undergo several drilling operations.

A group of drilling tools was selected from the product range of a leading tool manufacturer based in Germany. The product range offers a wide spectrum of drilling tools for flood cooling conditions and for the selected bore geometry and workpiece material, including high speed steel (HSS-E) and solid carbide (SC) tools. The nominal cycle time for drilling a Ø7 x 35 mm hole of the tools ranges from 0.8 to 8.6 s and drill costs from 3.30 to 68 €. Tools with different levels of removal rates were chosen for the drilling tests (highlighted with arrows in Figure 1).

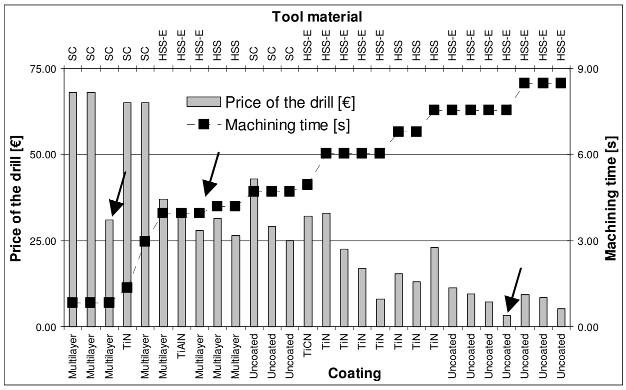

Figure 1: Drilling tool spectrum for machining a Ø7 x 35 mm bore on EN-GJL-250 cast iron

Table 1: Tested drills

Type	RT 100 U		GT 100 G	GU 100 DZ
Material	Solid Carbide		HSS-E	HSS-E
Coating	Multilayer		Multilayer	none
v_c [m/min]	210		60	36
f_{rev} [mm]	0,266		0,212	0,17
Price [€]	31		28	3,30
Cooling	flooded	dry	flooded	flooded

Drilling tests with SC tools were conducted both dry and with flood cooling; the HSS-E tools were only tested under flood cooling conditions. The cutting conditions for each tool are listed in Table 1.

The cutting force (torque and feed force) was measured by means of a Kistler™ HS-RCD 9125A dynamometer. Based on the measured forces the process power was calculated. The machine tool electric power consumed from the grid was measured with a power meter (YOKOGAWA WT130).

Each drilling tool was used until the wear criterion of either tool failure of very strong burr formation was met. Tool wear was measured on each tool after every 90 holes using an optical microscope. At the same intervals, exit burr heights were measured by confocal microscopy. Likewise, roughnesses R_a and R_z of the generated inner surfaces were measured to characterize hole quality.

3.2 Experimental results

The process and machine power rates for each of the different drilling tools and cutting regimes are presented in this section. The energy consumption characteristics of each regime are then compared.

Drilling energy consumption - uncoated HSS-E tool and flood cooling

In contrast to SC tools, drilling with HSS-E tools is relatively slow and the inherent cutting forces small. In this case, the steady-state cutting power was measured at approximately 300 W. At the same time, the machine power from the grid was close to 4800 W. This power was only slightly larger than the consumption during the non-productive time with active cooling fluid supply ($P_0 \approx 4500$ W). Figure 2 presents the process and machine power rates as a function of elapsed time during one drilling cycle. Cycles start as soon as the tool engages the workpiece and end immediately after rapid-movement tool retraction at 2 mm elevation from the entrance surface. The signals show that the machining process power has virtually no effect on the machine power consumption signal. The machine power during non-productive time was approximately 15 times the cutting power.

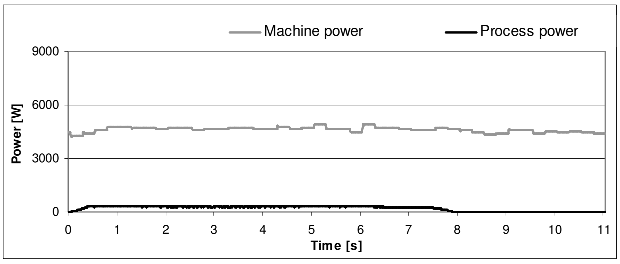

Figure 2: Machine power and process power during drilling with uncoated HSS-E drill

Drilling energy consumption – coated HSS-E tool and flood cooling

The specific power consumption during the steady-state cutting regime reached approximately 780 W. This process power requirement was about 2.5 times the power of drilling with uncoated HSS-E tools. However, the cycle time with coated tools was shortened by a factor of 2.4. In this case, the machine power signal did show an appreciable effect from the process signal.

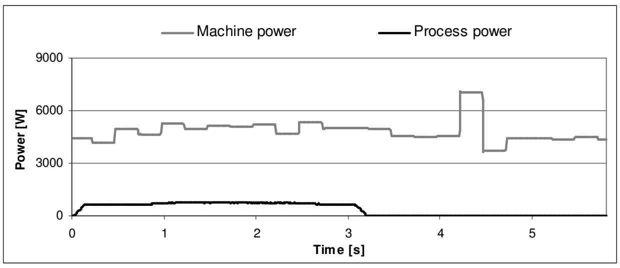

Figure 3: Machine power and process power during drilling with coated HSS-E drill

Drilling energy consumption – coated SC tool and flood cooling

Drilling cycle time was in this case 0.8 s –about 1/9th of the cycle time of the uncoated HSS-E drill.

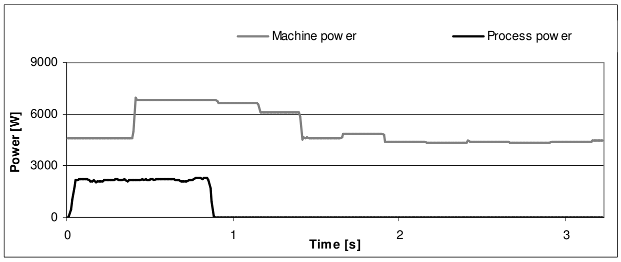

Figure 4: Active power and process power during drilling with coated SC drill (flood cooling)

The process power was 2.2 kW and it showed a marked effect on the machine power signal. The delay of 0.3 s for the machine power signal based on electrical energy transformations in the machine.

Drilling energy consumption – coated SC tool and dry cutting

With dry cutting the energy required by the coolant supply system is eliminated and considerably reduces the machine power consumption by 1.5 kW. The process energy rate only increases slightly when the SC tool is used under dry cutting conditions, all other cutting parameters are identical, in comparison to cutting under flood cooling.

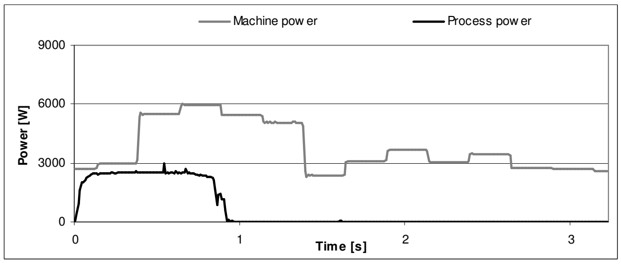

Figure 5: Machine power and process power during drilling with coated SC drill (dry)

Comparison of energy and tool cost

A comparison of energy, productivity, and cost-related variables of the four tests are shown in Table 2.

Table 2: Test results

	SC dry	SC flooded	HSS-E, coated	HSS-E uncoated
Machine energy per hole (kWh)	0.202	0.278	0.467	0.850
Process energy per hole (kWh)	0.035	0.030	0.036	0.036
Machining energy efficiency factor (%)	17.3	10.8	7.8	4.3
Machining time for Ø 7 x 35 mm (s)	0.8	0.8	3.1	7.5
Material removal rate (cm^3/s)	6.52	6.52	1.75	0.71
Lifetime of the drill (m)	3.78	24.15	28.175	31.5
Price of the drill (€)	31.00	31.00	28.00	3.30
Machine energy per drilled length (kWh/m)	5.78	7.94	13.34	24.29
CO_2 emission for electrical energy per drilled length (g/m)	3609	4952	8322	15155
Machine costs (1h=120€) per drilled length (€/m)	0.79	0.79	2.93	7.19
Tool cost per drilled length (€/m)	8.20	1.28	0.99	0.10
Machine energy cost per drilled length (€/m)	0.58	0.79	1.33	2.43
Total cost per drilled length (€/m)	**9.57**	**2.86**	**5.25**	**9.72**

The values of energy per drilled hole correspond to the cycle time from tool engagement to tool retraction as defined previously in this section. The cost per kilowatt-hour correspond to the average price paid by mid-size industrial companies in Germany in 2009, at 0.10 € / kWh [5]. CO_2 emissions per drilling cycle were calculated based on the estimate by the German Ministry for Environment of 624 g emitted per kilowatt-hour generated in Germany in 2009 [6].

Surface quality comparison

The surface roughness parameters for the different drilling regimes and tools tested are shown in Figure 6. Drilling with SC tools yielded improved surface finish in comparison to HSS drills with the added benefit of higher machining energy efficiency and material removal rate. Dry cutting and the use of uncoated tools worsened surface finish.

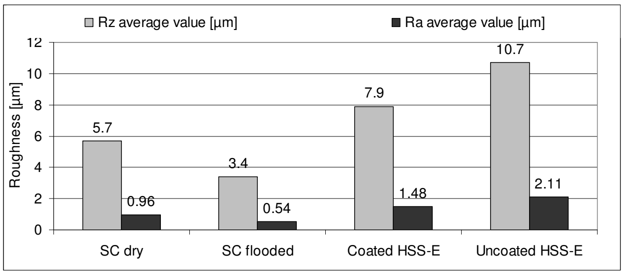

Figure 6: Surface roughness of the inner wall of the drilled holes

As regards to the byproducts chips and burrs, some differences were observed among the different cutting regimes and tools. As expected, very small chips were generated in the drilling tests on cast iron, ranging from 1 to a few millimetres in length. Sporadic, short-time peaks were observed on the cutting force signal of the steady-state drilling period and they are attributed to inefficient transport of such small chips out of the cutting zone. The most peaks were observed when drilling with HSS-E drills.

Figure 7 shows a micrograph and a confocal microscopy topographic map of a ring exit burr generated by the SC tool under flood cooling conditions. This burr is representative of the very small burrs produced by all drill types before any significant tool wear was detected and their maximum height ranged from 40 to 80 µm.

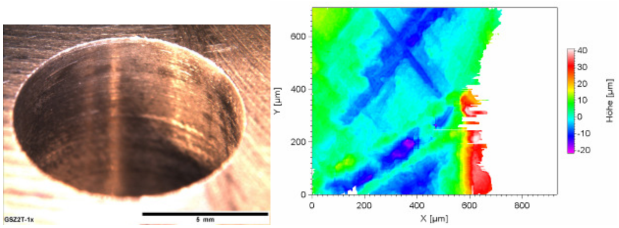

Figure 7: Burr shape of drilling EN-GJL-250 (SC flood cooling)

Once tool wear started to develop, burr height increased dramatically and burr morphology changed from ring to crown burr –a typical phenomenon observed when drilling cast iron. Crown burrs must be removed by deburring steps owing to their large size and instability. After tool wear became even more significant, cracking of the workpiece on the tool exit surface was observed. For comparison purposes, it was desired to create an energy balance for defect-free holes without the need of deburring steps. Therefore, the first appearance of crown burrs was selected as the tool life criterion and holes that showed crown burrs were not accounted for in the energy balance.

3.3 Discussion

The machine and process energies per drilled hole and resulting energy efficiency factors for the cutting regimes tested are compared in Figure 8.

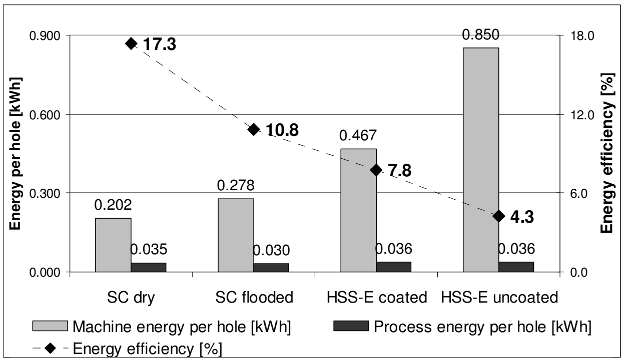

Figure 8: Process and machine energies per hole and machining efficiency factor for different drilling tools and cutting regimes

The process energy at the higher removal rate capability of SC drills was up to 17% smaller than the same metric for HSS-E drills. More significant differences were observed in the machine energy consumption of SC *vis-à-vis* HSS-E tools. The smallest machine energy consumption measured corresponded to dry drilling with a SC tool. A comparison of the three drilling regimes under flood cutting reveals that the faster cutting speeds and higher feed rates result in a sharp increase in the machining energy efficiency. The machine energy consumption was decreased by up to 68 %. Given that the non-productive operation of the machine with a running spindle and cooling system (tool disengaged) consumes 4.5 kW, the removal rate or cycle time becomes the dominant influence on machining energy efficiency (Figure 9).

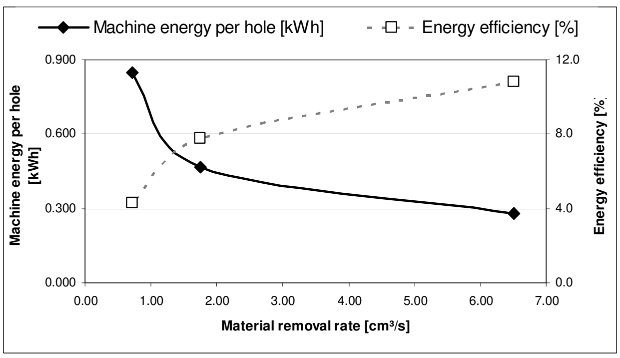

Figure 9: Influence of material removal rate on machine energy and energy efficiency

A resources balance for each of the four drilling regimes tested was devised based on a combination of the machine energy costs and the fixed and variable costs of the machine tool and the costs of the drilling tools. Ideally, a thorough resources balance would include the energies associated with the manufacturing of, machine tool, cutting tools, and consumables such as cooling fluid. However, these values have not yet been clearly determined. The inclusion of machine and tool costs was intended to provide an initial estimate of the overall resources consumption that has practical value for decision-making in current industrial environments.

For the resources balance, the machine and drill tool costs were calculated per meter depth of generated holes of 7 mm in diameter. A price of 120 € per machine tool working hour that is common in industrial practice was selected to account for the machine tool fixed and variable costs. The machine costs associated with non-productive time were not included in the balance. The rationale of this omission is that non-productive time strongly depends on workpiece geometry and complexity which can vary widely from one case to the other.

The ressource balances for the different cutting regimes tested are shown in Table 2 and a comparison plot is presented in Figure 10.

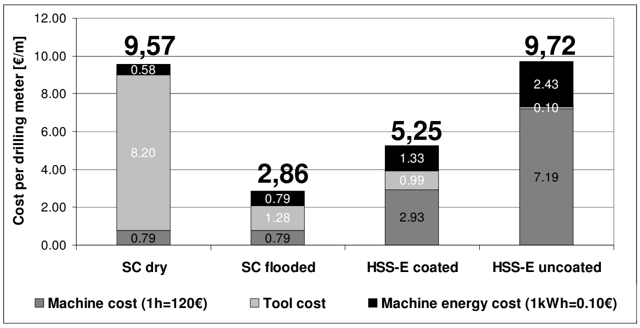

Figure 10: Resource balance of different cutting regimes per metre

The most salient contrast is that drilling at the high removal rate capability of SC drills in comparison to HSS-E drills brings a significant overall cost reduction –by a factor of 3. This cost saving is mostly due to the inherently shorter cycle times of the SC tools (roughly 9 times shorter). Similarly, machine energy costs per meter of drilled holes drops more than threefold –a drop that will sharpen as the cost per kilowatt-hour increases in the next years.

As expected, the tool cost of uncoated HSS-E drills have little impact on the resources balance. Although the coated HSS-E tools have a higher price than their uncoated counterparts, their higher productivity rate more than compensate the added tool costs in the resources balance.

Dry cutting with SC drills incurred the least machine energy costs mainly owing to the inherently short cycle times and the absence of coolant supply. However, the cost of tools becomes much higher than in the case of flood cutting because tool life decreased by 85% (Table 2).

The effects of the cost of 1 kilowatt-hour on the resource balance of flood-cooled drilling with uncoated HSS and SC tools are contrasted in Figure 11.

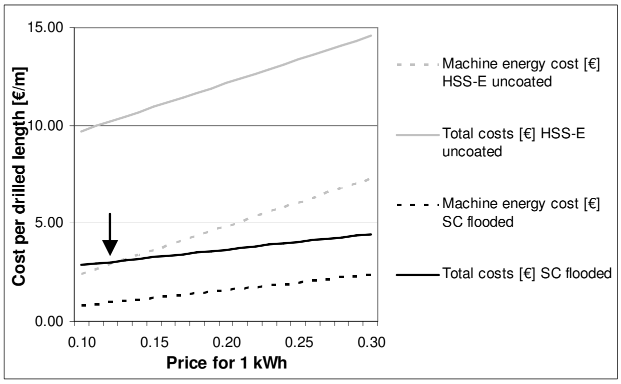

Figure 11: Influence of the price of one kilowatt-hour on the machine energy cost and total cost (Uncoated HSS-E and SC flooded)

It is clear that as the energy price increases, the total cost advantage of the SC drills widens. Of particular interest is the fact that by the time the energy price reaches 0.13 € per kilowatt-hour, the cost of energy with the HSS-E tools already surpasses the total operation costs with the SC tools per meter of drilled hole (marked with arrow).

As for the effect of the byproducts chips and burrs, for comparison purposes it was not necessary to include them in the resource balance. Before the tool life criterion was met, virtually the same degree of burr formation and chip morphology was observed under all cutting regimes and drilling tools. However, a completely different behaviour is expected when drilling ductile materials, given that burr formation and chip morphology are more sensitive to and change more gradually with varying cutting conditions. In such cases, the effect of the byproducts, chips and burrs should be included.

4. Energy balance in process planning - Numerical simulations

The experimental results showcased the significant energy and resources savings that could be realized by carrying out a resource balance of machining processes. Yet, experimental measurements would become too expensive and unwieldy when planning complex mass production chains. Numerical simulations for the prediction of energy parameters and tool wear are, therefore, necessary to effectively implement a resource balance analysis at the planning stage.

Calculations of cutting forces are often based on the model proposed by Kienzle [7]. The specific cutting force values for different materials in turning have also been published by Victor and Kienzle [8] and their applicability in drilling has been validated [9]. However, the model incorporates the influences of cutting speed, tool geometry, and tool wear by means of correction factors which severely limit its accuracy and applicability.

Further, tool life prediction –an important task in resource balance analysis– and estimation of the byproducts chips and burrs are not possible to perform using these models. Alternatively, numerical simulations of cutting processes using the Finite Element Method (FEM) can overcome the limitations of the existing models. FEM simulations can be used to predict the process energy, tool wear, chip and burr formation [10], as well as the temperature distribution in the cutting zone. In combination with the tool costs and the machine tool energy efficiency factor, they can be used at the planning stage for the selection of resource-efficient cutting parameters and tooling (Figure 12).

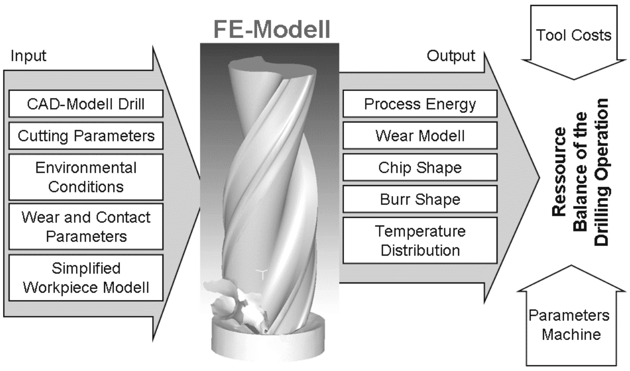

Figure 12: Numerical simulation for the determination of a resource balance

Specifically, the temperature distribution predictions can be applied in the selection of appropriate cooling strategies.
A first run of simulations was carried out to determine the energy balance of drilling a Ø7 mm x 35 mm bore on AISI-4140 applying the same tools used in the experiments.

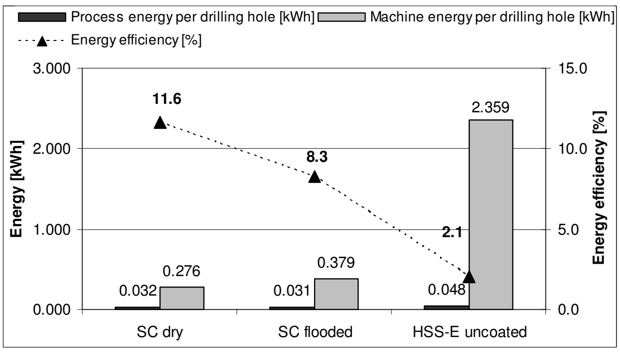

Figure 13: Numerically determined energy balance for drilling AISI-4140

Machining of this alloy steel is much more pounding on the cutting tool in relation to cast iron, and hence the material removal rate for this steel is significantly smaller. This explains the lower machining energy efficiency factors calculated as shown in Figure 13. Likewise, energy-efficient machining is only possible by using high material removal rates.

5. Conclusion

Experimental investigations on the energy and resources balance of drilling processes showed that an increase in cutting speeds and feed rates yield significant savings in the total cost of machining including the energy costs. Hence, HPC hold great promise in the development of cost-effective as well as energy-efficient machining process chains. A comparison of dry vs. flood-cooling drilling revealed that energy savings are possible by use of dry cutting. But, the cost of dry drilling is greater than its flood-cooled counterpart owing to the accelerated tool wear. Future experimental analysis will focus on the energy consumption of different cooling strategies and systems, including Minimum Quantity Lubrication (MQL) and internal drill bit cooling.
Preliminary FEM simulations of drilling processes showed their applicability in the planning of energy-efficient and cost-effective machining process chains. Future simulations will incorporate the machine efficiency factors and further improvements of the tool wear model.

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