Energy Efficient Process Planning Based on Numerical Simulations

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Abstract
The main goal of energy-efficient manufacturing is to generate products with maximum value-added at minimum energy consumption. To this end, in metal cutting processes, it is necessary to reduce the specific cutting energy while, at the same time, precision requirements have to be ensured. Precision is critical in metal cutting processes because they often constitute the final stages of metalworking chains.

This paper presents a method for the planning of energy-efficient machining processes based on numerical simulations. It encompasses two levels of planning flexibility: process adjustment and process design. At the process adjustment level, within the constraints of existing machines and tools, numerical simulations of orthogonal cutting are used to determine cutting parameters for increased energy efficiency. In this case, the model encompasses specific cutting energy, tool wear, chip geometry, and burr shape. These factors determine the energy and resources required for the chip formation itself, tool replacements, cleaning and deburring and with that the overall energy efficiency and precision.
In the context of process design, with the ability to select machines, machine configurations, tools, and cooling systems, numerical simulations of cutting processes that incorporate machine and tool conditions are applied in the planning of energy-efficient machining. The method is demonstrated for the case of drilling processes and supported by experimental investigations that identify the main influences on energy efficiency in drilling.

1. INTRODUCTION

There has been a drastic increase worldwide in the level of primary energy consumption in recent decades. Models designed to predict the consequences of this development, have come up with a diverse range of scenarios [1-3]. However, it seems certain that energy prices will soar as the demand for energy continues to rise while reserves dwindle and that the availability and effective use of energy will be of key importance to national economies.
Analysis of the energy consumption in Germany in 2007 showed that industrial users accounted for approx. 28% [4] of primary energy consumption, illustrating that a high level of responsibility for energy and resource efficiency lies with industry and the entire manufacturing sector.
Dornfeld [5] demonstrated that all levels of the manufacturing process, starting with manufacturing processes at the highest level through the factory itself, production lines, groups of machines, individual machines, machine components and even machining operations must be analyzed and optimized in order to achieve maximum manufacturing efficiency.
The investigations detailed here, focus on the core areas process and machine, with the spotlight on the machining process.

2. MATERIAL AND ENERGY FLOWS IN THE MACHINING PROCESS, GENERAL

The analysis of energy and material flows must be the starting point in energy and resource/efficient process design. This can be achieved in a highly abstracted form using an Input-Throughput-Output ITO model. A generalised model of a cutting process conducted using a geometrically defined cutting edge is shown at process level in the diagram below (Figure 1).

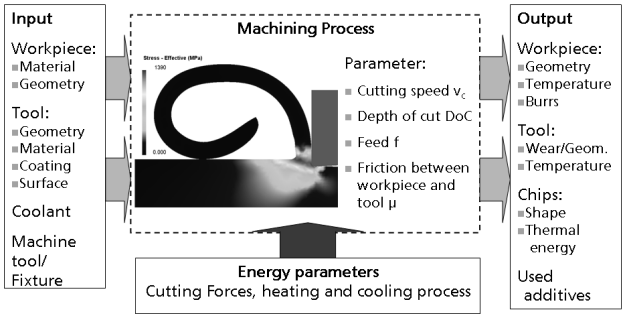


Figure 1: ITO-model of a machining operation conducted using a geometrically defined cutting edge

The workpiece and tool along with its characteristics are the decisive input variables. In addition to these material-related variables, ener-

getic variables such as cutting forces and temperature are included in the study. In turn, on the output side, the tool and workpiece characteristics are scrutinised. The process-specific secondary products, chip and burr, are also considered in the analysis. The aim of energy-efficient process design is to achieve the maximum increase in workpiece value using a minimum of energy. In terms of the machining process, this means that a defined volume of the workpiece material must be removed with minimum energy input. It is vital to include the tool, which is subject to process-related wear as a resource since tool manufacture ties up energy and costs. In terms of the secondary products, the objective is to avoid energy-intensive finishing operations such as cleaning and de-burring.

3. NUMERICAL ANALYSIS OF THE INFLUENCE EXERTED BY MACHINING PARAMETERS ON PROCESS EFFICIENCY

3.1 Approach

There are a number of methods of analysing processes, which take a more or less abstract view of the process. The statistical test planning tool DoE (Design of Experiments) is frequently used to analyse processes. This investigates the influence exerted on output quantities by input variables. Depending on the experimental design selected, the influence exerted by variables on one another and in various combinations can be determined in value-oriented terms. In the literature, the test is usually of an experimental nature. However, the experimental test frequently involves considerable time and cost.

This paper will demonstrate on the basis of an exemplary investigation of an orthogonal cut, how resource-optimised process and tool parameters can be identified using a full factorial DoE plan combined with numerical simulations. Substitution of the experimental test by Finite Element FE simulations, achieves both a reduction in the time and cost involved and permits design planning.

The full factorial plan is characterised by very high levels of accuracy in terms of the value-based determination of the influences exerted by individual input variables on output variables as well as the influence exerted by various combinations of input variables on one output variable. A considerable number of tests have to be conducted in order to achieve this high level of accuracy. Although other plans require less testing, this is achieved at the expense of accuracy.

The cutting speed v_c, cutting depth DoC and the rake angle SW were selected as input variables. As illustrated in Figure 2 below, these input quantities are arranged in various process-typical ranges and a combination of FE simulations and DoE is used to pinpoint exactly what influence they exert on the outcome.

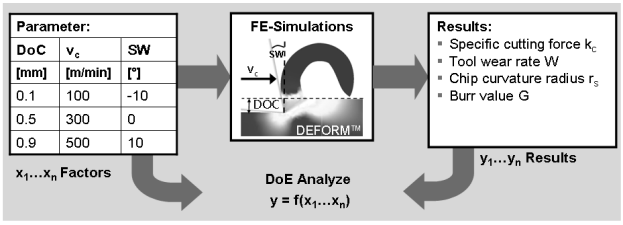


Figure 2: Combination of FEM and DoE

The output quantities specific cutting force k_c, tool wear W, burr value G and the chip curvature radius r_s were selected as output quantities and as characteristic quantities for energy and resource consumption within the process and in finishing operations.

3.2 Orthogonal Cut FE-Model

The program DEFORM™2D V10.1 was used to perform the numerical calculations. In addition to the varied input quantities (Figure 2), the following parameters were selected:

- **Workpiece:** Material 42CrMo4 (AISI4140), plastic deformation character and crack criteria in accordance with the normalized Cockcroft & Latham model, finite element distribution determined by a mesh window → more than 5 elements above cutting depth, tool length 20 mm
- **Tool:** Uncoated, solid carbide, assumed as rigid, friction (Coulomb) against the workpiece $\mu = 0.5$, heat transfer, clearance angle 9°, 900 Finite Element (adaptive distribution, determined by local temperatures and the mesh window)
- Ambient conditions for dry machining

The wear model used to calculate tool wear, was that presented by Usui [6] and the constants in the contact coupling were taken from Attanasio [7]. The success criterion was defined as the removal rate over the entire cutting edge per unit of time. The temperature, pressure and speed values measured at the cutting edge after 15 mm cutting path were used to determine the wear model. After this cutting path, the temperature and state of stress at the cutting face are quasi-stationary.

The specific cutting force k_c, was averaged over a cutting path of 5 mm in the stationary range of chip formation.

The burr and its geometry are the key factors in determining the level of finishing work required and the associated energy consumption and cost. A slight burr requires only a small amount of deburring or, in the best case scenario, can be left on the workpiece as noncritical. The burr value G as described by Link [8] was designated as an output quantity.
The shape of the chip, which is a by-product, determines the time and effort required for chip evacuation and, more importantly for cleaning. The aim is to achieve a low chip volume [9]. This is directly dependent on the chip curling, which can be described in value-oriented terms by the chip curvature radius, r_s. The chip curvature radius was determined in the numerical machining simulation conducted prior to contact between the chip and the workpiece surface.

3.3 Statistical evaluation and results

As described in the previous chapter, DoE techniques are used in investigations conducted in order to achieve an accurate, value-based description of the correlations between the machining and tool parameters and the resultant output quantities relating to energy and resource consumption. The quantities specific cutting force k_c, material removal at the tool cutting edge W, chip curvature radius r_s, and burr value G, are described graphically and in a polynomial regression on the basis of the result of the DoE, using the equations (2) to (5). The individual quantities are then weighted and summarised in order to generate a polynomial, which defines the total energy and resource consumption.

Specific cutting force k_c

The influence exerted by the depth of cut DoC, the cutting speed v_c, and the rake angle SW, on the specific cutting force, are shown in Figure 3.

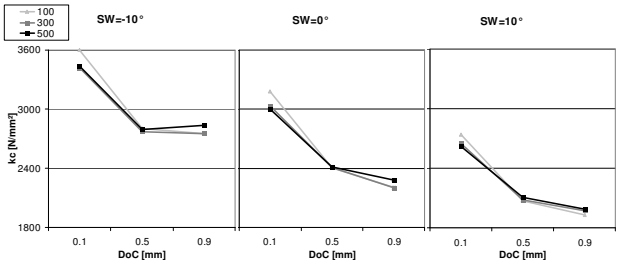


Figure 3: Influence of the tool and cutting parameter on the specific cutting force k_c

It is clear that there is a reduction in the specific cutting force with increasing cutting depth and at higher cutting angles. There is no visual evidence that any significant influence is exerted by cutting speed at this cutting speed range.

Before the results were analysed, the cutting and tool parameters were normalised to -1…0…+1 as follows:

$$x_{DoC} = \frac{DoC - 0{,}5}{0{,}4} \qquad x_{vc} = \frac{vc - 300}{200} \qquad x_{SW} = \frac{SW}{10} \tag{1}$$

The following equation (2) is given as a polynomial regression for the specific cutting force y_{kc}.

$$y_{kc} = 272x_{DoC}^2 - 376x_{DoC} + 58x_{SW}^2 - 390x_{SW} + 32x_{vc}^2 - 12x_{vc} + x_{DoC}x_{SW} + 5x_{DoC}x_{vc} + 36x_{SW}x_{vc} + 2610 \tag{2}$$

The weighting of the factor can be read from the co-efficient of the standardised factor in the polynomial regression. The cutting depth and the rake angle are shown to exert considerable influence on the specific cutting force. The influence exerted by cutting speed and by the interactions among the factors $x_{DoC}x_{SW}$, $x_{DoC}x_{vc}$ and $x_{SW}x_{vc}$ is relatively low.

Wear rate W

In line with the approach used with specific cutting force, Figure 4, shows the graphical analysis of the influence exerted by the input parameters on the wear rate W.

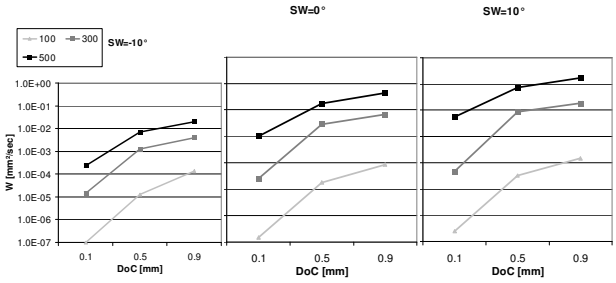


Figure 4: Influence of the tool and cutting parameter on the tool wear rate W

The graphical analysis shows that cutting speed is the main influencing parameter. Any increase in the cutting speed results in a substantial rise in the wear rate. The influence exerted by the rake angle and the cutting depth are also clearly visible. An increase in any of the factors results in a higher wear rate.
These tendencies are reinforced by the value-oriented results of the polynomial regression.

$$y_W = 0{,}003x_{DoC}^2 + 0{,}014x_{DoC} + 0{,}01x_{SW}^2 + 0{,}014x_{SW} + 0{,}014x_{vc}^2 + 0{,}02x_{vc} + 0{,}014x_{DoC}x_{SW} + 0{,}02x_{DoC}x_{vc} + 0{,}004x_{SW}x_{vc} + 0{,}014 \tag{3}$$

Thus cutting speed show the largest coefficient and the coefficients are positive for all factors. In addition to the effect of the factors alone, there are interactions among the factors which affect the output quantities. The cutting depth in

association with the rake angle, for example, ($x_{DoC}x_{SW}$) or with cutting speed ($x_{DoC}x_{vc}$) exerts considerable influence.

Chip curvature radius r_c

Figure 5 shows the graphical analysis of the influence exerted by the chip and tool parameters on the chip curvature radius, which determines the level of cleaning required.

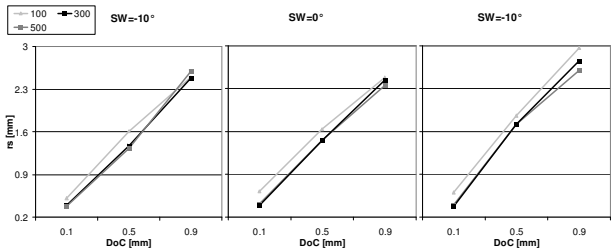


Figure 5: Influence of the tool and cutting parameter on the chip curvature radius r_c

The graphic shows that the dominant influencing factor as far as the chip curvature radius is concerned, is the cutting depth. The chip curvature radius increases with greater depth of cut. There is no evidence that cutting speed or rake angle exert any influence. This is confirmed in the DoE by the relatively high coefficient of the linear influence exerted by cutting depth and the low values of the cutting speed and rake angle.

$$y_{rc} = -0{,}06x_{DoC}^2 + 1{,}06x_{DoC} + 0{,}09x_{SW}^2 + 0{,}1x_{SW} + 0{,}1x_{vc}^2 - 0{,}08x_{vc} + 0{,}06x_{DoC}x_{SW} - 0{,}02x_{DoC}x_{vc} + 0{,}09x_{SW}x_{vc} + 1{,}53 \quad (4)$$

Burr value G

The influence exerted by the input factors on the burr value, which is the determining parameter for the level of deburring required, is shown graphically in Figure 6.

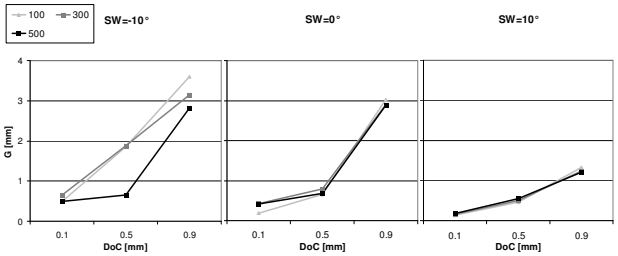


Figure 6: Influence of the tool and cutting parameter on the burr value G

As in the case of the specific cutting force and the chip curvature radius, the influence exerted by cutting depth is the determining factor. The graphical analysis shows a steep increase in the burr value at greater depths of cut, particularly at smaller rake angles.

$$y_G = 0{,}18x_{DoC}^2 + 1{,}06x_{DoC} - 0{,}07x_{SW}^2 - 0{,}62x_{SW} - 0{,}04x_{vc}^2 - 0{,}04x_{vc} - 0{,}39x_{DoC}x_{SW} + 0{,}06x_{DoC}x_{vc} - 0{,}07x_{SW}x_{vc} + 1{,}28 \quad (5)$$

The high influence exerted by the depth of cut effects a high coefficient for the linear influence of the depth of cut in the polynomial regression (5). The combined effect of cutting depth and rake angle is described by the factor $x_{DoC}x_{SW}$. The coefficients of this and of the linear part of the rake angle, are very negative, which shows that the burr value falls sharply as the rake angle increases.

Overall view

As the studies showed, the degree to which the input parameters influence the output quantities, varies enormously. An extensive graphical analysis covering all input and output quantities, would lack clarity and lead to confusion. Here, the value-oriented description of the influencing factor, can be used by the polynomial regression. In the first step, the polynomials must be normalised, since the output values extend from several thousand (specific cutting force) to values approaching zero (tool wear). The normalisation was conducted using the x_0 factor in the polynomial. This value is determined by the average value of the results. The outcomes are listed in Table 1.

	x_{DoC}^2	x_{DoC}	x_{vc}^2	x_{vc}	x_{sw}^2	x_{sw}	x_{DoC} x_{vc}	x_{DoC} x_{SW}	x_{vc} x_{SW}	x_0
y_{kc}	0.10	-0.14	0.02	-0.15	0.01	0.00	0.00	0.00	0.01	1
y_{vc}	0.20	1.01	0.67	0.96	1.01	1.33	0.95	1.31	-0.28	1
y_{sw}	-0.04	0.69	0.06	0.07	0.07	-0.05	0.04	-0.01	0.06	1
y_G	0.14	0.82	-0.05	-0.48	-0.03	-0.03	-0.30	0.05	-0.05	1

Table 1: Normalised polynomial regression

The results (k_c, W, r_s, G) must subsequently be weighted in terms of their influence on the total energy. The results were evaluated immediately in the case of the investigations presented here. When an output quantity such as tool wear, is of particular interest to the process because, for example, tool costs are very high, this output quantity should be more heavily weighted than the other output quantities.
A model for the total energy requirement is obtained by totalling the normalised polynomials. Correspondingly, the resultant polynomial (6) represents the energy equivalent EA for the machining process and thus unites several output quantities in one overall description.

$$y_{EA} = 0{,}25y_{kc} + 0{,}25y_W + 0{,}25y_{rs} + 0{,}25y_G = 0{,}1x_{DoC}^2 + 0{,}6x_{DoC} + 0{,}17x_{SW}^2 + 0{,}1x_{SW} + 0{,}26x_{vc}^2 + 0{,}31x_{vc} + 0{,}17x_{DoC}x_{SW} + 0{,}34x_{DoC}x_{vc} - 0{,}06x_{SW}x_{vc} + 1 \quad (6)$$

The influence exerted by the input quantities (DoC, v_c, SW) on the energy equivalent, can be

determined using the polynomial thus obtained. This is demonstrated graphically in Figure 7.

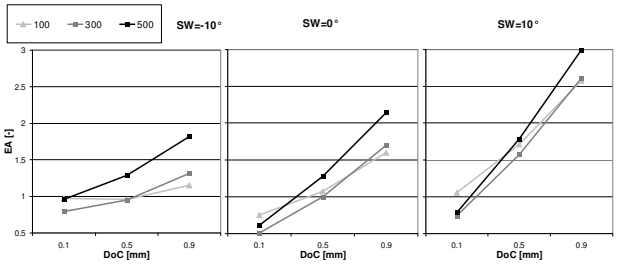


Figure 7: Influence of the tool and cutting parameter on the Energy equivalent EA

The graphic and the value-oriented analysis demonstrate that as cutting and tool parameters increase, there is always a rise in the energy equivalent. In general terms, this means that the energy consumption level is lowest during the process and in finishing and cleaning operations, when the cutting parameters are low and the tool rake is small.
It is the cutting depth followed by the interaction between cutting depth and cutting speed, which exert most influence. The cutting speed also wields considerable influence whereby the quadratic term is relatively high. The influence exerted by the rake angle is much lower than that of the depth of cut and cutting speed but when combined with greater depths of cut, it is not negligible. The interaction between cutting speed and rake angle is the only variable which is low enough to be regarded as negligible.

4. EXPERIMENTAL ANALYSIS OF THE INFLUENCE EXERTED BY MACHINING SPEED ON THE ENERGY FLOWS IN PROCESSES AND MACHINES

The previous chapters focused on the energy-related design of metal cutting manufacturing operations at process level. In the following section, the energy-oriented investigation is extended to the machine and investigated on the basis of the example of drilling into solid material.

4.1 Drilling Tests

The energy flows and the measured variables in tests are illustrated in the following graphic.

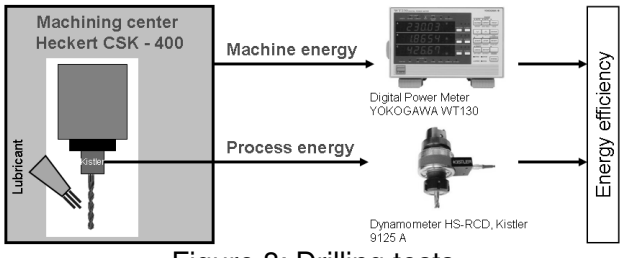


Figure 8: Drilling tests

In the tests, holes Ø7mm … 35mm deep were drilled into a workpiece made of gray EN-GJL-250 cast iron. In contrast to the numerical investigations, the machine capacity and machine energy were recorded as well as the process forces (cutting forces). Machine energy is the term used to describe the electrical energy drawn by the entire machine from the grid. To achieve this, a digital power meter was inserted at the supply connection to the entire machine (with an emulsion coolant system).
In the experimental drilling tests, the resultant energy efficiency levels of tools with various material removal rates Q, were investigated.

	Coated solid carbide drill SC		Coated high speed steel drill HSS	Uncoated high speed steel drill
Material	Solid Carbide		HSS-E	HSS-E
Coating	Multilayer		Multilayer	none
Q [mm³/s]	1684		435	180
Price [€]	31		28	3,30
Cooling	Flooded	Dry	Flooded	flooded

Table 2: Tested drills

All tools were tested till tool life end was reached or until a maximum of 900 holes had been drilled. In the case of flood cooled operations, these were conducted both with emulsion and dry. In dry machining operations conducted using an SC tool, no coolant or lubrication of any sort was used. Turning off the pumps for the coolant equipment results in a reduction of 1.5 kW in the machine power required.

4.2 Results

The results of the tests were summarised to form an energy balance sheet. This is shown graphically in Figure 9. The machine energy and the process energy were compared.

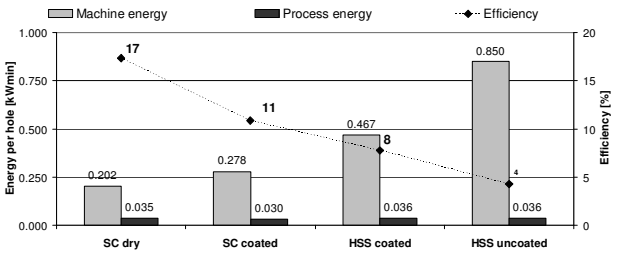


Figure 9: Energy Balance of the drilling tests

The balance shows that even when the machining operation is conducted using high-performance tools, the machine energy is several times higher than the energy used in the process. This ratio deteriorates significantly with falling material removal rate although the level of required process energy rises only slightly. The reason for this lies in the additional machine components which are needed in order to control the machine and the process. It

can be concluded from this that the process time is a key element in the energy efficiency in machining processes.
The smallest amount of electrical energy was taken from the grid in dry machining operations since the coolant pumps were switched off. This results in a saving of 28 % in electrical energy. However this is accompanied by a drastic reduction in tool life.
Ultimately, it can be concluded from the experimental tests that energy consumption at machine level, depends heavily on the material removal rate and that the process forces are therefore of only secondary importance. Although it was possible to achieve energy savings in the process by machining in dry mode, this resulted in increased tool costs and indirect energy consumption in the tool manufacturing operation, which were disproportionately high in relation to the energy saving in the machining process itself. More detailed results are listed by Neugebauer [10]. Gray cast iron can be categorised as completely reliable in terms of chip and burr formation. At low levels of tool flank wear, a very slight, ring-shaped burr forms, which can be regarded to be a minor inconvenience in most applications. It is only when serious tool wear occurs that the burr shape becomes more of a problem. In the case of cast iron, the chips usually break off easily and the chips are very small.

5. PLANNING THE DESIGN OF MACHINING PROCESSES USING NUMERICAL SIMULATION

As demonstrated in the previous numerical and experimental investigations, any increase in the efficiency of machining processes represents a challenge to the manufacturing engineer due to the complexities and the number of influencing factors involved.
A planning design based on empirical models and calculations can result only in a solution in a highly abstract form, which fails to take adequate account of energy-relevant factors such as tool wear, chip and burr shape. The aim must be to bridge this gap using FE-analysis and to permit a comprehensive planning of machining processes. This approach is presented schematically in Figure 10.
The starting point in the design of the process is the pre-selection of a suitable tool. As described in Chapter 4, the aim is to ensure that the resultant machining time is as short as possible. The trend, therefore, is to select high-performance tools. It is vital to conduct FE calculations in order to determine the characteristic energy and resource consumption quantities prior to making a final decision as to the most suitable tool.

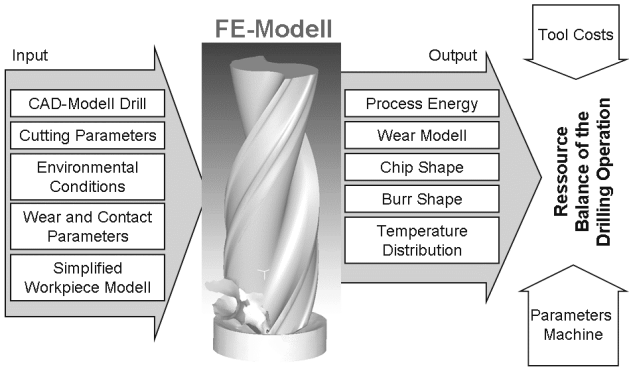


Figure 10: Approach to planning resource-efficient processes using FEM

In future, it would be useful to introduce a standardised energy equivalent to permit the tool to be rated in terms of energy requirement at the point of manufacture.
In the FE model of the process, key parameters such as the cutting parameters for example and coolant conditions can be tested in order to determine the influence they exert on energetic variables, the secondary products and on tool wear. The machine data must be included in the overall balance for the process. One of the first steps in this process would be to specify the base load, describing the power required by the machine when the spindle with the machine tool is rotating and ready for work but not in engagement. The cutting capacity and the feed capacity required are determined via FE simulations, permitting the power requirement in machining time to be calculated.
In initial calculations, this approach was tested in relation to drilling operations conducted on 42CrMo tempered steel. An overview of the initial results is given in Figure 11.

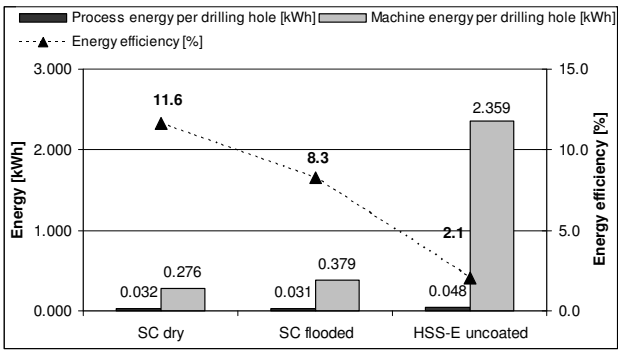


Figure 11: Numerical determined energy balance for drilling

It is apparent, that as in the experimental drilling tests, machining at high machining speeds results in an improved energy balance. It is also

clear that the machining speed and therefore the energy-efficiency in relation to the volume of material removed, falls with increasing material hardness.
This basic model must be further developed in subsequent steps in order to extend the capacity to specify consumption of electrical energy to cover the resource machine tool, energy-intensive secondary products and coolant requirements.

6. CONCLUSION

The investigations outlined here, show that FE models can be used successfully to reduce energy and resource consumption in machining operations. Consequently, existing processes can be optimised and new processes can be designed more efficiently in the planning phase prior to implementation within a manufacturing environment
It became apparent in the course of analysis conducted at process level, that a combination of statistical test planning and FE calculations permits the influencing factors to be evaluated in value-oriented terms and in combination with one another, which increases both the level and clarity of detail provided. The simulation results still require verification via experimental analyses.
Additional experimental investigations included the machine level with process-dependent machine efficiency as well as process energy. This demonstrated that the machining time and the material removal rate are of key importance. The demand for higher material removal rates stands in direct conflict with the demand for smaller cutting parameters, lower levels of tool wear and low requirement for finishing work. This provides an indicator as to the aim of future studies. It is vital to ensure that energy and resource-efficient process design including all relevant factors can be conducted at machine and at process level in the planning phase, which includes all relevant factors.
Numerical modelling is the key factor in future developments.

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