Productivity improvement within machining technology through advanced theoretical methods

New model points the way for practice: Cost savings up to 71% possible

Abstract

The determination of cutting data in machining technology is largely based on empirical means. Theoretical models have brought merely minor benefit till now. The complexity of machining technology prevented a successful derivation of cutting data from results of common model calculation.

The present paper, which was conducted within the scope of a study of the University of Applied Sciences Upper Austria, presents a novel theoretical method. This method enables a practical description of the machining process and consequently to calculate the optimal cutting data.

Cutting tests with milling tools on two different steels showed the beneficial interaction of theoretical calculation and ideal practical machining. It was verified, that the cutting parameters derived from the model, significantly reduce the wear of tools and cut the imputed costs of processing up to 71%.

Improved tools and ongoing research of machining increase continuously the cost-effectiveness of the process. The focus of development lies in the optimisation of tool geometry and the use of new, respectively concerning coating, in common cutting materials. This approaches are usually associated with considerable additional cost and, if seen individually, allow only a minor competitive advantage for producers.

In this paper originates from a market with state of the art tools and concentrates on the optimisation of the machining process. It is assumed, that with already developed tools better characteristics regarding wear and productivity could be achieved as common in current applications. This means, the profitability of process can be improved significantly on the basis of fundamental research of cutting parameters. The objective is to find an alternative to expensive coating- and material developments.

The economical importance of a continuous increase in productivity of the machining process is clearly evident when considering that the machining process covers the major part of industrial production. Activities in development as well as innovations within this field of manufacturing engineering will contribute to a great extent to ensure the competitiveness of industrial production in high-wage economies in the future.

Theoretical Model

The present paper is based on the theory developed by *E. Schäpermeier* [1]. It describes in the course of a new approach the kinematic and thermodynamic coherences of the machining process and enables a mathematical optimisation of cutting parameters.

The theoretical and practical work is achieved by milling because it represents beside turning one of the most important machining processes.

As tools common carbide cutting materials as uncoated version and as titanium nitiride coated version are used.

Basis of the theory of *E. Schäpermeier* is the amount of heat which emerges during the machining process. Its distribution, flow and influence on the material (workpiece) is linked to kinematic conditions. With this approach *Schäpermeier* creates the possibility to analyse the process on the basis of physical laws. [1]

The importance of high temperatures for the forming of material is known from material sciences. Furthermore, high temperatures contribute primarily to reduce forming forces [2,3]. Due to the fact, that during machining high temperatures as well as high degrees of deformation occur, it's obvious that higher temperatures lead to improved conditions during separation of the material.

Because of scientific studies in machining (Kronenberg und Vieregge nach [4]) it's know, that a temperature field (fig. 1) develops within tool and workpiece, with it's temperature maximum at the cutting face [4, 5].

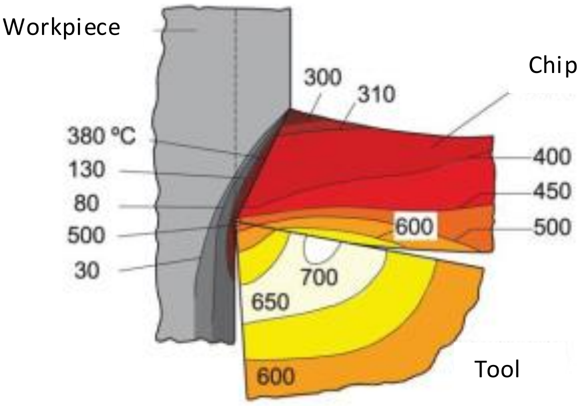

Figure 1: Temperature distribution during machining process [5]

The expected maxium temperatures for steel materials are around 1100°C. If such peak temperatures are achieved, a major defortification could be expected in the shear zone. Meaning, the more energy is transformed into heat during machining, the higher the temperatures and subsequently the better the process operation. The maxium temperature is only limited by melting temperature of the material and the temperature hardness of cutting material.

Schäpermeier [1] basically depicts in his publication *„Zerspanungsoptimierung beim Drehen von Stählen"* the contact relation of a chip with the cutting edge as a function of temperature. Due to the formation of the chip as a flowing chip at higher temperatures, the contact length increases over temperature as a smooth chip emerge. A larger contact length leads to an increase in cutting forces. However, at higher temperatures a considerable drop of yield point occurs which implicate one the one hand a large contact length but on the other hand a distinct decrease of resulting forces caused by the decreased yield point. As a result the course of forces can be classified in three areas as follows [1].

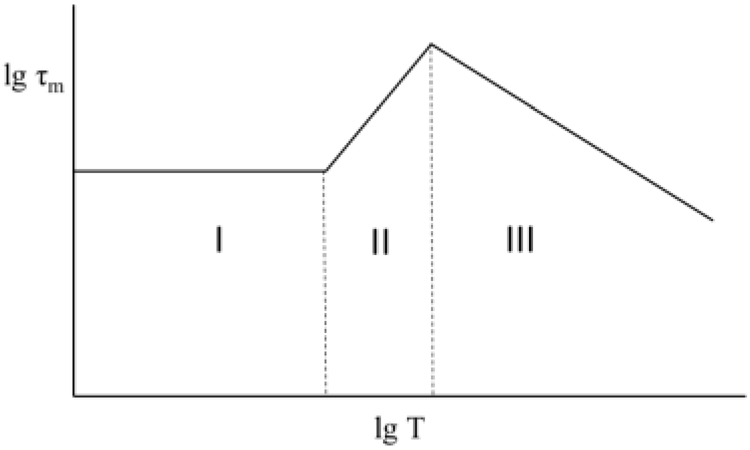

Figure 2: Dependence of shear strengh over temperature according to [1]

In area I the necessary force respectively shear strength remains constant [1]. The second area is characterised by an growing contact length which leads to increased tensions. *Schäpermeier* points out that this area is largely influenced by formation of build-up edges and thus has to be avoided. [1] Within the third area forces are declining as the temperature exerts a significant influence on the yield point of the material.

Schäpermeier [1] depicts following conditions for optimal machining: For optimal usage of the applied tool it must be tried to achieve that kind of temperature level so the machining is performed in area three. In this area forces at the cutting edge as well as adhesion tendency of the material are in their optimal range [1]. Hence, the crucial factor is the temperature of the tool and the material.

However, a measurement of the temperature is technically difficult. Therefore the attempt is being made to determine the temperature out of the cutting conditions. To achieve this *Schäpermeier* makes use of the so called similarity mechanics. This allows to describe complex relations like machining process with the help of dimensionless factors [1].

Schäpermeier specified the Peclet number to describe the influence of temperature and heat quantity of the machining process. This number is mainly used in thermodynamics to describe temperatures within a temperature boundary layer [1, 6].

The Peclet number is especially dependend of the cutting speed, chip thickness and thermal diffusivity of the material. *Schäpermeier* was able to divide the machining areas according to the peclet number and due to this specific values was found which define the limits of the areas. The transition from area one to two was defined with Peclet number 7 whereas area 3 starts with a Peclet number of 13 [1].

For the cutting parameters used in this paper the necessary peclet number of 13 was assumed to achieve the favourable conditions of area three.

The results of the calculation provide the forward- and cutting speed which are solely dependent of material property, thermal conductivity, Peclet number and geometric conditions. Chip thickness is calculated through present geometric conditions.

Thermal conductivity is a crucial variable within the calculation. The higher the hermal conductivity, the faster the dissemination of the temperature field in the chip. In other words, to achieve a certain temperature at the chip underside the drained of heat within the chip has to be compensated by process heat generated during machining. That’s the reason why cutting parameters have to be increased in case of a high thermal conductivity, so enough heat can enter the contact zone. Due to this step the desired temperature can be achieved and maintained.

Beside *Schäpermeier* other authors such as *W. King and F. Klocke* [4] prove the decisive influence of temperature on the cutting process. They investigated the wear depending on cutting temperature and worked out that only with a certain combination of forward speed and cutting speed the desired aim of minimal wear can be achieved.

Thus, to be able to work with low cutting speed and simultaneously low wear the forward speed has to be increased. Meaning, to reach the necessary temperature for the optimal process which can’t be achieved anymore due to decreased cutting speed, the forward speed must be increased [4].

Experimental investigation

The machining trials was carried out on a HSC milling machine produced by Niigata company.

The workpieces was choosen out of different classes of steel to estimate the optimisation process in a proper way. An unalloyed tempered steel C45E (1.1191) and the corrosion resistant X5 CrNi 18-10 (1.4301) was investigated. Both steels was used as massive 250x150x150mm Blocks.

As milling tools coated and uncoated solid carbid tools was choosen. The coating is titanium aluminum nitride as multilayer version. A cutter diameter fo 6mm was choosen.

A abrasion curve was recorded to compare and evaluate the cutting parameters. The wear was determined by measurement of the flank wear (wear marks = VB) The measurement of the wear marks and load of the cutting face was carried out with a stereomicroscope SNZ-168 of the company Motic.

With a scanning electron microscope (EDX) Vega of the company Tescan further investigations of the milling tools were made. EDX images enabled visual tracking element distribution and chemical composition of near-surface areas.

All machining trials was was carried out as climb milling. As lifetime criteria a wear mark of 0,2mm and an maximum shaping length of 25m was defined.

Zwei Versuchsreihen wurden gefahren, wobei für jede Reihe zwischen Hersteller- und optimierten Parametern und den zu zerspanenden Materialien variiert wurde. Alle Versuche wurden als Trockenspanversuche durchgeführt.

Two test series have been done, where every series was varied between manufacturer- and optimised parameters and milling material. All trials was done as dry-chip trials.

Results of calculation

The ideal range for material C45E resulted in increasing the rotation of about 1.7 to 2.6 times and in rising 16 times the forward speed. Thereby the material removal rate is increased by approximately 7 times.

For coated tools, the number of revolutions must be increased by 2 to 3 times and the forward speed has to be 15 times higher compared to manufacturer’s instructions to achiev ideal conditions. Thereby the material removal rate is increased by approximately 6 times.

For material X5CrNi 18-10 optimal conditions are established if rotation is increased by 1.7 to 2.1 times and forward speed by 12 to 15 times compared to manufacturer’s instructions. Thereby the material removal rate is increased by approximately 13 times.

Coated tools require about 2 to 2.5 times higher revolutions and 11 to 13 times higher forward speed. These parameters cause an growth of material removal rate of about 11.5 times.

Calculations shows, that due to optimisation ambitious cutting parameters could be applied. All parameters are summarised in table 1 and table 2.

Table 1: cutting parameters C45E

	type of milling tool	n	v_f	a_e	a_p	Q_w
		[1/min]	[mm/min]	[mm]	[mm]	[cm^3/min]
manufacturer's parameters	uncoated	6,048	387	1.19	6.0	2.8
	coated	10,080	847	1.19	6.0	6.0
optimised parameters	V1 uncoated	15,731	6,279	0.50	6.0	18.8
	V2 uncoated	12,892	6,279	0.50	6.0	18.8
	V3 uncoated	10,044	6,279	0.50	6.0	18.8
	V1 coated	31,462	12,558	0.50	6.0	37.7
	V2 coated	25,855	12,558	0.50	6.0	37.7
	V3 coated	20,088	12,558	0.50	6.0	37.7

Table 2: cutting parameters X5 CrNi 18-10

	type of milling tool	n	v_f	a_e	a_p	Q_w
		[1/min]	[mm/min]	[mm]	[mm]	[cm^3/min]
manufacturer's parameters	uncoated	3,183	178	0.50	6.0	0.5
	coated	5,305	382	0.50	6.0	1.1
optimised parameters	V1 uncoated	6,539	2,133	0.50	6.0	6.4
	V2 uncoated	5,340	2,133	0.50	6.0	6.4
	V3 uncoated	6,746	2,666	0.40	6.0	6.4
	V1 coated	12,834	4,186	0.50	6.0	12.6
	V2 coated	10,480	4,186	0.50	6.0	12.6
	V3 coated	13,240	5,232	0.40	6.0	12.6

Wear of machining with optimised parameters

For investigation of wear behaviour the wear marks (VB) of tools over shaping length was measured

Figure 3 depicts how wear develops at the cutting edge of applied tool and how the measurement takes place. The figure after process indicates that the wear hasn't equally developed over the whole cutting edge. For comparison reasons the maximum VB was looked up and measured on all four cutting edges The values were averaged and entered in wear curves.

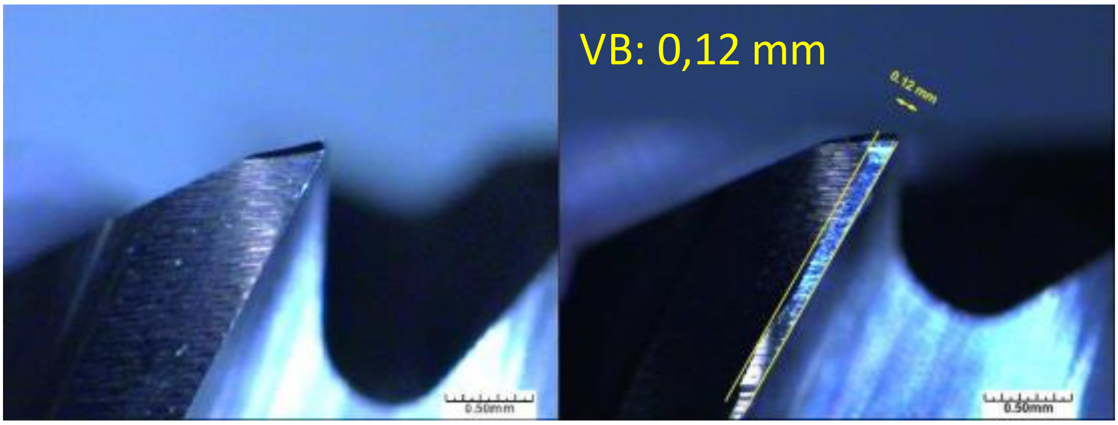

Figure 3:Comparison of cutting edge before and after processing, 30x

Trials C45E with uncoated tools

Figure 4 indicates a comparison of VB of uncoated tools after process with manufacturer's parameters and optimised parameters. It can be easily seen that the wear is significantly smaller with optimised parameters. While the lifetime criteria is already surpassed with manufacturer's paramters, with optimised parameters a 65% smaller VB was determined. Meaning, with higher cutting paramters decreased wear was found.

Within figure 4 all wear curves of the trials with material C45E and uncoated tools are indicated. Every wear developed linear with sufficient approximation.

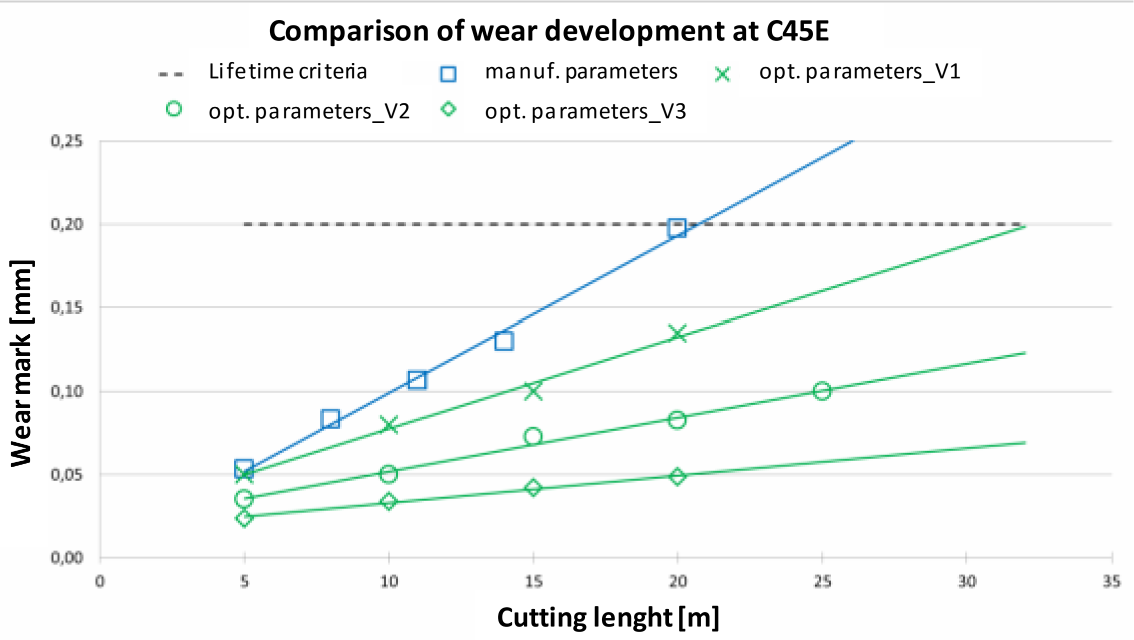

Figure 4: Wear development at C45E, uncoated tools

It is clearly visible that all tests done with optimized parameters show smaller wear than the experiments with conventional manufacturers parameters. At 20 m cutting length the difference is evident. While tools running on manufacturer's parameters already surpassed the lifetime criteria of 0.2 mm, tools running on optimised parameters showed wear marks around 0.14 mm to 0.05 mm. In other words, through defined optimisation wear can be reduced up to 75%.

Trials V1 and V3 weren't able to reach the planned 25m cutting length. Tool V1 broke after a length of 24 m and tool V3 after 21 m. Despite these breakings every tool was longer in use compared to tools running on manufacturer's parameters which reached theire lifetime critera at 20 m.

Trials C45E with coated tools

No significant wear was detected at coated tools with the stereomicroscope. Because of this a EDX Mapping of cutting edges was carried out with a scanning electron microscope

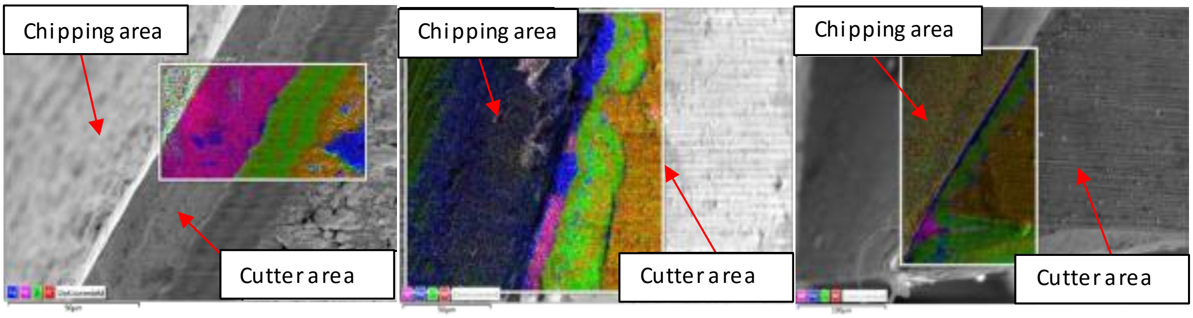

Figure 5: SEM pictures of cutting areas of coated tools, left manufacturer's parameters, middle optimised parameters V2, right optimised parameters V3, after 25m cutting length

Based on figure 5 significant difference can be detected between the cutting edges running on optimised- and manufacturer’s parameters (Distribution of elements according to figure 5: Fe blue, W pink, Ti green, Al red). With manufacturer’s parameters the whole layer is already attrited and due to this carbide substrate can be identified. In the case of the tools running on optimised parameters show only small spalling occure and are largely intact.

In summary, optimised parameters are of advantage for the operation of coated cutters because the coating is able to fully exploit it’s potential under this conditions. In addition, it has to be mentioned that no breakage of tools has taken place.

Trials X5 CrNi 18-10 with uncoated tools

The wear development of corrosion-resistant steel X5 CrNi 18-10 behaved similarly to C45E.

Comparable with the results of material C45E, even with corrosion-resistant steel smaller wear marks was measured if optimised parameters was compared to manufacturer’s paramters. However, the differences were not as great as with C45E. The wear reduction potential lies at about 13 to 22% at 15 m cutting length.

The comparison of VB had to take place at a cutting length of 15m because the tool became inoperative at 20 m according to manufacturer’s parameters. Within the flutes, chips welded and made the tool inoperable (fig. 7). This led to blocked flutes and because of this no further processing was able. A reliable determination of the wear wasn’t possible anymore under such circumstances. With respect to this circumstances no problem at all occurred with tools running on optimised parameters. At all trials the full cutting length of 25m could be reached. Beside this, there was no breakage of tools like it occurred with C45E. Without any doubt these facts already prove that the optimisation offers advantages.

Figure 6 displays wear curves of uncoated tools with material X5CrNi 18-10.

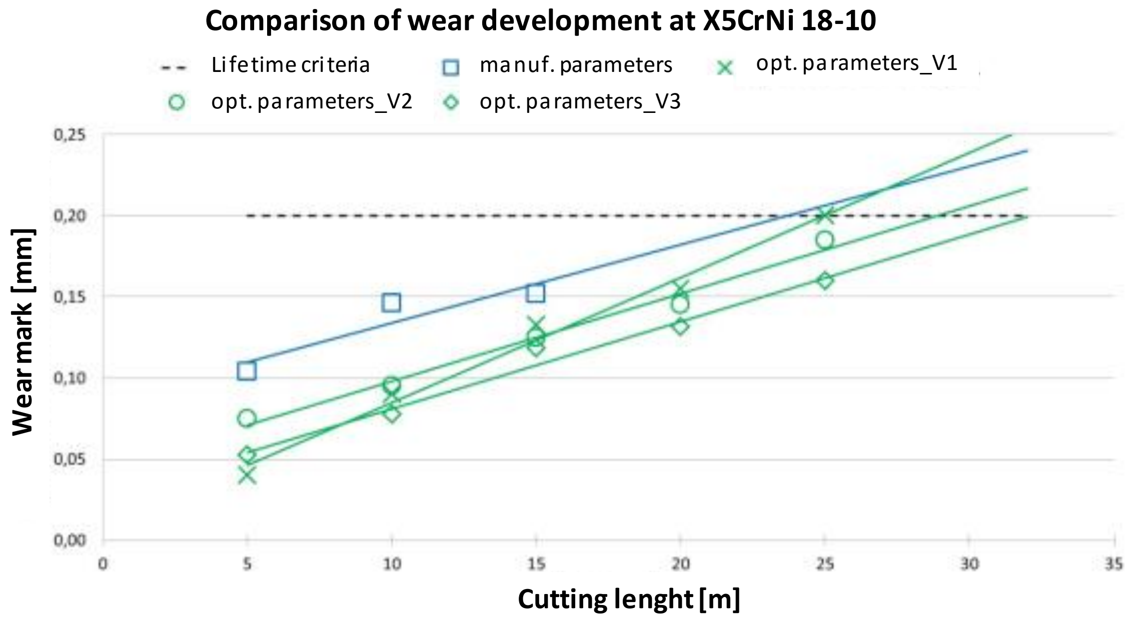

Figure 6: Cutting development at X5 CrNi 18-10, uncoated tools

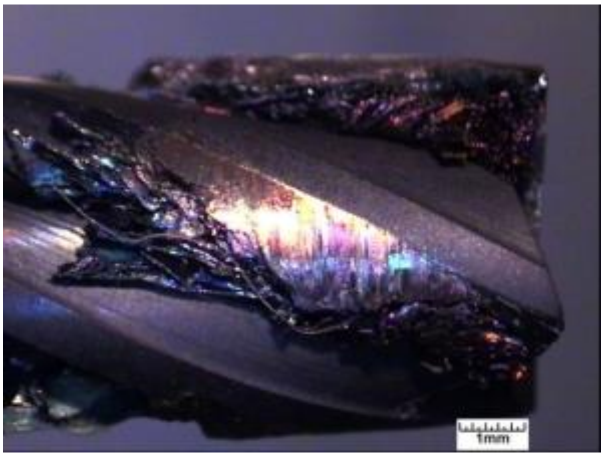

Figure 7: Molten chips in flutes, manufacturer's parameters, cutting length 20m, 10x

The values for wear marks are in general a little bit higher compared to material C45E and the differences between manufacturer's parameters and optimised parameters are smaller than with C45E

Trials X5 CrNi 18-10 with uncoated tools

Also the cutting areas of coated tools tested with material X5 CrNi 18-10 were investigated with scanning electron microscope and EDX mapping. In figure 8 can be seen that no significant spalling or abrasion occurred at the cutting area for both tool group with manufacturer's and optimised parameters. A significant difference can be identified at the chipping area. With manufacturer's parameters the coating is already completely gone wheras with optimised parameters no indicators for spalling or abrasion can be seen. If a coating is still existing can't be clarified with this images.

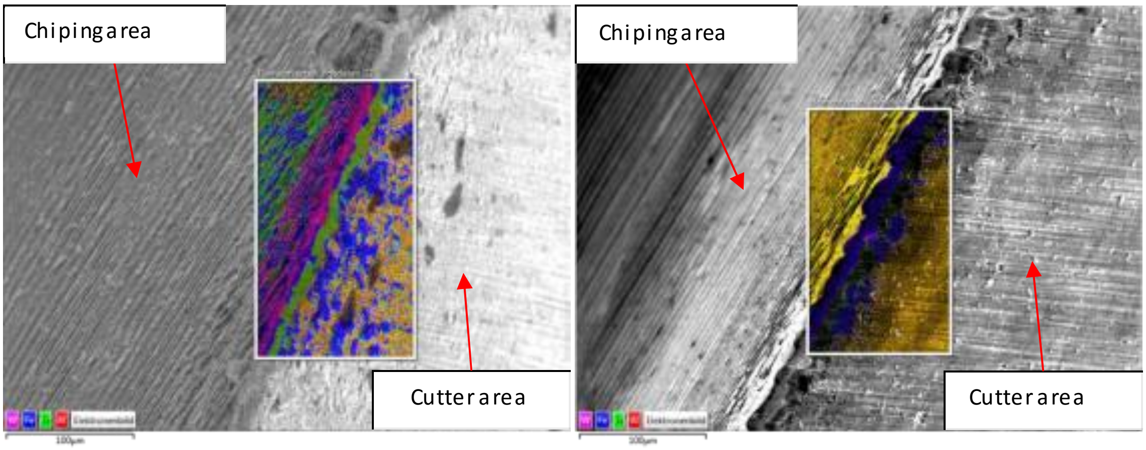

Figure 8: SEM pictures of cutting areas of coated tools, left manufacturer's parameters, right optimised parameters V3, after 25m cutting length

Chips

Chips C45E uncoated tool

In table 3 chips of trials with different manufacturer's parameters and with optimised parameters of material C45E are compared. It can be easily seen that different tempering colours occoured. Chips out of trials with manufacturer's parameters exhibit already discoloration at less cutting lengths. With increased cutting length obvious coloring can be identified. Chips are already blue black at the end of the cutting length. This is valid for up- and underside of the chip. With the optimized parameters, the chips showed from the top until the tail no strong discoloration. Only the downside of the chips showed discoloration.

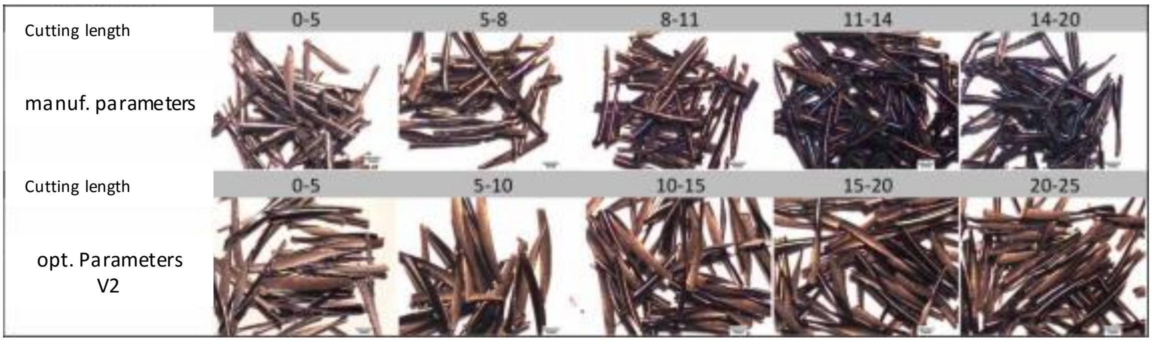

Figure 9: Comparison of chips with different cutting length

Chips C45E coated tool

A similar picture can be seen with coated tools. In experiments with factory parameters the chips are continuously blue colored wheras chips originated from trials with optimised parameters only colored downside. The coloring is Compared to the trials with uncoated tools not that intense. Meaning, the chips weren't heated enough to dye the complete surface blue.

The increase of discoloration with cutting length can be investigated with coated tools and factory parameters as well.

Chips X5 CrNi 18-10

The surfaces of chips originated from coated and uncoated tools respectively factory parameters and optimised parameters, doesn't show distinct differences like as seen with C45E. This was expected, since X5 CrNi 18-10 doesn't tend as strong to oxidation like tempering steel.

In general it can be said that the machining process releases more or less heat depending on choosen cutting parameters. This heat drains off via the chips and causes a discoloring of the surface, a oxidation layer. The qualitative differences of manufacturer's parametes and optimised parameters correspond with the choice of cutting parameters. The observations are consistent with perceptions of the model.

The unequal characteristic of discoloration within a chip are probably coused of temperature gradients within the chips.

Profitability of optimisation

As optimisation happens solely through the choice of cutting parameters, meaning tools and milling machine stays the same and no additional expenditure arise, savings results only from calculatory unit costs namely machine-hour rate and price of tool. Thus it's possible to reduce the comparison to the cutting time.

Results show that optimisation through adaption of cutting parameters has a significant influence on total costs of manufacturing (fig. 9).

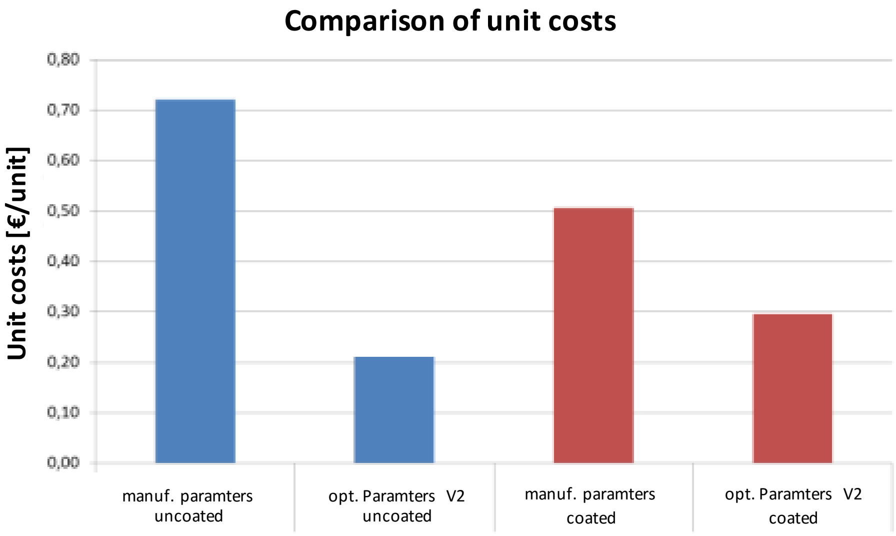

Figure 10: Comparison of costs in dependence of choice of cutting parameters

A optimisation of costs up to 71% is possible with uncoated tools and of about 42% with coated tools. Looking at the comparison it can be seen that the cost savings are substantially higher with uncoated tools. This is attributed to higher tool costs due to tool life. But in this case tool lifespan is clearly underestimated as coated tools are able to cover longer shaping length.

Discussion

Resulsts of calculation

The calculation resulted in completely different cutting parameters as common till now. Progess can't solely be seen in the statement of a factor to increase the forward speed. Instead it must be seen as a combination of an increment of forward speed and cutting speed.

From calculation derived increment of cutting speed is only possible because of a fundamental understanding of the machining process, an unconventional analysis and particularly due to the consideration process heat.

The unique combination and correlation of cutting speed and forward speed presents the substantial innovation in the presented calculation method.

The extend of improvement is remarkable. Forward speeds should be increased up to 16 times to achieve optimal conditions. An increase like this wouldn't be imaginable with convetional factory parameters.

Out of the new understanding of the process it can be realised how the chip thickness is modified with a combination of values for cutting speed and forward speed. This offers substantial advantages. A small chip leads to enhanced friction between tool and workpiece which leads to force backs and undefined states of machining. The calculated parameters offers more reserves regarding the chip thickness. In this case chip thickness is the key to success. Therewith machining performance can be increased in combination with a safe process.

The practical application of the presented method might experience difficulties as it wasn't common up till now to undertake such fundamental calculations and to deal with physical values like thermal diffusivity and Peclet number.

Wear

Regard wear significant improvements have been observed with material C45E and X5CrNi 18-10. All trials done with optimised paramters showed less wear compared to trials with manufacturer's parameters. Despite a gain in performance capability less wear was observed. This make the optimisation economically very interesting because great improvements can be achieved with available tools opposite to conventional methods of optimisation.

The statement that higher cutting values and same milling paths leads to less wear can't be understand in the first moment. In literature it is said that an increase of cutting speed comes along with more wear [7, 8]. The described theory concentrates primary on forward speed and chip thickness. Literature refers to an improvement of machining if chip thickness is increased because shearforce is diminished [7]. Moreover, a higher forward speed in connected with higher temperatures which infuences the wear behaviour in a positive way [4].

Thus, an optimimsation in the course of chip thickness respectively forward speed represents the most effective approach to improve the machining process. Due to the fact that chip thickness is dependent on kinematic circumstances an optimisation has to be controlled over the values v_c *and* v_f

Chips

When comparing the chips of different trials it can easily seen that differences were present during machining. Is was proven by *S. Zhang* und *Y. B. Guo* [9] that the more blue and darker chips are oxidised the higher the temperature on the surface of the chip has been. Different tempering colors showed that temperatures have been of different magnitude. In the book *„Zerspantechnik" ofE. Paucksch et.al.* [7] and *Satish, Chinchani-kar* and *S.K. Choudhury* [10] it is noticed that a higher cutting speed as well as a higher forward speed leads to higher temperatures.

From this it can be said that tempering color, tint, intensity and distribution on the chip surface are defined by local and temporal generation of process heat as well as thermal diffusivity.

Due to the very high velocities of optimised parameters temperatures aren't able to distribute quickly and thus chips aren't heated enough to establish tempering colors.

The temperature distribution velocity is limited by material properties. This is the main reason why there are partially or none oxidation of chips made with optimised parameters.

In summary a investigation of tempering colores can be seen as means of study for the targeted steering of the process temperature. During optimimsation it will be necessary to find a tradeoff between wear and speed. Less wear leads to low temperatures without high velocities in distribution to reduce the strength within the chip.

Meaning a sufficient wear is necessary to optimise temperatures for machining.

Profitability of optimisation

Profitability calculation depicts that productivity can be substantially increased with optimised parameters. Because of very high forward speeds time per workpiece drops tremendously which reduces the costs per unit. As a consequence the availability of the machine is invreased. If higher production is requested investments in new machines are not necessary

Tool lifetime was calculated on the basis of cutting lengths. In the case of coated tools maxiumum values weren't achieved as the trials ended at 25 m.

With optimised parameters coated tools would have managed substantial higher cutting length because the coating was still intact. Because of this the potential of coated tools is still underestimated.

This case is similar with uncoated tools. The tool running on optimised parameters hasn't reached the wear defined by the lifetime criteria. This means a longer lifetime can be expected and thus a decrease in costs.

However, with every optimisation it has to be thought about if process safety is still given. Set-up time due to tool breakages shouldn't consume the time savings gained through the application of optimised parameters.

The big advantage of this optimisation lies within the application of the same tool. This means no new and expensive tools have to be purchased for the improvement.

Summary

The results of the presented work show clearly that common used tools enables a more profitable machining if optimised parameters are used which are calculated according to a novel approach based on kinetic and thermodynamic theories.

The optimisation of machining with calculation offers an alternative way apart from common cost intensive developments in tool coatings and cutting edge geometrics. It shall be possible to achieve substantial deveopments in productivity with given tools and state of the art machinery

To examine the potential of the theoretical approach machining trials were carried out. Representative for machining processes milling was choosen.

Results show that the theory has a big potential. Cutting parameters and especially the forward speed could be increased dramatically. Optimisation of chip thickness offers a wide range for process steering. A sufficient chip thickness offers andvantages in economics and wear.

With the help of a spezified chip thickness the wear can be influenced and loads are shift to cutting areas and tool areas. This is a novel kind of stearing and has indeed potential to be practically applied.

The profitability assessment shows cost savings because of substantial decreased process time.

Every optimisation project has to find a tradeoff between sufficient process uncertainties and achievable cost savings. The feasibility of such optimisations rely on machinery to achieve the necessary rotations and forward speeds.

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