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Energy balance of the orthogonal cutting process

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Abstract The objectives of this research were to estimate energy quotas during orthogonal machining of medium density fiberboard (MDF), to investigate the extent to which input energy is utilized during pure cutting, and to determine how much energy is dissipated in other unintentional phenomena which accompany the machining process. The effects of cutting speed and feed rate on the energy balance were also investigated.

The experimental results show that effectiveness of the cutting process mostly depends on the efficiency of the electric motor. Cutting efficiency decreases dramatically when the load on the electric motor is less than 50% of the nominal torque. The amount of pure cutting energy increases significantly with increasing cutting speed. Cutting efficiency reaches 68% under machining at a cutting speed of 30 m/s. The most significant undesirable phenomenon accompanying orthogonal cutting is thermal output, which can reach 28% of the input energy. Values for vibrational and noise energy emitted during machining of MDF are insignificant.

Energiebilanz beim rechtwinkligen Fräsen

Zusammenfassung Ziel der vorliegenden Arbeit war es, die Energieanteile beim rechtwinkligen Fräsen von MDF- Faserplatten zu schätzen und zu untersuchen, welcher Anteil der aufgewendeten Energie für den reinen Fräsvorgang verbraucht wird und wieviel Energie durch andere unbeabsichtigte Nebenerscheinungen beim Bearbeitungsprozess verloren geht. Weiterhin wurde der Einfluss der Frägeschwindigkeit und des Vorschubs auf die Energiebilanz untersucht. Die Versuchsergebnisse zeigen, dass die Effizienz des Fräsprozesses hauptsächlich von der Leistung des Elektromotors abhängt. Die Fräseffizienz verringert sich dramatisch, wenn der Elektromotor zu weniger als 50% seiner Nennleistung ausgelastet ist. Mit zunehmender Frägeschwindigkeit steigt auch die zum reinen Fräsen benötigte Energie deutlich an. Bei einer Frägeschwindigkeit von 30 m/s wird eine Fräseffizienz von 68% erreicht. Die bedeutendste unerwünschte Begleiterscheinung während des rechtwinkligen Fräsvorgangs ist die Wärmeabgabe, welche 28% der Energiezufuhr erreichen kann. Die Werte für Vibrations- und Geräuschenergie, welche bei der maschinellen Bearbeitung von MDF-Faserplatten auftreten, sind unerheblich.

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1 Introduction

Machine cutting is a very complex process and consequently, accurate control of machining requires knowledge of all phenomena occurring during processing. From the technical viewpoint two different types of phenomena which occur throughout machining process can be distinguished, there are suitable phenomena when the outcome is compatible with our expectations and unsuitable phenomena when the results are undesirable, but sometimes unavoidable. In the case of woodworking, the desirable effect of cutting is to remove superfluous material to obtain elements with preplanned shape, dimensions and surface smoothness. However, undesirable phenomena such as noise, vibrations and heat generations also occur during machining.

Many studies have been made of cutting forces, vibration, heat generation, noise and acoustic emission during woodworking. However, studies of full energy balance during cutting have not been reported. Machining control systems using acoustic emission signals have been developed to produce desired surface roughness by automatic control of the workpiece feed rate for routing (Tanaka et al. 1997) and sawing (Tanaka et al. 1993). Acoustic emission signals have also been used to detect tool wear (Lemaster and Tee 1985, Murase et al. 1998, Tanaka et al. 1992). Ko et al. (1999) reported studies concerning cutting force progress during machining of medium density fiberboards. The above studies investigated the relationship between cutting distance, feed rate, tool geometry and cutting forces during orthogonal machining of MDF. The problem of temperature of the machined surface has also been examined (Sokojowski and Gogolewski 1999). In addition, the use of vibration, acoustic emission, power consumption and machined surface temperature for on-line monitoring of the cutting process have been proposed.

The purpose of this study is to advance understanding of desirable and undesirable psychical phenomena and the energy distribution during orthogonal cutting. In particular, the specific objectives of this research are to: 1) determine energy quotas during orthogonal machining of MDF; 2) to investigate how input energy is utilized for pure cutting and how much is dissipated by unintentional phenomena; 3) to establish how the energy balance changes during machining at various cutting speeds and feed rates.

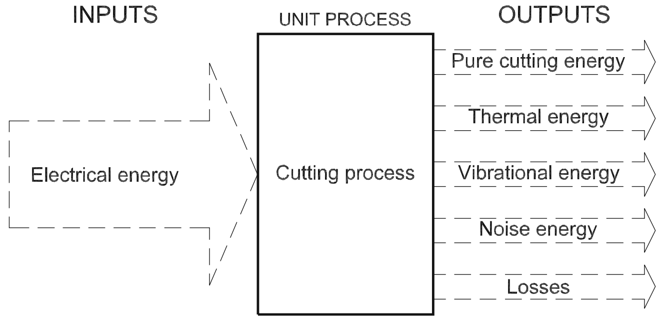

Fig. 1 Inputs and outputs of the cutting process
Abb. 1 Energiezufuhr und Energieeingabe beim Fräsen

2 Experimental procedures

2.1 Cutting conditions

Cutting tests were conducted using a CNC router equipped with an electronic control system for regulating the cutting speeds and feed rates. The tool used for the experiment was a router bit 30 mm wide, made of tungsten carbide. The wedge angle, rake angle and clearance angle of the tool were 56, 18 and 16 degrees, respectively. Machining tests were performed at cutting speeds of 1, 3, 5, 10, 20, 30 m/s and feed rates of 0.1 and 0.2 mm/rev. The workpiece (spindle) rotation rate was adjusted each time to obtain the desired cutting rate. All tests were performed using standard configuration for wood machining tests that is, machining across the peripheral surface of a disk, which comprises orthogonal cutting. The workpiece for the experiment was medium density fiberboard (MDF) with a moisture content of 8%–10%, specific gravity of 0.73 and thickness of 9 ± 0.2 mm. The workpieces used in this study were disks with initial diameters of 300 ± 0.5 mm. The disks were fastened in special a clamp mounted on the machine's spindle. Every cutting test was performed six times.

2.2 Measurement method

Every machining process requires the provision of mechanical energy. The mechanical energy, which consists mainly of rotating movement, is obtained using electric motors of various types. Electricity is chiefly used as the energy form to drive the motors. This is the system energy input. As mentioned above, the cutting process is conducted with the aim of separating unnecessary wood mass from the workpiece and to create a finished element with established shape, dimensions and surface smoothness. The sole goal of the cutting process is mechanical change in the machined material. In this paper, mechanical changes such as removal of superfluous material during machining is called "pure cutting". Undesirable phenomena including heat generation, noise and vibration also occur during machining. The energy inputs and outputs for the cutting process are shown in Fig. 1. A number of sensors and apparatus were used to calculate input and output energies in these experiments, as shown in the schematic diagram of the experimental setup (Fig. 2). The signals from all sensors were transferred through several amplifiers and low-pass filters to a Personal Computer using an Analog-Digital converter.

All inputs and outputs energy flows to and from the system must be measured to make an energy balance. Electrical energy consumption as an input was measured and calculated by power-meter as a product of instantaneous power consumption and length of duration. The value of the electrical energy consumed by the main and feed electric motors was calculated as the difference between energy requisitions by the CNC machine during the tests and energy consumption during stand-by.

Pure cutting energy is one component of the whole cutting process, and is the main aim of the machining. The larger the proportion of pure cutting energy in machine cutting, the more proper and efficient the cutting process is. In this experiment the pure cutting energy was calculated based on cutting forces and cutting distance. Figure 3 shows parallel, normal and resultant cutting forces during orthogonal machining. Machining where the tool edge is perpendicular to the feed direction does not cause any other force components other than parallel and normal. Measurement of the parallel and normal cutting forces plus cutting distance permits calculation of pure cutting energy.

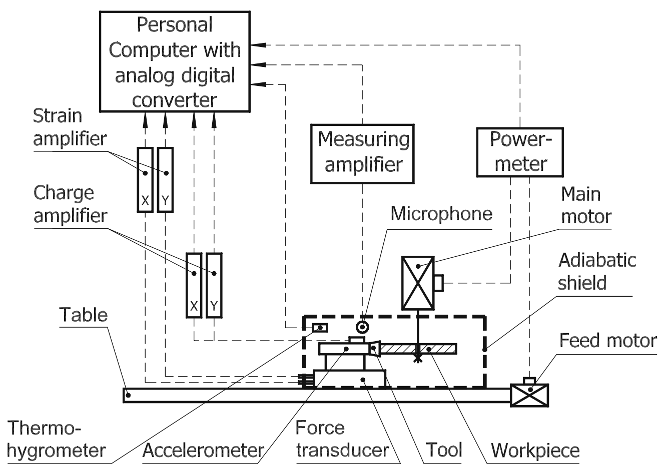

Fig. 2 Schematic diagram of the experimental setup
Abb. 2 Versuchsaufbau

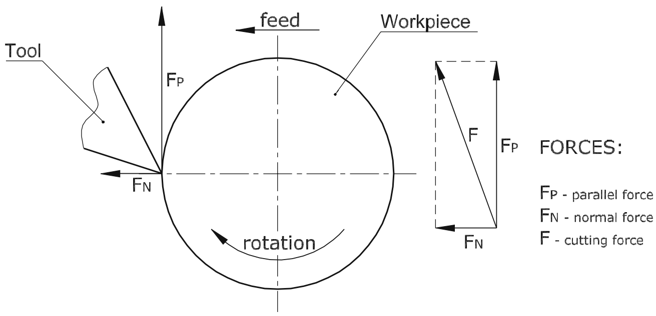

Fig. 3 Schematic diagram of orthogonal cutting with specified cutting forces
Abb. 3 Schema des rechtwinkligen Fräsens mit Angabe der Schnittkräfte

Thermal energy appears during cutting as a result of friction between the knife and the workpiece's surfaces, and friction between the cut chips and the rake surface of the wedge. The amount of heat emitted depends on many factors including cutting parameters, the state of cutting blade, the type of material being machined, and others. This part of the energy is normally dissipated to the environment. However, in our experiments the thermal energy was stored and the thermal energy volume evaluated. To evaluate the thermal energy, an adiabatic shield was built to isolate the cutting zone from its surrounding. Polystyrene board of 20 mm thick was used as a structural material due to its low heat conductivity coefficient. The thermal energy during cutting was calculated as the difference between the enthalpy of the system (adiabatic shield and all components within) before cutting, and that after establishment of equilibrium temperature inside the chest. An example of temperature behavior during cutting at a cutting speed of 20 m/s and feed rate of 0.1 mm/rev (Fig. 4) shows that during cutting the temperature inside the adiabatic walls rises significantly from

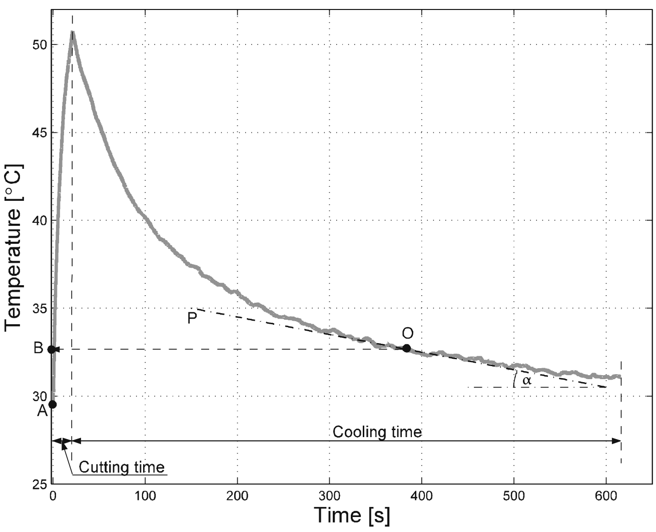

Fig. 4 Temperature behavior inside the adiabatic walls during cutting and 10 min after completion
Abb. 4 Temperaturverlauf innerhalb der wärmeisolierten Einhausung während des Fräsens und der folgenden 10 min

point A, which is treated as the initial temperature of the system. Once machining stops the temperature gradually reduces until the equilibrium temperature is reached. Since the adiabatic chest was not completely closed (some part of the spindle penetrated the adiabatic walls, as shown in Fig. 2) it was not possible to reach a stable, asymptotically convergent, final temperature. We decided to measure the equilibrium temperature (B), when the cooling velocity (derivative of the cooling curve in point O–straight line P) reached an arbitrary rate of 0.01 °C/s (angle α).

It is easy to observe that the machine or some of its parts vibrate during machining of wood and wood based materials. Vibration levels depending on the kind of cutting and its parameters, machine condition, state of blade and other factors. In our experiments, vibrations were measured with accelerometers. A triaxial accelerometer was positioned on a tool-holder near the cutting zone where the amplitude of vibrations was largest. The vibrational energy was calculated according to the relationship below:

$$E_V = \frac{m\omega^2 A^2}{2} e^{\gamma t} \tag{1}$$

where m, ω, A, γ and t are the vibrating mass (data obtained from the CNC machine manufacturer), angular acceleration, displacement amplitude, energy disappearance coefficient and time, respectively. The vibrational energy was calculated from the difference between the vibrational energy level during machining and the energy level during idling.

Sound waves contain kinetic energy, as a consequence of the particle velocity, and potential energy, as a result of sound pressure. During the experiment Sound Pressure Level was measured using a microphone installed inside the adiabatic chest, 100 mm in front of the cutting edge. Treating the sound source as a monopole, the Sound Pressure Level can be transformed into the Sound Power Level using Eq. 2 (Ginn 1978).

$$\mathrm{SWL} = \mathrm{SPL} + 20\log_{10}(r) + 10\log_{10}(4\pi) \tag{2}$$

where SWL, SPL and r represent Sound Power Level, Sound Pressure Level (re 2×10^{-5} Pa) and distance between sound source and microphones (in meters). The noise energy can then be expressed as:

$$E_\mathrm{N} = W_0 \left(\frac{\mathrm{SWL}}{10}\right)^{10} t \tag{3}$$

where W_0, SWL and t are reference acoustic power (10^{-12} W), Sound Power Level and noise duration, respectively. Total noise energy was derived from the difference between the sound energy level emitted during the test and noise energy level produced during idling.

As shown in Fig. 1, the energy balance also includes loss components. Differing kinds of energy losses occur during any technical process. In this experiment, the loss component includes efficiency of the electric motors and transmission gears, and heat generation inside bearings, among others.

3 Results and discussion

3.1 Electrical energy

Electrical energy is the input component for the cutting energy balance. The effect of cutting speed on energy demand per cm^3 of cut shavings (Fig. 5) shows that energy consumption during machining at a cutting speed of 1 m/s is up to four times greater than that at a cutting speed of 30 m/s. As shown in Fig. 5 the energy consumption during machining with low cutting speeds (1–3 m/s) is enormously large in comparison to the faster cutting speeds. Although the power demand during machining rises linearly when cutting speed increases, cutting energy decreases due to its dependence on cutting time. Since the machining time is inversely proportional to the cutting speed, the energy consumption decreases significantly. Figure 5 clearly shows that processing with low cutting speed is not effective. Moreover, relative to the genuine effect (volume of cut shavings), the energy consumption is about 40% larger in the case of cutting with a feed rate of 0.1 mm/rev than it is at 0.2 mm/rev. It follows that orthogonal machining at faster cutting and feed speeds is more effective in respect of energy consumption.

3.2 Pure cutting energy

Pure cutting energy is the one output energy whose contribution in energy balance is desired to be as big as possible. This is the output component which determines the cutting efficiency. Figure 6 shows the pure cutting energy per unit volume of shavings at several machining speeds and two feed rates. Pure cutting energy at feed rate of 0.1 mm/rev is around 30% greater than that at 0.2 mm/rev. It means that from energy efficiency viewpoint, cutting with higher feed speed is more effective than cutting with low feed rate. Although there are other technological conditions which are limit cutting speed e.g. surface smoothness, tool and machine condition, permissible noise level. On the other hand cutting with faster feed speed leads to shortening of machining time, which is also economically reasonable. Figure 6 also shows that pure cutting energy rises slightly when cutting speed increases. From this, one could say that machining at faster cutting speed is less efficient than machining with slower cutting velocity. However, when machining with slow cutting speed, the energy consumption is enormously high (Fig. 5). Considering energy consumption and pure cutting energy outlay, machining with faster cutting velocity is more desirable from an energy efficiency viewpoint.

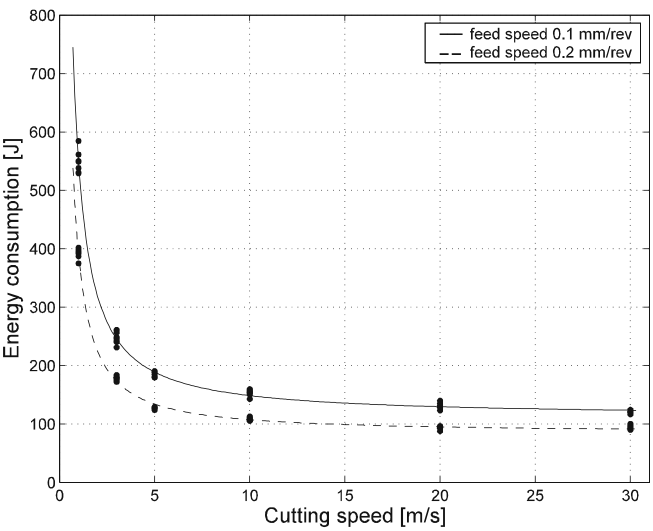

Fig. 5 Relationship between energy consumption per cm^3 of cut shavings and cutting speed
Abb. 5 Verhältnis zwischen Energieverbrauch pro cm^3 Frässpäne und der Fräsgeschwindigkeit

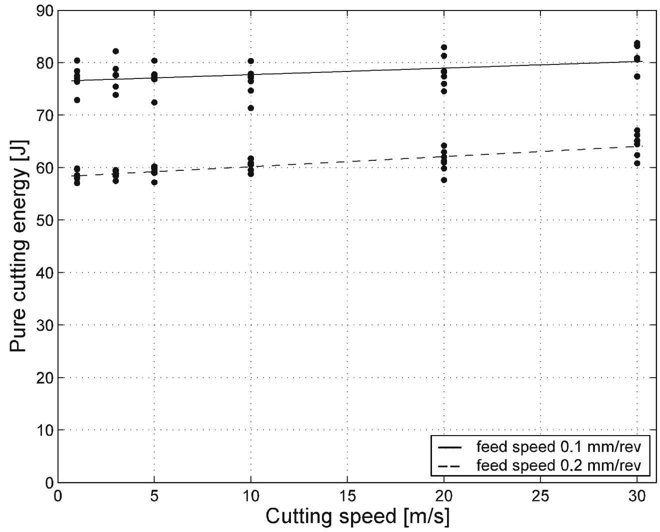

Fig. 6 Relationship between pure cutting energy per cm^3 of cut shavings and cutting speed
Abb. 6 Verhältnis zwischen dem Energieverbrauch für das reine Fräsen pro cm^3 Frässpäne und der Fräsgeschwindigkeit

3.3 Thermal energy

Thermal energy outlay during cutting has been calculated based on temperature increase within the limits of the cutting zone. The thermal energy outlay is expressed as the number of energy units per cubic centimeter of cut shavings (Fig. 7). The thermal energy outlay per unit volume of cut shavings is the same over range of cutting speeds from 1 to 10 m/s. When cutting speed exceeds 10 m/s, thermal energy outlay for cutting with feed speed of 0.1 mm/rev is greater than for machining at a feed rate of 0.2 mm/rev. This means that machining which produces very thin chips is not efficient because the energy expended for friction is greater and thereby thermal outlay is higher. From the process efficiency viewpoint it is desirable to decrease thermal energy during machining by increasing the chip thickness, although there are other restrictions that influence chip thickness, e.g. surface roughness. The thermal energy expense rises considerably when cutting speed increases (Fig. 7). However, the

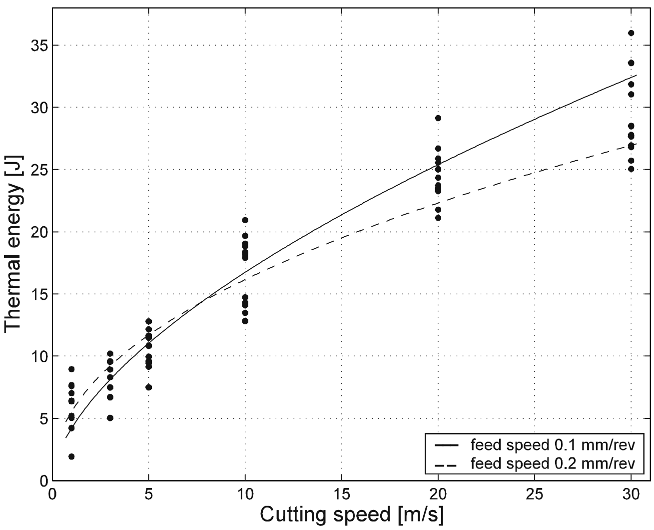

Fig. 7 Results of cutting speed on thermal energy outlay per unit volume of cut shavings
Abb. 7 Einfluss der Frägeschwindigkeit auf den Wärmeenergieverbrauch je Volumeneinheit Frässpäne

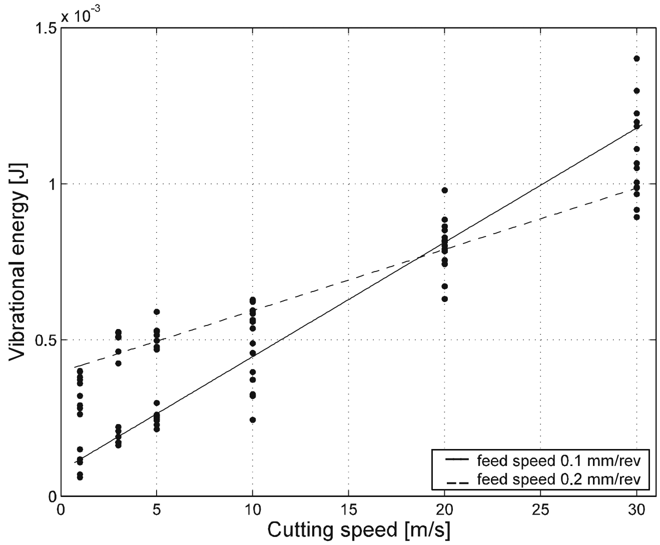

Fig. 8 Vibrational energy behavior during orthogonal machining of MDF at different cutting speeds
Abb. 8 Einfluss der Frägeschwindigkeit auf den Vibrationsenergieverbrauch beim rechtwinkligen Fräsen von MDF-Platten

thermal energy expense is larger when processing with faster cutting speed, and the energy consumption (Fig. 5) decreases more rapidly when cutting speed increases. It follows that even though the thermal energy increases, the cutting process is more efficient due to lower electrical energy consumption.

3.4 Vibrational energy

Vibration velocity, vibration amplitude, and processing time, were measured during the experiments, and the vibrational energy outlay calculated according to Eq. 1. The vibrational energy outlay per cm^3 of cut shavings is shown in Fig. 8. The vibrational energy increases linearly as cutting speed increases, because machining with higher cutting (rotation) and feed speed affects vibration amplitude, vibration velocity, and in effect, vibrational energy outlay. The vibrational energy values are very small in comparison to pure cutting energy or thermal energy outlay. This means that only a small part of the total energy which is needed for the cutting process is dispersed as vibration phenomena.

3.5 Noise energy

In our experiments the Sound Pressure Level was measured using free field microphones and suitable amplifiers. The noise energy expressed as a product of an average acoustic power of the noise source and time of sound duration can be calculated using Eq. 3. The results of noise energy outlay are expressed as a number of energy units per unit volume of cut shavings (Fig. 9). The noise energy is directly proportional to time, as shown in Eq. 3, and consequently the noise energy values fall as cutting speed increases and cutting time decreases. Consequently, machining at faster cutting speeds causes less noise energy output. It is also evident that noise energy outlay is greater when cutting with slower feed rate. The fact that cutting with higher feed speed causes less noise energy per unit volume of cut shavings confirms the argument that cutting with faster feed rate is much more effective.

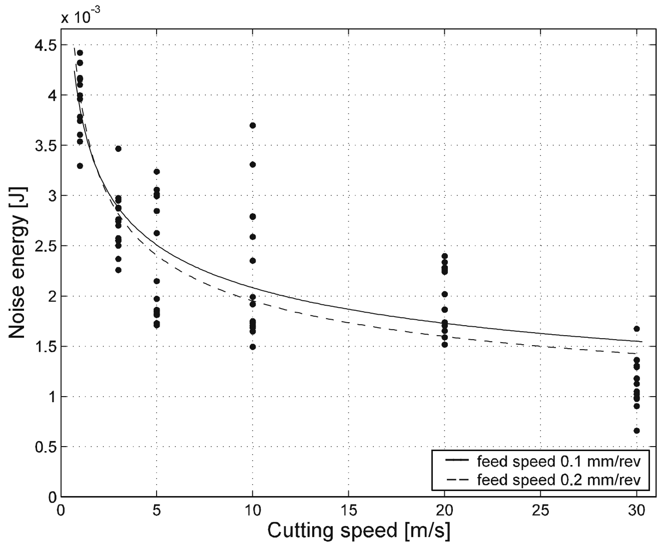

Fig. 9 Relationship between cutting and feed speed on noise energy outlay during orthogonal machining
Abb. 9 Einfluss der Frägeschwindigkeit und des Vorschubs auf den Lärmenergieverbrauch beim rechtwinkligen Fräsen

3.6 Energy balance

The above analyses of energy consumption, pure cutting energy, thermal, noise and vibrational energy allow the energy balance

Cutting speed m/s	Pure cutting energy %	Thermal energy %	Noise energy %	Vibrational energy %	Losses %
1	14.0	0.94	0.68×10^{-3}	0.028×10^{-3}	85.0
3	31.5	2.69	1.01×10^{-3}	0.049×10^{-3}	65.8
5	41.8	5.08	1.53×10^{-3}	0.072×10^{-3}	53.1
10	49.9	12.4	1.81×10^{-3}	0.119×10^{-3}	37.7
20	59.9	19.4	1.29×10^{-3}	0.298×10^{-3}	20.8
30	67.3	26.3	0.82×10^{-3}	0.478×10^{-3}	6.42

Table 1 Energy and losses contribution during orthogonal machining of MDF at feed rate of 0.1 mm/rev
Tabelle 1 Energie- und Verlustanteile beim rechtwinkligen Fräsen von MDF-Platten bei einem Vorschub von 0,1 mm/U

Cutting speed m/s	Pure cutting energy %	Thermal energy %	Noise energy %	Vibrational energy %	Losses %
1	14.9	1.62	1.05×10^{-3}	0.082×10^{-3}	83.4
3	33.0	5.34	1.65×10^{-3}	0.193×10^{-3}	61.6
5	46.6	9.08	1.42×10^{-3}	0.269×10^{-3}	44.3
10	56.0	13.2	1.57×10^{-3}	0.338×10^{-3}	30.8
20	65.8	25.1	2.41×10^{-3}	0.519×10^{-3}	9.10
30	68.3	28.2	1.37×10^{-3}	0.651×10^{-3}	3.53

Table 2 Energy and losses contribution during orthogonal machining of MDF at feed rate of 0.2 mm/rev
Tabelle 2 Energie- und Verlustanteile beim rechtwinkligen Fräsen von MDF-Platten bei einem Vorschub von 0,2 mm/U

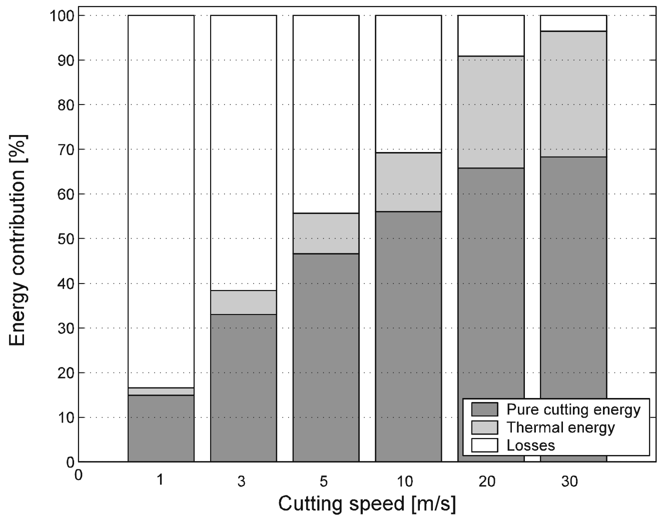

Fig. 11 Effect of cutting speed on energy contributions during orthogonal machining at feed rate of 0.2 mm/rev
Abb. 11 Einfluss der Frägeschwindigkeit auf den relativen Energieverbrauch beim rechtwinkligen Fräsen mit einem Vorschub von 0,2 mm/U

for orthogonal machining of MDF to be determined. Energy contribution during machining at various cutting speeds and feed rate of 0.1 and 0.2 mm/rev are presented in Tables 1 and 2, respectively. The energy balance was computed assuming that the input energy is equal to the electrical energy consumption, and the output consists of all other energies including pure cutting, thermal, vibrational, noise and losses. Noise and vibrational energies comprise only a small part of the energy balance, and their values do not exceed 0.001% relative (Tables 1 and 2). Energy balances of orthogonal machining at feed rate of 0.1 and 0.2 mm/rev are shown in Figs. 10 and 11, respectively (insignificant values of noise and vibrational energy are neglected). The figures show that energy efficiency is different at all cutting speeds. Energy consumption during machining with low cutting speeds is incommensurately high compared with machining at faster cutting speeds. Typical three-phase current electric mo-

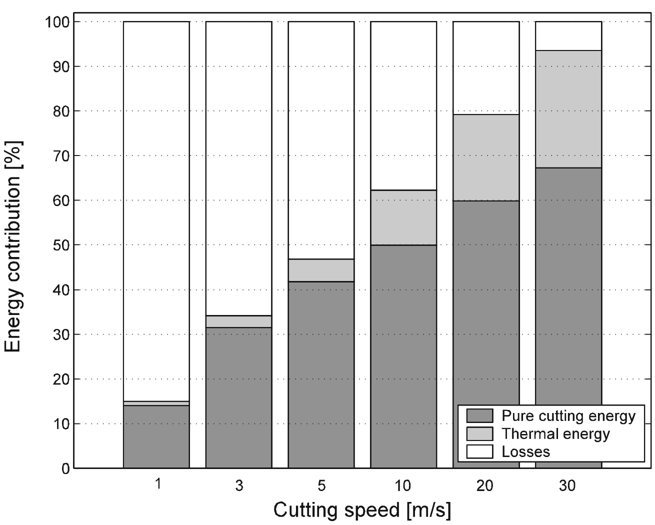

Fig. 10 Effect of cutting speed on energy contributions during orthogonal machining at feed rate of 0.1 mm/rev
Abb. 10 Einfluss der Frägeschwindigkeit auf den relativen Energieverbrauch beim rechtwinkligen Fräsen mit einem Vorschub von 0,1 mm/U

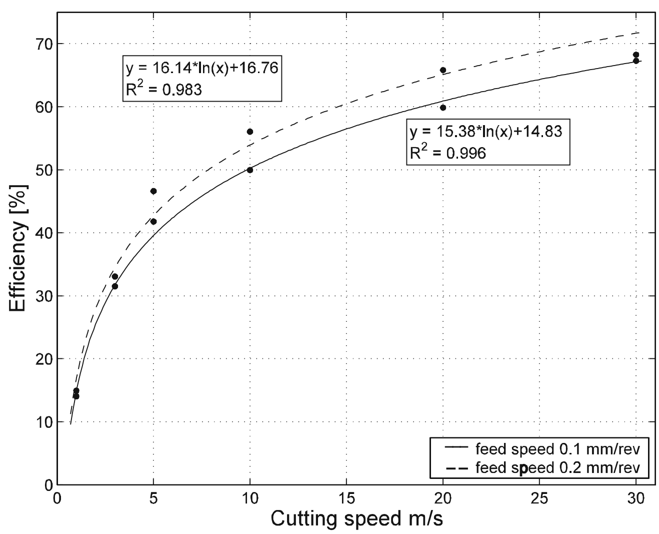

Fig. 12 Efficiency of orthogonal cutting during machining with different cutting and feed speeds
Abb. 12 Effizienz des rechtwinkligen Fräsens in Abhängigkeit der Frägeschwindigkeit und des Vorschubs

tors are relatively efficient when working at full or nearly full loads. Electric motor efficiency decreases dramatically when the load is less than 50% of the nominal torque, hence the volume of losses during cutting at slow cutting speeds becomes large. Machining at full (or nearly full) nominal torque permits fuller energy use and consequently a more effective process. Figures 10 and 11 show that pure cutting energy is the main component of the output, excluding losses which depend mostly on electric motor efficiency. Thermal energy is the most significant undesirable phenomenon accompanying cutting and reaches 28% of input energy when machining with a cutting speed of 30 m/s. The efficiency of the cutting process (Fig. 12) is the percentage contribution of the pure cutting energy in relation to the input energy. As noted above, cutting effectiveness depends mostly on electric motor efficiency. When the load of the electric motor is closer to the nominal load, efficiency increases logarithmically. It is notable that when cutting at a feed rate of 0.2 mm/rev (the load of the electric motor is closer to nominal) the cutting efficiency is slightly larger, and reaches 68% during machining with cutting speed of 30 m/s.

4 Conclusions

Based on the results of this study, we conclude that:

1. The efficiency of the cutting process depends mostly on the efficiency of the electric motor. Cutting effectiveness decreases dramatically when the load on the electric motor is less than 50% of nominal torque. Although cutting efficiency is improved by performing cutting as near to the full nominal load as possible, this carries the attendant risk of overloading the motor, with possible disastrous consequences. Safety tolerances should not be exceeded.
2. The contribution of pure cutting energy amount in relation to electrical energy consumed during orthogonal machining of MDF rises significantly when cutting speed increases. For machining with full nominal torque moment, the efficiency of pure cutting reaches 68%.
3. Thermal output is the most significant undesirable phenomena accompanying cutting. Up to 28% of input energy can be dissipated by heating of the tool and chips during orthogonal machining of MDF. Cutting with thicker chips slightly reduces the thermal energy output.
4. The proportion of vibrational and noise energy during machining of MDF is very small and does not exceed 0.001% of the total energy input.

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