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Emission of dust in planing and milling of wood

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Dust created in the machining of wood is a major problem in the working environment. Minute wood particles carried through the air create a serious health hazard, in extreme cases even leading to cancer. This paper presents the influence of cutting data and tool geometry in reducing dust emissions at the source, i.e. at the tip of the tool. Three different wood materials were investigated; pine, beech and fiberboard (MDF). Specimens were processed in a milling machine where it was possible to alter the cutting data. The dust emissions from the tool (defined here as particles with a diameter less than 10 μm) were measured. The parameters altered in the experiments were moisture content of the wood, average chip thickness, direction of feed (up or down) and rake angle of the tool. The experiments showed that the average chip thickness had the greatest influence on the amount of dust created when machining wood and the moisture content of the wood a fairly great influence, while the direction of the feed and the rake angle had little or no influence. The results show that dust emissions increase rapidly when reaching a certain average chip thickness (which is the result of the chosen cutting data). It is therefore important to calculate and control the average chip thickness in order to minimize dust emissions from the cutting operation. Furthermore, there is a large difference in dust emissions between the three wood materials tested. Machining MDF creates about six times the amount of dust compared to machining solid pine. When machining beech, the dust emissions are about 50% higher compared to machining pine.

Staubemission beim Hobeln und Fräsen von Holz

Staubentwicklung bei der Holzbearbeitung ist eins der Hauptprobleme der Arbeitsumgebung. Winzige Holzteilchen in der Luft können ein ernstes Gesundheitsrisiko darstellen, im Extremfall zu Krebserkrankungen führen. Diese Arbeit beschreibt den Einfluß der Maschinendaten und der Werkzeuggeometrie auf die Verminderung der Stauberzeugung schon an der Quelle, d.h. an den Werkzeugspitzen. Drei verschiedene Werkstoffe (Kiefer, Buche, MDF) wurden mit einer Fräse bearbeitet, die veränderliche Schneideinstellungen ermöglichte. Gemessen wurde die Emission von Staub, definiert als Partikel mit weniger als 10 μm Durchmesser. Die veränderlichen Parameter waren: Feuchte, mittlere Spandicke, Fräsrichtung (von oben oder unten) und der Spanwinkel des Werkzeugs. Die Spandicke hatte dabei den größten Einfluß auf die Staubmenge während der Bearbeitung; auch die Feuchte hatte einen deutlichen Einfluß, während die beiden anderen Parameter nur einen geringen oder keinen Einfluß aufwiesen. Nach Erreichen einer bestimmten mittleren Spandicke (als Ergebnis der gewählten Einstellungen) steigt die Staubmenge rasch an. Zum Minimieren der Staubbelastung ist daher die Berechnung und Steuerung der Spandicke von großer Bedeutung. Weiter ergab sich, daß die Staubemission der drei Werkstoffe sehr unterschiedlich ist. Beim Bearbeiten von MDF entsteht etwa die sechfache Menge an Staub im Vergleich zur Bearbeitung von massivem Kiefernholz. Beim Bearbeiten von Buche entsteht etwa 50% mehr Staub als bei Kiefer.

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1 Introduction

Dust created during machining in the woodworking industry presents one of the greatest practical problems in the working environment. In particular, it has proved a hazard to workers' health, especially in the form of cancer of the nasal and paranasal sinuses. A summary of investigations of wood dust and the risk of cancer can be found in Nylander and Dement (1993), where the authors state that operatives in the woodworking industry face a higher risk of developing nasal cancer, especially those working with machines that generate wood dust. In Sweden, for example, wood dust is classified as carcinogenic, and occupational exposure is regulated by the Swedish Health and Safety Department.

Scientific papers in this specific field are scarce. On the other hand much can be found in other areas concerning cutting of wood. Wood machining and cutting forces is an area where for example Jin and Cai (1996) are studying the effects on the cutting force at different oblique angles of the cutting edge and Huang (1994) is concerned with the relationship between the cutting force and different rake angles of the tool. A lot of work has been done to evaluate different tool materials and their resistance to wear. Examples of work in this field are Stewart (1989), about if wear of high speed steels tools increases at high temperatures during machining, Stewart et al. (1992), on tool wear in different high speed steels and heat treatments, Bayoumi et al. (1983) on wear resistance of various grades of cemented carbides. An analyze to investigate if the electrical discharge between the workpiece (MDF) and the tool is causing tool wear is described in Stewart et al. (1994).

Another interesting research area is the evaluation of surfaces created by a wood machining process. This is important knowledge when choosing cutting data and tool geometries. The choice should be based on a specified, preferably numerical, surface specification. Different measuring methods for surface roughness that is interesting for evaluation of wood surfaces can be found in Westkämper and Riegel (1992) and Westkämper and Riegel (1993).

A great deal of the basic research of wood machining was done between 1940 and 1960. Much of the present research and knowledge is based on this. Example of research from this period includes, different kinds of chip formations depending on various factors, understanding of various factors influencing cutting forces, influencing factors on surface quality and much more. A lot of the research from this period is summarized in Koch (1964) and Kollmann and Côté (1984).

However, there is little or no knowledge about ways of influencing dust emissions where they are created, i.e. at the tip of the tool. If these emissions can be reduced and combined with an effective dust hood and ventilation system, the dust spread to the operator's environment will be reduced.

The objective of this study was to determine the relationship between critical factors for planing or milling, and the creation of dust (airborne wood particles). These critical factors include cutting data (such as feed speed, rotational speed, depth of cut etc.), edge geometry and the moisture content of the wood.

2 Method

An experiment was set up in which solid pine, solid beech and MDF (Medium Density Fiberboard) were milled. A ventilation system was designed to separate the larger chips from the smaller wood particles and transport these smaller particles to a measuring equipment. Four different variables were tested to determine the effect on the amount of dust created.

2.1 Choice of variables

When milling or planing wood, there are many variables which influence the result in terms of surface quality and working environment parameters. The following factors, see Fig. 1, have been recognized as important for the result.

Testing all of the factors (in Figure 1) would be tedious and create other problems, since certain variables are very difficult to control. In this work, four variables have been examined. Other influential factors were kept as constant as possible. The four variables tested were the rake angle of the tool (α), direction of feed (upward or downward milling/planing), moisture content of the wood (%) and average chip thickness (δ_m), see Figures 2 and 3.

The average chip thickness provides a large amount of information on the actual cutting process. It makes it possible to compare planing and milling operations in which different cutting data and tools are used. This is because the average chip thickness indicates how much cutting is performed by each tooth of the tool. The average

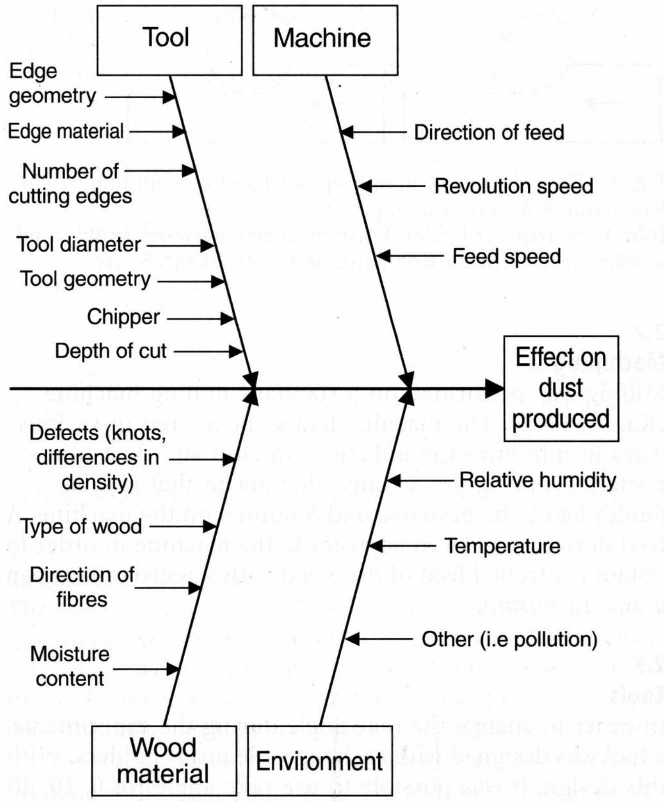

Fig. 1. Cause and effect diagram. Factors influencing the amount of dust produced
Bild 1. Ursache/Effekt-Diagramm. Faktoren, die die Staubemission beeinflussen

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chip thickness is calculated from the feed speed, number of teeth on the tool, rotational speed, depth of cut and diameter of the tool according to the equation. Koch (1964), pp. 114–118.

$$\delta_m = 1000 \cdot \frac{S}{n \cdot z} \cdot \sqrt{\frac{a}{D}}(\mathrm{mm}) \qquad (1)$$

where

$S =$ feed speed in m/min.
$n =$ rotational speed in r/min.
$z =$ number of teeth on tool
$a =$ cutting depth in mm
$D =$ the tool's diameter in mm

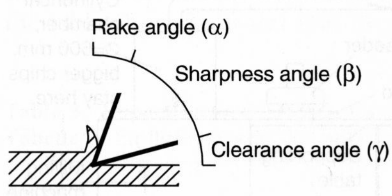

Fig. 2. Geometry of the tool edge according to Koch (1964), pp. 111–112. (The sharpness angle is also referred to as wedge angle or edge angle in the literature.)
Bild 2. Werkzeuggeometrie nach Koch (1964), S. 111–112 mit Spanwinkel (α), Keilwinkel (Schärfe, β) und Freiwinkel (γ)

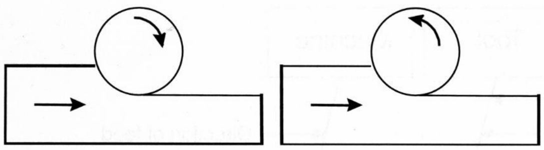

Fig. 3. The principle of upmilling (left) and downmilling (right), Kollmann and Côté (1984), p. 517
Bild 3. Prinzip der beiden Fräsrichtungen: aufwärts (links) und abwärts (rechts) nach Kollmann und Côté (1984), S. 517

2.2 Machining

Milling was performed on a standard milling machine (Kamro FM2). The machine had to be altered in various ways to minimize the influence on chip and dust transportation during processing. This meant that special guides had to be designed and mounted on the machine. A feed device was placed adjacent to the machine in order to obtain controlled feed of the wood with a speed of between 0 and 12 m/min.

2.3 Tools

In order to change the rake angle during the experiments, a tool was designed with exchangeable insert holders. With this design, it was possible to use rake angles of 0, 10, 20 and 30 degrees in the same tool. The diameter of the tool was 100 mm, width 30 mm, and one cutting edge was used to avoid the extra work of adjusting all the edges to the exact diameter. The edge material throughout the experiments was tungsten carbide (K10), with a sharpness angle of 55°. The inserts were replaced after every 10 runs to avoid the influence of wear of the tool edges.

2.4 Measurements/apparatus

In order to monitor the amount of dust created during the machining process, a special ventilation system was constructed. A cylindrical chamber (diam. 600 mm, height 500 mm) was placed around the spindle and tool. Slots were made in the chamber through which the wood was fed. A pipe (diam. 150 mm) was connected to the top of the chamber. The pipe was approximately 3 meters long and at the end of the pipe a fan exhausted air at a constant speed in the pipe of 2 m/s. The purpose of this design was to separate large, heavy chips from tiny dust particles. The heavier chips remained in the cylindrical chamber and the light dust particles followed the air stream in the pipe. A measuring tube was placed in the airflow at the middle of the pipe and connected to a measuring instrument and air pump. The air pump exhausted air through the instrument at the same speed as in the larger pipe (2 m/s), see Fig. 4. The purpose of this setup was not to determine the exact amount of dust created during machining, but to compare different experiments with each other.

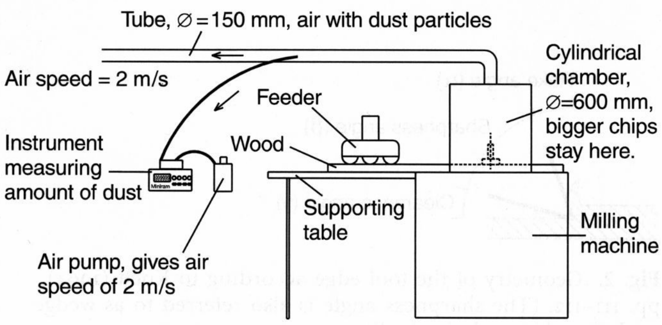

Fig. 4. Experiment setup seen from front
Bild 4. Vorderansicht der Versuchsanordnung

The instrument used was a Miniram Personal Monitor model PDM-3 from MIE (Monitoring Instruments for the Environment, Inc, Bedford, Ma, USA). The Miniram (Miniature Real-time Aerosol Monitor) is based on the principle of detection of scattered electromagnetic radiation in the near infrared wavelengths. It continuously senses the combined scattering from the population of particles present within its sensing volume whose dimensions are large compared with the average separation between the individual airborne particles. The measuring principle used here, a gravimetric measurement method for total or respirable airborne dust, is often used to supplement or replace the fiber count membrane filter method. The diameter of the particles sensed by the instrument ranges from 0.1 to 10 μm. The output from the instrument during the experiments was an analog signal, which was used to permit continuous recording of the dust emissions. By connecting a computer via a data logger to the instrument, the readings from each experiment were saved for evaluation. Before and during the experiments, the instrument was calibrated according to the manufacturer's manual.

2.5 Experiments

The experiments started with machining solid pine. The intention in choosing pine was to begin with the material that was most difficult, due to its inhomogenities (differences in density and fiber structure). The dispersion in the results was expected to be greatest in pine and therefore would be accurate for the other materials tested. After adjusting the desired cutting data and tool (according to the experimental design), sampling with the instrument started and machining took place for about 1.5 minutes. This machining time was essential in order to obtain dust readings for about 50–60 seconds. After every five runs the equipment was disassembled and cleaned.

2.6 Experimental design and analysis

To obtain as much information as possible from the experiments and to minimize the number of tests needed to ensure a significant result, the method of "factorial design at two levels" was used. The method is described in detail in Box et al. (1978) pp. 306–344, but a short practical paper on the method can be found in Gustafsson et al. (1994). The method is based on selecting a number of test variables, in our case four, and one result variable (dust). The test variables are permitted to have two values (levels), one high and one low. The method provides information on the extent to which individual variables and combinations of variables affect the result variable. The number of ex-

Table 1. "Low" and "high" values chosen for each variable
Tabelle 1. "Niedrige" und "hohe" Werte für die untersuchten Variablen

Variable	Low value	High value
Rake angle (°)	0	30
Average chip thickness (mm)	0.03	0.30
Direction of feed	down	up
Moisture content (%)	6	18

periments required is determined by the number of variables included in the experiment. In our case, this meant that $2^4=16$ tests had to be performed. To obtain more significant information from the experiments, the number of tests (number of triplicates) can be doubled, tripled and so forth. For the experiments described in this work, 64 ($4 \cdot 16$) tests were performed. The 64 tests were randomized in order to avoid unspecified disturbances affecting a series of tests. Table 1 shows the values chosen for each variable.

To obtain the moisture content values, wood was stored outdoors and sprinkled with water every day until the desired moisture content was reached. Wood stored indoors reached the low moisture content after a certain time. To obtain the desired chip thicknesses, the following cutting data were used (Table 2).

The output from the dust measuring instrument was a voltage reading every 5 seconds during machining. This meant that about 15 readings were produced from each run. The average value was calculated from readings in the middle of the run (where dust production from milling was stable). This calculated value was given in volts and did not provide any information on the quantity of dust per unit volume of cut wood. In order to be able to express the result in the desired way, the values from the instrument were adjusted to feed speed and depth of cut. Also the values were multiplied by a factor of 100 to obtain easier numbers for calculation (e.g. 12.1 instead of 0.121). The new result value was expressed in "Dust units". The formula used for calculating this value was:

$$\text{Dust units} = A \cdot K,$$

where

A = The monitored value, and
$K = 100 \cdot \frac{5.0}{S} \cdot \frac{1.6}{a}$,
S = feed speed in m/min,
a = depth of cut in mm

Table 2. Parameter settings for obtaining "low" and "high" average chip thickness
Tabelle 2. Einstellungen zum Erzielen einer "niedrigen" und "hohen" mittleren Spandicke

Parameter	High value	Low value
Rotational speed (rpm)	6000	6000
Depth of cut (mm)	3.2	1.6
Feed speed (m/minute)	10	1.5
Gives average chip thickness (mm)	0.03	0.30

The equation compensates the values to a reference machining where the feed speed is set to 5.0 m/minute and the depth of cut is 1.6 mm in order to relate the dust readings to the amount of cut wood. This means that, when machining at the low average chip thickness, the feed speed is 1.5 m/min. and the depth of cut is 1.6 mm, which gives the factor $K = 333.3$. The high value of the chip thickness gives the factor $K = 50$. In other words, "Dust units" indicates the amount of dust produced per unit volume wood instead of the amount produced over a certain period of time.

Using the factorial design method gives factors (here called impact factors) for each variable that indicate how much the variable affects the result variable (dust) when changing from the low to the high value (the impact factor is termed "main effect" in Box et al. (1978)). The method also indicates whether the result from each variable is significant.

3
Results and discussion

The experiments clearly show that the average chip thickness has the greatest effect on dust generation when machining wood. The second most important variable is the moisture content of the wood, followed by direction of feed and rake angle. This is shown in Table 3.

The "impact factor" indicates how much each variable influences the dust emissions. The greater the impact factor (negative or positive) the greater will be the effect. A negative value of the impact factor means that the lower value of the variable increases the result variable and a positive value decreases the result variable (dust). In Table 3, this means that the low values of the average chip thickness and the moisture content will result in more dust.

To be able to know which results that are significant, an interval (of the impact factor) has to be calculated. This interval is termed the confidence interval. If the impact factor for a variable is within this interval, the result is not significant. In other words, if an impact factor for a variable is within the interval, the result may be dependent on the statistical dispersion. The interval is calculated on the dispersion of the total experimental material. In this case, the significance interval for the material was calculated as +/−0.54 (with 99% certainty).

This means that there is no significant proof that the two last variables (direction of feed and rake angle) have any effect on the dust created during machining.

The impact factors describe the effect on the result variable when changing from one value to the other (low to high value). For example, the impact factor −5.7 in the table above indicates that the dust created during

Table 3. Impact factors for each tested variable
Tabelle 3. Einflußfaktoren der untersuchten Variablen

Variable	Impact factor
Average chip thickness	− 5.70
Moisture content	− 2.00
Direction of feed	− 0.50
Rake angle	0.33

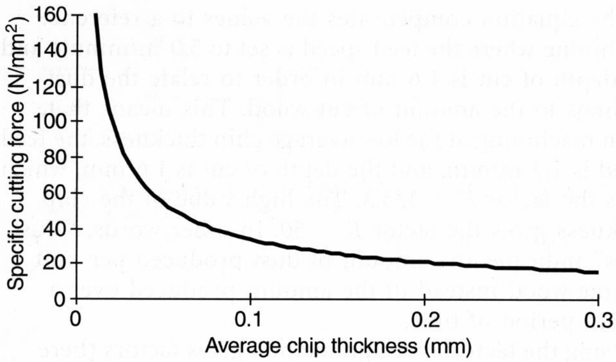

Fig. 5. The specific cutting force is dependent on the average chip thickness and increases dramatically at approximately 0.1 mm average chip thickness. Kollmann and Côté (1984), p. 522
Bild 5. Die spezifische Schnittkraft ist abhängig von der mittleren Spandicke und steigt ab etwa 0,1 mm Dicke dramatisch an. Nach Kollmann und Côté (1984), S. 522

machining is 5.7 dust units lower when machining with the high average chip thickness compared to machining with the low average thickness.

The results from the experiments clearly show that the average chip thickness has a critical effect on emissions of dust particles with diameters in the range 1–10 μm. This is interesting because this variable is critical also for other conditions when machining wood. It is well known that tool life is dependent on average chip thickness. When milling or planing using cutting data which give an average chip thickness of less than 0.1 mm, tool wear will increase dramatically. This is due to the specific cutting force (Ks), which is dependent on the average chip thickness (Fig. 5). The correlation between the average chip thickness and the specific cutting force is described in literature such as Kollmann and Coté (1984) p. 522.

Machining with low average chip thicknesses will create problems with for example tool life and surface defects. The experiments also show that the moisture content of the wood influences the amount of dust created. It has less influence than the average chip thickness and it is also a more difficult factor to control for a woodworking com-

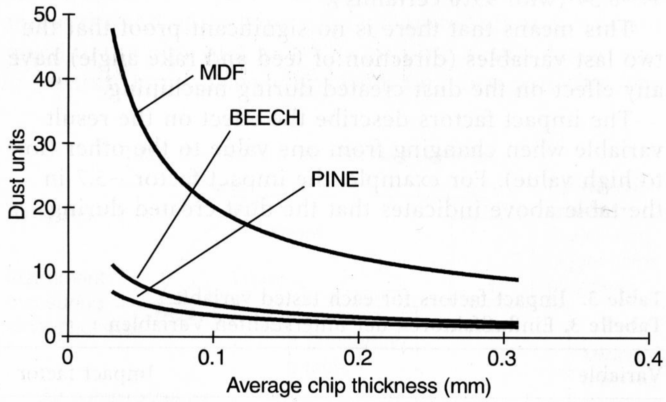

Fig. 6. Relationship between the average chip thickness and the dust created during machining
Bild 6. Beziehung zwischen mittlerer Spandicke und Stauberzeugung während der Bearbeitung

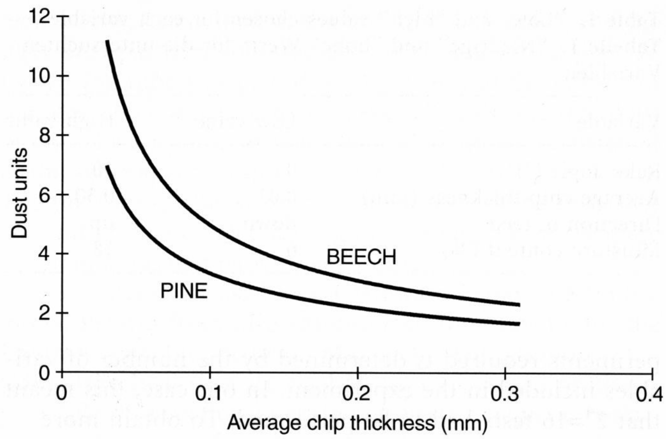

Fig. 7. The same relationship as in Fig. 6, but with a different scale on the vertical axis in order to show the similar shape of the curves
Bild 7. Die gleiche Beziehung wie in Bild 6, jedoch mit vergößerter Skala der Ordinate, um den ähnlichen Verlauf der Kurven zu demonstrieren

pany. In the experiments, the values for the moisture content were 6% and 18%. However, it would be impossible for a furniture producer to increase the moisture content from 8% to 16%, for example, in order to benefit from less dust. This is because the product will shrink when placed in a drier environment.

Therefore, the easiest way of minimizing the dust created is to control the average chip thickness. Because the experiments show what happens at only two levels of each variable, it was decided to run tests where the average chip thickness was varied in order to determine whether or not the relationship between the average chip thickness and the amount of dust created was linear. These tests were performed on all three wood materials described earlier. Exactly the same equipment and methods were used in these tests as in the previous experiments. The values of the average chip thickness tested ranged from 0.03 mm to 0.31 mm. The results from this test are shown in Figures 6 and 7.

The shape of the curve is similar to that in Fig. 5. As seen in Figs. 6 and 7, it is very critical at average chip thicknesses below 0.1 mm, where dust emissions increase dramatically. If logarithmic scales are used, the relationship will appear as a straight line.

It is also notable that the dust emissions vary greatly between the different wood materials. When calculating the differences between pine, beech and MDF at each average chip thickness, the ratio is approximately 1/1.5/6. The MDF material creates about six times more dust in the diameter range 0.1–10 μm compared to solid pine.

Both the experiments and the literature (Kollmann and Côté (1984), p. 521) indicate that the average chip thickness is a vital factor for a successful machining result in many respects. However, the average chip thickness is a more complex concept than it at first appears. This is because one specific average chip thickness can be obtained with different cutting data settings. In the experiments above, the method used to alter the average chip thickness was to vary the feed speed and keep the rota-

Table 4. The desired average chip thickness value can be reached either by changing the feed speed at constant rotational speed (left) or by changing the rotational speed at constant feed speed (right)
Tabelle 4. Die gewünschte mittlere Spandicke kann erreicht werden entweder durch Änderung des Vorschubs bei konstanter Umdrehungsgeschwindigkeit (links) oder durch Ändern der Rotationsgeschwindigkeit bei konstantem Vorschub (rechts)

Change of feed speed		Average chip thickness (mm)	Change of rotational speed	
Feed speed (m/min)	Rotational speed (rpm)		Feed speed (m/min)	Rotational speed (rpm)
1.8	4500	0.05	8	20239
3.6	4500	0.10	8	10119
5.3	4500	0.15	8	6746
7.1	4500	0.20	8	5060
8.9	4500	0.25	8	4048
10.7	4500	0.30	8	3373
12.5	4500	0.35	8	2891

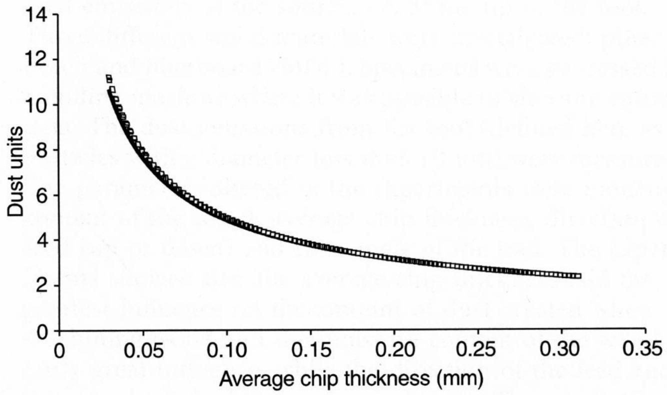

Fig. 8. Relationship between average chip thickness and dust created (beech); average thickness is reached by changing feed speed (dottet line) or revolution speed (solid line)
Bild 8. Beziehung zwischen mittlerer Spandicke und Staubemission (Buche); die Spandicke kann entweder durch Kontrolle des Vorschubs (gestrichelte Linie) oder der Umdrehungsgeschwindigkeit (ausgezogene Linie) erreicht werden

tional speed of the tool constant. The desired average chip thickness could also be achieved by changing the rotational speed and keeping the feed speed constant, according to (1). Table 4 shows how the average chip thickness can be obtained in different ways where the tools diameter (D) is 100 mm, $z = 1$ and the depth of cut (a) is 1.6 mm.

When analyzing the results from the tests, it is difficult to state whether the results would be different if the rotational speed was altered to obtain the desired average chip thickness. It is possible that the feed speed or the rotational speed has an influence on the dust emissions. To examine this, a third test was performed in which the rotational speed was altered at a fixed feed speed. This test was also based on the same equipment and methods as before. In Figure 8, it is obvious that it is unimportant how the desired average chip thickness is reached. The solid curve represents the relationship when the average chip thickness is varied by changing the revolution speed. The two curves coincide for larger average chip thicknesses. The significant factor is the average chip thickness, not how the average chip thickness is obtained.

4
Summary and conclusions

The experiments show that it is possible to reduce the amount of wood dust in the diameter range 0.1–10 μm (airborne dust) by choosing accurate cutting data in a specific way. The main results are:

- The most important factor for the amount of dust created from machining is the average chip thickness. In order to reduce the amount of dust, cutting data should be chosen so that the average chip thickness is greater than 0.1 mm. It is of no importance how the average chip thickness is obtained (feed speed, rotational speed etc.); the dust emitted will be the same.
- Different types of wood will generate different levels of dust. The experiments show that the MDF material creates up to six times as much dust as pine. Beech creates about 50% more dust than pine.
- The moisture content of the wood has an influence on the dust created, although not as much as the average chip thickness. Wood with a higher moisture content will create less dust when machined.

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