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Energy-efficient control of dust extraction for the machining of fibre-reinforced plastics

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Abstract

Fibre-reinforced plastics (FRPs) are becoming increasingly important in aerospace and automotive applications. However, dry machining of FRPs generates abrasive and electrically conductive dust particles that can furthermore cause explosive dust-air mixtures in the enclosed workspace of the machine tool. In order to protect the machine operator and the machine tool, powerful extraction systems (engine power > 5 kW) are usually installed and operated with a constant flow rate, resulting in a significant increase of the machine tool's overall energy requirement. This paper introduces a novel approach for a demand-oriented control of the flow rate to increase the energy efficiency of dust extraction systems. The objective of the developed control mechanisms is to maintain the maximum permissible dust limit with minimum energy demand. A low-cost dust sensor serves as a feedback system for the applied control mechanism. In a further stage, a force measuring platform was added to provide additional signals for an increased performance of the controlled system. To evaluate the presented approach, milling tests were carried out with carbon-fibre-reinforced plastic (CFRP). The experimental results show that the energy requirement can be reduced by up to 70%.

Keywords: Fibre-reinforced plastics; extraction system; dust sensor; energy-efficient control; dry machining

1. Introduction

Fibre-reinforced plastics (FRPs) are characterised by their heterogeneous and anisotropic material properties. Even specifically adjustable strength or oxidation resistance capabilities are feasible with these composite materials. Carbon-fibre-reinforced polymers (CFRPs) in particular exhibit an exceptionally high strength-to-weight ratio [1, 2]. Hence, FRPs are commonly used in contemporary high-performance applications such as aerospace, military, automotive and sports industries [1, 3, 4].

Standard machining operations such as trimming, milling or drilling of FRPs are usually performed on conventional machine tools. Because there is no suitable cutting fluid, dry machining of FRPs is common [5]. However, a main issue of dry machining of FRPs is the dust formation. Haddad et al. conducted a comprehensive investigation on the formation of dust during the milling of CFRP. Depending on the process parameters, the measured particle size was within the range between 0.25 μm and 15 μm [6]. This poses a serious health risk for the machine operator because the highly abrasive dust particles are also respirable and can reach the deepest parts of the human respiratory system. In addition to their unhealthy properties, dust particles are electrically conductive and can damage or even destroy mechanical as well as electronic machine components. Hence, dust extraction systems are indispensable in order to protect human resources and machines [4, 7].

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Nowadays, dust extraction systems are equipped with powerful fans and generally do not provide a demand-oriented control of the suction power. However, there are different approaches to achieve a higher dust capture efficiency and reduced energy requirements. Local suction systems attached to the work spindle of the machine tool or robot are presented in patents [8] and [9] as a possible solution to achieve a more effective dust extraction. Schneider et al. patented an enhanced extraction system based on a camera and an adjustable suction pipe [10]. The system analyses the dust movement during the milling process and accordingly adjusts the position of the suction pipe for an improved dust collection. Another approach utilises the exhausted air of the extraction system [11]. The processed air is fed back into the interior of the machine, creating a directed circulation that lifts the dust particles towards the suction pipe. As a result, the effectivity and energy efficiency of the overall system increases.

The first machine tool specifically designed for series production of CFRP components is presented in [12]. In particular, the machine is designed for an efficient dust and chip extraction. It features air inlets in the ceiling and suction boxes at the bottom of the workspace, creating a directed air flow along the vertically aligned machine table.

The presented approaches verifiably improve dust capture efficiency. However, there is no demand-oriented adjustment of the suction power depending on the actual dust concentration or the processing state. Thus, indicating a considerable potential for further improvement of the energy efficiency in FRP machining.

This paper introduces a novel approach for the demand-oriented control of dust extraction systems in FRP machining. For this purpose, a cost-effective dust sensor was integrated into the machine tool working space. Subsequently, a force measuring system was implemented to provide additional signals for the control system. A demand-oriented control mechanism to adjust the suction power was designed and finally evaluated in milling experiments.

2. Experimental setup and control mechanism

The experimental setup in the machine tool working space is illustrated in Fig. 1. A 5-axis machining centre for metal processing was used for the experimental procedure. The machining centre was equipped with a horizontal spindle (integrated in a vertical cross table) and rotary swivel table (mounted on a linear feed axis). An optional suction hood was attached to the spindle in order to capture chips and dust particles during the machining process. For measuring the dust concentration in the closed working space, a cost-effective dust sensor (PMS1003) was employed. During the experimental investigation, the dust sensor was mounted at one of the four highlighted positions on the machine table (Fig. 1). Moreover, a force measuring platform was mounted between workpiece and machine table to provide additional signals for the control system. The control mechanism was designed in MATLAB® Simulink® and implemented on an industrial computer. Moreover, a frequency converter was installed to adapt the rotation speed n of the extraction system's fan (maximum electrical power 5.5 kW). A power meter was used to record the extraction system's power input. To generate chips and dust particles, CFRP samples were trimmed.

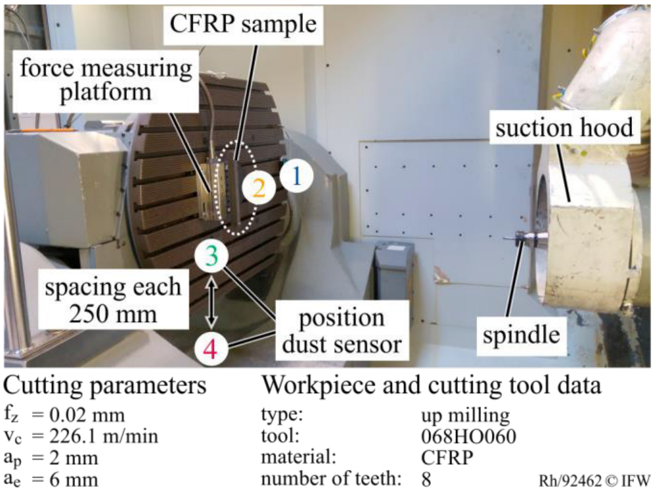

Fig. 1: Experimental setup in the machine tool working space

The experiments were subdivided into three parts. First, the standard process control was considered. For this purpose, the extraction system was set to its maximum performance. The operating status (on/off) was selected by the machine operator. The dust sensor was mounted at position 1, as this is the farthest from the processing position. Moreover, it is not in the falling direction of the chips. In a second step, a control mechanism utilising the measured dust concentration to control the extraction capacity was analysed. For this series of tests, the dust sensor was alternately placed at the four highlighted positions on the machine table as depicted in Fig. 1. The objective was to determine the influence of the direction and velocity of the dust spreading on the control concept. Finally, the control mechanism was enhanced to process the signals of both dust sensor and force measuring platform. For this experiment, the dust sensor was placed at position 1. Since sensor position 1 is the most difficult measuring position for the dust sensor, it was considered for the extended control concept.

In order to achieve the objective of a demand-oriented, economical and energy-efficient dust extraction, a control concept was developed and experimentally evaluated. The control mechanism utilises the measured dust concentration to adjust the extraction capacity. By using only one dust sensor, the system is both cost-effective and easy to implement. By extending the concept using a force measurement platform, the exact determination of the first tool engagement is enabled. Thus, a faster response of the extraction system is achieved. However, the integration effort and costs are higher.

Fig. 2 presents the control concept, which features an easy to implement P-controller. Initially, the dust concentration setpoint w was defined based on the European Parliament directive 2008/50/EC on ambient air quality and cleaner air for Europe.

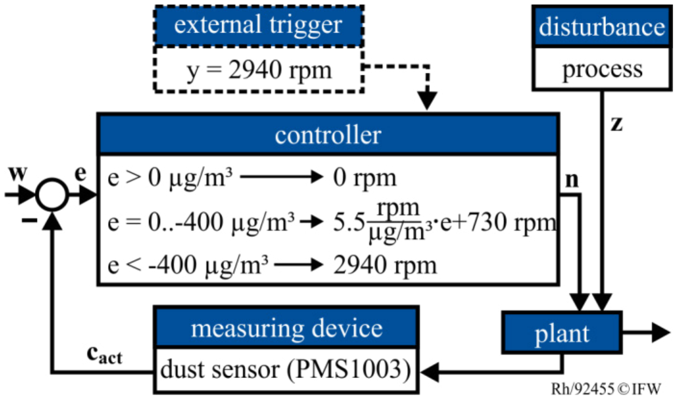

Fig. 2: Schematic control loop for a demand-oriented dust extraction

Compared to other regulations, e.g. TRGS900, the safety values are more stringent [13, 14]. Accordingly, the dust concentration setpoint was set to 100 μg/m³ for the experimental investigation. Therefore, opening the enclosed workspace is only allowed if the measured dust concentration is smaller than the setpoint.

The controller provides an allocation function for the rotation speed n of the fan in dependence of the determined error value e. The allocation function is subdivided into three sections. For an error value of $e > 0$ μg/m³, the fan is turned off ($n = 0$ min^{-1}). If the actual dust concentration c_{act} exceeds the setpoint ($e < 0$ μg/m³), a linear function applies. The ordinate intersection point of the function is set to a rotation speed of $n = 730$ min^{-1}, which is the minimum rotation speed of the fan motor. The gradient of the function is determined by the maximum rotation speed of the fan motor $n = 2940$ min^{-1} and the recommended measuring range of the dust sensor $c_{max} = 500$ μg/m³. Considering the setpoint, the maximum control deviation is $e = -400$ μg/m³. When the error value exceeds -400 μg/m³, the dust extraction system works at full capacity with a rotation speed of $n = 2940$ min^{-1}.

Within the extended concept, the fan motor is activated by the force measuring platform (dashed box in Fig. 2). For this purpose the control system is extended by an S-R flip-flop which is a basic module in digital technology. If the measured force is lager then a defined threshold, the set signal of the S-R flip-flop is true. Consequently, the control system actives the dust extraction. The rotation speed is kept constant at $n = 2940$ min^{-1}, until the error value falls below -400 μg/m³. By falling below the threshold value of -400 μg/m³ for the first time, the reset signal is true and disables the S-R flip-flop. Consequently the control of the fan speed is transferred to the controller described above.

3. Experimental results

3.1. Evaluation of the dust capture effectivity

Fig. 3 illustrates the measured dust concentration for the standard process at sensor position 1. The measurements show qualitatively similar characteristics. The time offset t_{offset} between the start of the machining process (first contact between cutting tool and workpiece) and the increase of the dust signal is between 20 s and 30 s. Towards the end of the machining process, the dust concentration reaches its maximum. Then, the dust concentration in the working space decreases continuously. Since the extraction system was operating before the machining process started, all chips could be captured before falling to the ground.

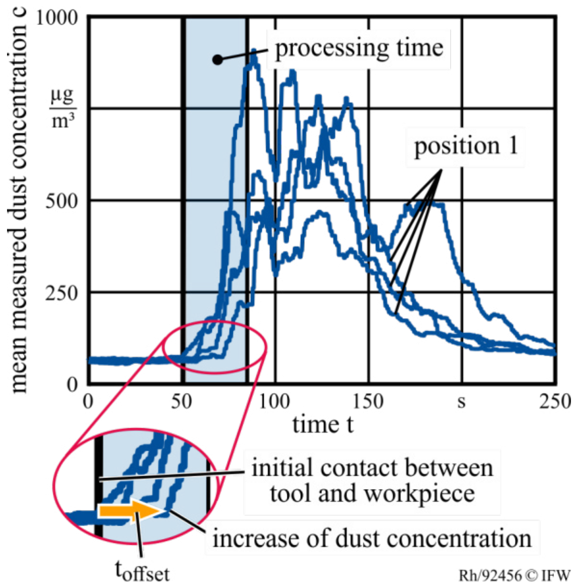

Fig. 3: Dust concentration over time (standard process)

However, a quantitative comparison of the individual measurements demonstrates that identical process parameters and boundary conditions may result in significantly different dust concentrations. This can be traced back to various causes: Due to manual production of the CFRP material, air inclusions as well as varying matrix thickness and fibre orientation can occur. Additionally, chips and dust can have electric charges (due to the machining process), and they are therefore able to form large accumulation. Moreover, dust deposits can occur on the workpiece, the spindle or other components. Fig. 4 presents the corresponding adhesion to the workpiece and spindle as an example. Besides the material properties, turbulences resulting from interfering contours also lead to a random dust distribution.

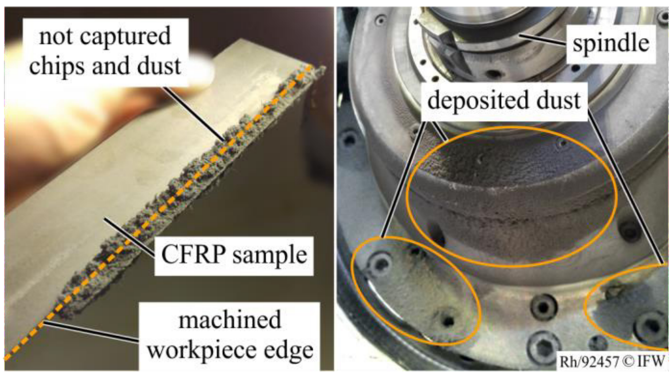

Fig. 4: Deposition of dust and chips on workpiece (left) and spindle (right)

The measurement results for the dust concentration with active control mechanism of the extraction system are shown in Fig. 5. Despite the variation of the curves within a series of measurements (see Fig. 3), it is possible to deduce the qualitative behaviour of the dust dispersion in the working area. Compared to the standard process, a significant reduction of the measured dust concentration at positions 1 (blue) and 2 (orange) can be identified.

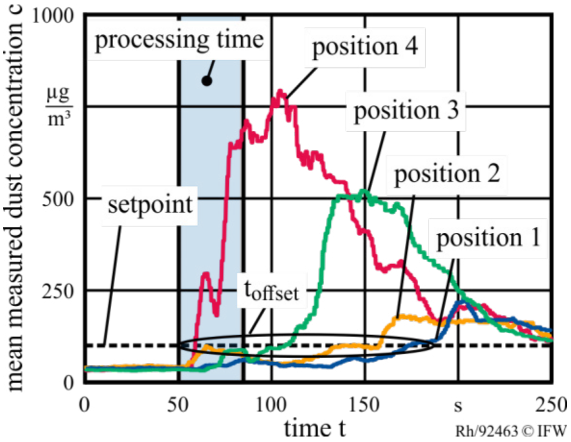

Fig. 5: Dust concentration for different sensor positions (with active control mechanism)

When compared to the standard process (Fig. 3), the maximum measured dust concentration at positions 1 and 2 was reduced by approximately 76%. In addition, the time offset increased to 30 s – 150 s, because the extraction system was inactive at the beginning of the machining process. Accordingly, no turbulence occurred that would support the dispersion of the dust particles in the workspace. Due to the low dust concentration and the high time offset, the control of the extraction capacity was insufficiently controlled. Accordingly, most of the chips and dust fell to the ground (Fig. 6 left).

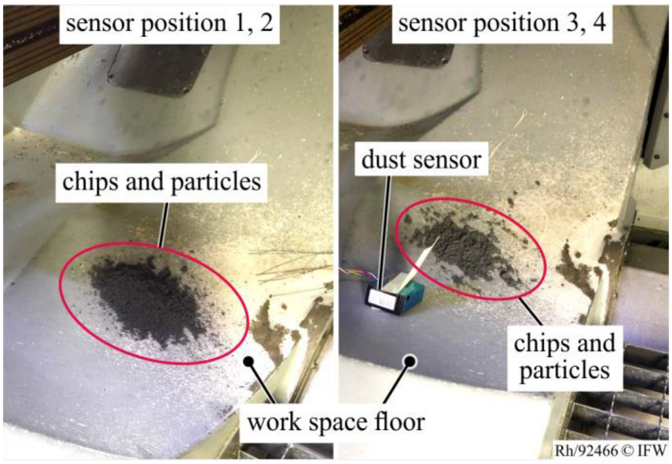

Fig. 6: Uncaptured CFRP chips and particles with active control mechanism

Compared to the horizontally aligned sensor positions 1 and 2, the measured dust concentrations for the vertically aligned sensor positions 3 (green) and 4 (red) were significantly higher. However, the maximum measured dust concentration at position 3 was reduced by approximately 23% and at position 4 by circa 7% compared to the standard process. Also, the time offset was reduced to 9 s – 15 s. This is due to the positioning of the dust sensor in the falling direction of the chips and dust. The maximum dust concentration was measured at sensor position 4. The impact of the chips on the workspace floor caused a stronger dispersion of dust particles in that area, resulting in a higher dust concentration near sensor position 4 (Fig. 6 right). Since a sufficiently high dust concentration was measured at both position 3 and 4 (see Fig. 5), more chips and dust were captured with the active control mechanism. However, the high time offset also led to an insufficient result (Fig. 6 right).

In summary, the horizontal dust dispersion for the considered process is low. For a demand-oriented control of the suction power, the dust sensor must be placed in the falling direction of the chips and dust. In addition, the sensor should be positioned as exactly as possible under the milling process. However, the collection of chips was unsatisfactory due to the high time offset. Accordingly, the control concept is unsuitable for demand-oriented control of the extraction system.

In order to decrease the response time of the dust extraction system, the signal of the force measuring platform was used as an additional trigger for the controller. Since sensor position 1 was the most difficult measuring position for the dust sensor, it was considered for the extended control concept. Fig. 7 shows a representative measurement of the dust concentration (blue) at position 1 including the actual (red) and set speed of the fan motor (green). The distribution of the dust concentration is similar to the standard process. Compared to the initial control concept, the response time of the fan is significantly lower. This is due to the trigger signal provided by the force measuring platform. As soon as the milling tool and the workpiece make contact, the controller forces the maximum fan speed (green). However, the actual speed (red) only reaches the setpoint after 4.2 s, due to the limited acceleration of the fan. The control is transferred to the dust based controller at time t = 87 s with the S-R flip-flop.

The measurement data shows a good correlation between the dust concentration and the speed of the fan. The dust concentration falls below the setpoint at t = 210 s. Simultaneously, the set fan speed is also forced to n = 0 min^{-1}.

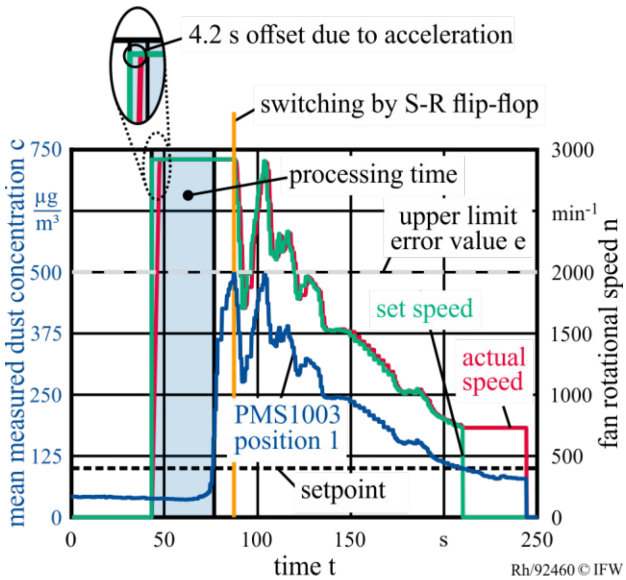

Fig. 7: Dust concentration and fan speed for the extended control concept

Compared to the initial control concept, a significant improvement of the dust capture effectivity at sensor position 1 is achieved by using the trigger signal. This is because the time offset is too large when using only the dust sensors. The dust particles are dispersed in the working area before the control system reacts. Thus, the chips and dust particles are not extracted from the working space. Accordingly, the application of a fast trigger signal is necessary in addition to the measurement of the dust concentration.

3.2. Evaluation of the energy demand

Fig. 8 illustrates a comparison of the fan motor operating time t_{fan} for the standard process (red) and the control concept extended by the force measuring platform (blue).

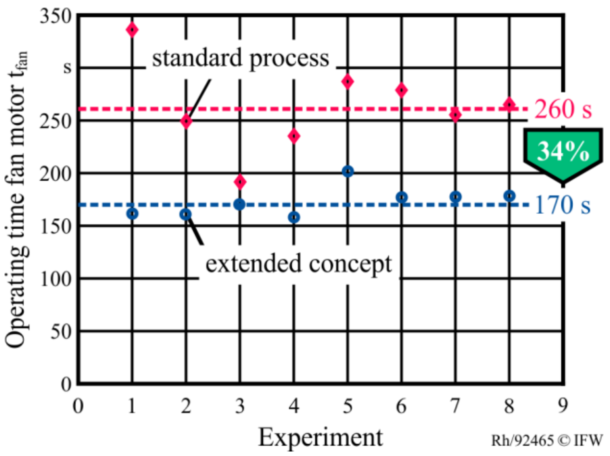

Fig. 8: Comparison of the fan motor operating time

Compared to the extended control concept, a high variance of the operating time is observed for the standard process with an average of 260 s. This is caused by the manual deactivation of the extraction system by the operator. Because there is no information about the actual dust concentration in the working space, the exact switch-off time (i.e. when the dust concentration is sufficiently small) is not known. With the extended control concept, both activation and deactivation of the extraction system are automatically performed by the control mechanism. Consequently, the operating time of the extraction system was reduced by 34%. Moreover, the variance of the operating time was minimised.

Fig. 9 presents the electrical energy demand for both the standard process and the extended control concept. As with the operating time, the standard process also demonstrated a high variance of the required electrical energy.

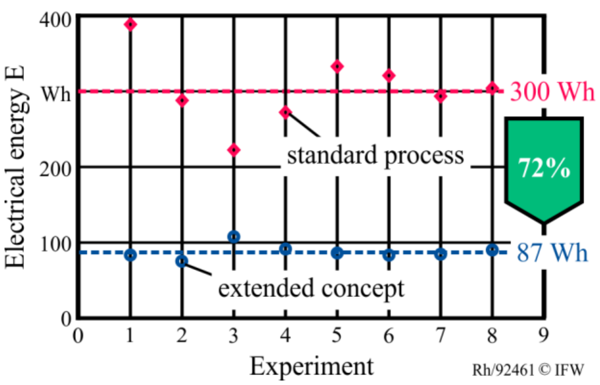

Fig. 9: Comparison of the electrical energy demand

Since the power consumption of the fan motor is constant over time in the standard process, the reason for the variance can be derived directly from the operating time. By using the extended demand-oriented control concept, the average energy consumption was reduced by 72% to 87 Wh. The dust collection was comparable to the standard process.

4. Conclusion and outlook

Based on the deficits in the state of the art in FRP machining, a control concept for a demand-oriented dust extraction of the machine tool working space was presented in this paper. The initial concept is based on the continuous measurement of the dust concentration in the working space as a control input for the extraction system. Admittedly, experimental results have shown that the initial concept is unsuitable for demand-oriented control. The reason is the slow dispersion of the dust particles in the working space ($t > 30$ s). As a result, the dust extraction system is not activated until the end of the milling process and therefore most of the dust is not captured.

Building on the first approach, the concept was extended by adding a further trigger signal (provided by a force measurement platform). Consequently, the response time was significantly reduced. The dust capture effectivity was comparable to the standard process (with the extraction system operating at maximum performance). With the integration of a cost-effective dust sensor to measure the current dust concentration in the workspace, the required operating time of the fan could be reduced by 34% compared to the standard process. Energy requirements were even reduced by up to 72%.

Since a permanent integration of a force measurement platform is not desirable, further investigations are being carried out. The objective is to replace the function of the force measuring platform with internal signals of the machine tool to control the extraction system according to current process requirements. In addition, this approach aims at a complete substitution of the dust sensor, allowing for a demand-oriented control of the dust extraction system without additional measurement hardware.

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