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Experimental Investigation of the Heat Flux Distribution in Grinding of Titanium Alloy

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Abstract

Generally, grinding involves high specific energy, compared to other machining processes. Most of this energy is changed into heat which makes harmful effects on surface quality as well as tool wear. In this respect temperature measurement techniques enhance cutting performance in terms of increasing wheel life and improving the quality of the ground part, especially when grinding temperature sensitive material like γ-TiAl. The distribution of the total grinding heat flux along the grinding zone does not follow a linear form. It increases at the trailing edge with sharp gradients and then varies nearls linearly for the renaibder of the contact length. In this paper a new method to measure relative temperature in the grinding zone is presented. The approach demonstrates a flexible arrangement of the thermocouple in the workpiece to measure at variable depth of cuts. The results of the experiments are further investigated to cover the mentioned complex distribution of the heat flux in the workpiece. With the known relative temperature in the grinding zone and the net spindle power is a simple analytical approach presented to estimate the absolute grinding temperature. It is shown that the measured and the calculated temperature diver up to 600%.

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Keywords: Thermocouple; Grinding; Temperature; Titanium; Aluminide

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1. Introduction

One of the major goals in grinding processes is to get rid of the heat generated in the contact zone between abrasive and workpiece. An inadequate or not efficient heat removal can lead to thermal damage at the ground surface. Thermal effects are not only caused by inefficient cooling they also emerge from the chosen material removal rate, dressing operation and the grinding strategy (up-cut and down-cut grinding). Therefore the temperatures within the grinding zone require careful measurements to determine if the process is detrimental to the surface integrity of the workpiece after grinding. The optimization of the grinding process requires a good knowledge of the workpiece input heat flux and of the maximum temperature rise which must be maintained below the burn threshold. The thermal models describing the process cannot estimate precisely the temperature field in the workpiece subsurface because of the great number of input parameters required to define the thermal load depending on the contact area affecting the shape of the heat source. Furthermore, grinding is particularly difficult and complex

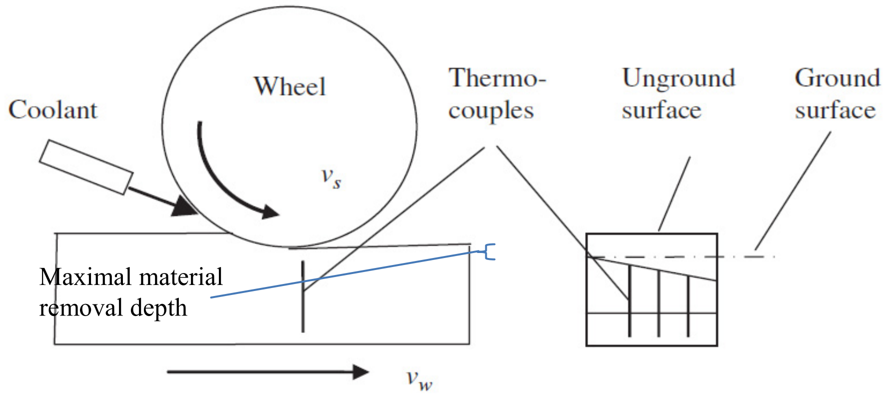

Fig. 1. Temperature measuring in the grinding zone with a thermocouple in a small hole and indication of the maximal material removal depth [1].

to study in comparison to other machining processes because several grains of the wheel remove the material instantaneously. During this process their geometry varies continuously with time.

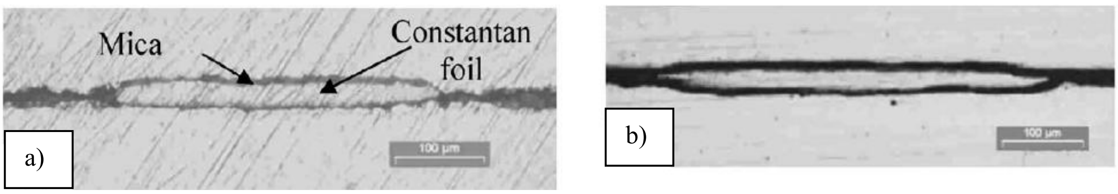

Fig. 2. Close up of the arrangement of the constantan foil and mica film before grinding (a) and after grinding (b) [3].

Various experimental techniques [1] have been used for measuring temperatures during grinding with one of the most common methods being the embedded thermocouple, in which a fine standard thermocouple is inserted into a small hole or bore in the workpiece. Although this type of measurement is easy and simple to apply it is limited to a certain number of experiments due to the chosen distance between the working surface and the thermocouple tip. Experiments can only be conducted as long as the thermocouple is not exposed to the abrasive. This temperature measurement approach is illustrated in **Fig. 1**.Another frequently used temperature measurement technique [2] is the foil/ workpiece thermocouple method. In this setup a thin constantan foil isolated by a mica film in combination with the workpiece forms a thermocouple junction. This approach allows on the one hand an unlimited number of experiments but is on the other dependent on certain workpiece materials and needs complex fixtures to mount the prepared workpiece. The setup of this measurement technique is illustrated in **Fig. 2**. It can be seen that the arrangement of the constantan foil and the mica film has to be very precise in order to avoid any gaps. An example fixture to mount the prepared workpiece is shown in **Fig. 3**. The clearance between all parts must be maintained at all times to avoid any short circuits before and during the grinding process.

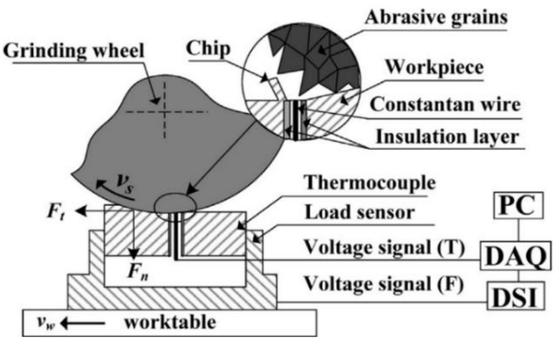

Fig. 3. Sketch of measurement system (DSI: dynamic strain indicator, DAQ: data acquisition card, T: temperature, F: force) [6].

The presented paper combines the two mentioned technologies and provides a possibility to measure relative temperature without being limited to a certain number of experiments or restricted to certain workpiece materials and fixtures. Furthermore, is a simple heat flux model presented which makes it possible to estimate roughly the absolute grinding temperature.

2. Experiment setup

The experiments were conducted with an aluminium oxide wheel of 130 mm diameter and 20 mm width on a Hermle C20U with 15 kW spindle power and an additional external high pressure unit (HPU) with max 150 bar and 11 kW. As dressing tool a fix mounted diamond with two rectangular shaped diamonds has been used. The workpiece material was gamma titan aluminide (γ-TiAl) with a grinding length of lg=44,3 mm. As working parameters a_e=0,4 mm (depth of cut), v_w=3000 mm/min (table forward feed) and v_s=25 m/s (cutting speed) have been chosen.

Table 1. Material properties of γ-TiAl.

Density [g/cm³]	Conductivity [W/mK]	Specific heat capacity [kJ/kgK]	Tensile strength [MPa]	Max. services temp. [°C]	Coefficient of thermal expansion [10^{-6}/°C]
4	17	0,8	450-800	900	11

The VIPER-cut (Very Impressive Performance Extreme Removal) technology has been chosen as cooling supply. This technology is a process that requires close coordination between the machine, the coolant supply and the composition of the grinding wheel. The principle behind VIPER grinding is that the coolant is injected into the grinding wheel under high pressure ahead of the grind, and centrifugal force then moves the coolant out of the wheel during the grind, cleansing the wheel and cooling the material. For that reason a porous wheel composition has been chosen. As in **Fig. 4** shown the process also uses a specially developed nozzle to deliver coolant at 50 bar and more, at a precise angle relative to the wheel and workpiece interface [9].

The process was developed during the 1990s as a higher performance alternative to CBN superabrasive and conventional creep feed grinding techniques for machining nickel alloys. The process has been applied at a number of turbine blade machining facilities. During grinding the coolant keeps the chip temperature low, preventing

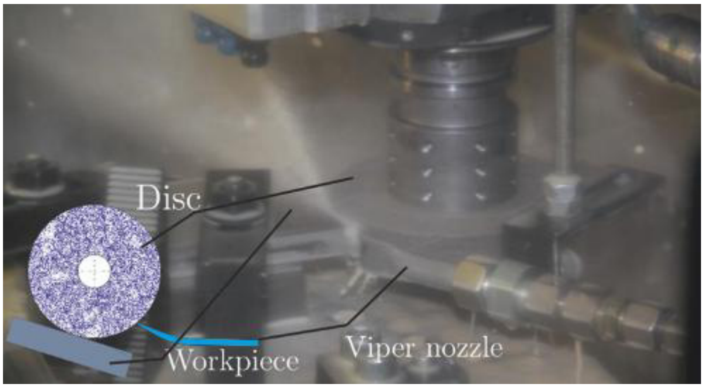

Fig. 4. ViperCut© nozzle with process illustration.

bonding of the micro-swarf to the abrasive medium, while the jet flushes the material away. This prevents "clogging" of the wheel, eliminating the need for intermediate dressing. This in turn helps to maintain a low rate of wheel wear, resulting in acceptable "tool" life for the small diameter wheels [5-6].

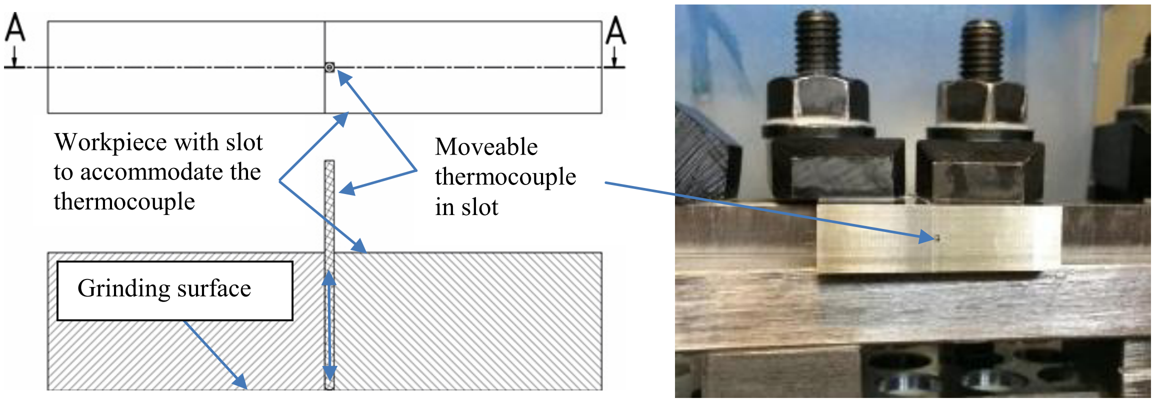

Fig. 5. Experiment setup with cross-section of the workpiece and thermocouple in the slot; left and mounted on the machine; right.

Combining the two state of the art temperature measuring techniques presented in **Section** 1 results in a new measuring approach. The result is illustrated in **Fig. 5**, whereas the left picture shows the cross-section of the setup with the moveable thermocouple in a slot and the right picture displays the setup applied to γ-TiAl workpieces mounted on the machine working table. For the first attempt a Type K thermocouple with1 mm diameter for easy handling has been chosen. The couple has the configuration 2G (tip welded with jacket) to realize a shorter responding time (0,15 s). Further investigations will be realized with a 0,5 mm couple for even faster responding time (0,025 s). The moveable thermocouple design allows a precise locating after each experiment for reproducible measurement results. In addition this setup material is independent and flexible according to various depth of cuts.

3. Experiment results

For the experiment the lubricant flow rate, the pressure (directly after the HPU) and the net spindle power consumption have been logged. During the experiment the lubricant flow accounts for 20 l/min and the pressure for

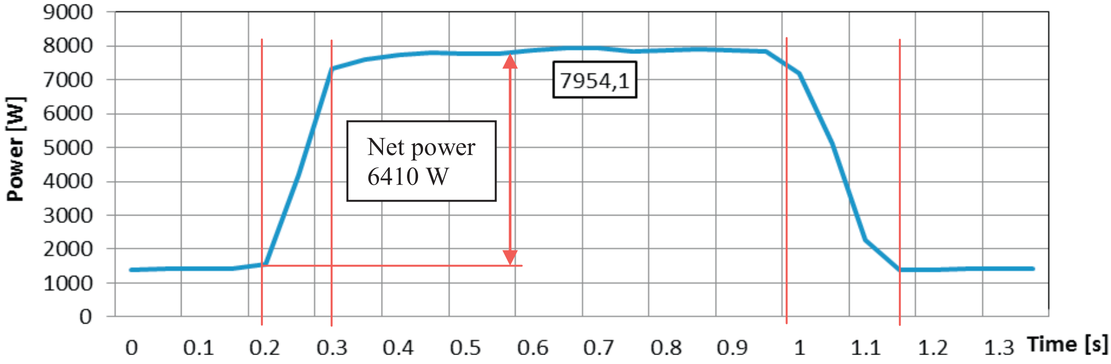

Fig. 6. Power curve of the spindle during the climb grinding operation.

50 bars. These parameters were kept constant during the grinding operation and vary about 5% due to the behavior of the piston pump. The result for the power consumption over time is shown in **Fig. 6**. From the first contact between the grinding wheel and the workpiece elapse 0,22 s until the max net power consumption of ca. 6,41 kW is reached. The power curve follows a typical grinding operation and shows no conspicuity.

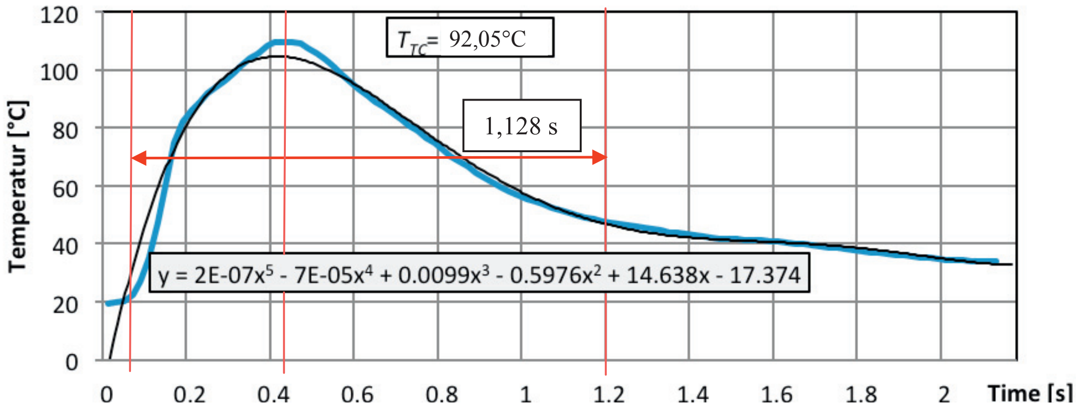

Fig. 7. Temperature curve of the thermocouple during up-cut grinding with a mean temperature of $\Delta T_{TC,mean}$=58°C for the contact length of 44,3 mm and t_{gl}=1,128 s.

The temperature plot in Fig. 7 shows the behavior of the thermocouple during the up-cut grinding operation. Starting with an ambient temperature of 18°C the value rises in a logistic growth and peaks in a maximum of 110°C at 0,44 s. From this maximum the temperature descents linear to 60°C at 1,2 s and slopes out in an exponential manner. Mohammadjafar [4] studied thermal effects of minimum quantity lubrication (MQL) in grinding processes with a similar graph shape as result. He used an embedded thermocouple in a bore to measure the temperature at various MQL-flows. From this accordance can be derived that the shape of the plot is reasonable. The temperature follows the equation provided in Fig. 7 and is thus a good approximation to describe the relative temperature yield in the workpiece and helps to predict areas of potential heat damage (grinding burn).

3.1. Estimation of the absolute grinding zone temperature

The estimation of the absolute grinding temperature is based on the specific grinding energy calculated in **Equation(3.1)**. Therefore, is the net grinding power from **Fig. 6** related to the consumed volume of workpiece material for a width of cut (b_c). The total amount of removed material during one grinding operation $V_{removal}$ is calculated in **Equation (3.2)** and for the contact length with the thermocouple V_{TC} in **Equation(3.3).**

$$e_{c,Pnet} = \frac{P_{net}}{v_w \cdot a_e \cdot b_c} = \frac{6410W}{50\frac{mm}{s} \cdot 0{,}4mm \cdot 11{,}8mm} = 27{,}16\frac{J}{mm^3} \quad (3.1)$$

$$V_{rmoval} = a_e \cdot b_c \cdot l_{WP} = 0{,}4mm \cdot 11{,}8mm \cdot 44{,}3mm = 210mm^3 \quad (3.2)$$

The thermocouple and the wheel overlap for a certain distance (l_g=6,93 mm) and time (0,139 s) [7]. For the presented model is the geometrical contact length l_g used to determine the volume of material, which is removed when the wheel moves past the thermocouple (see Fig. 8).

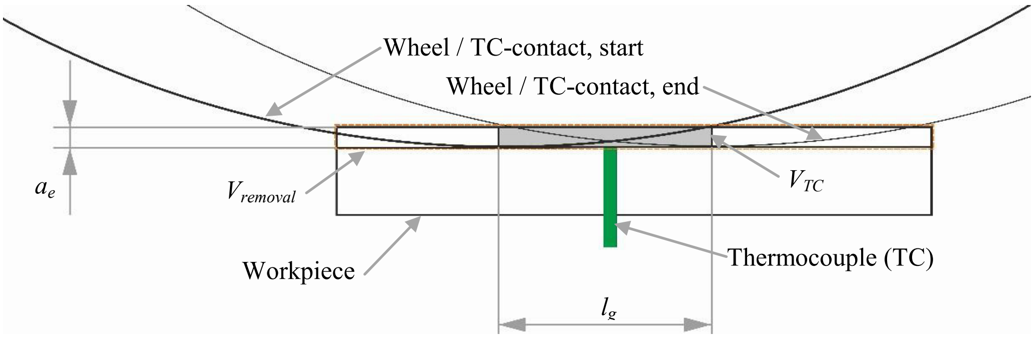

Fig. 8. The geometrical contact length l_g accounts for the distance when the wheel moves past the thermocouple.

The grinding heat is partitioned into different thermal sinks along the grinding length (see ***Figure 9***) and dissipated through the wheel, the coolant, the chips and the workpiece. To cover this behavior in a simple approach is assumed that the measured temperature of the thermocouple (ΔT_{TC}=92°C for t_{gl}=1,128 s) is constant in the

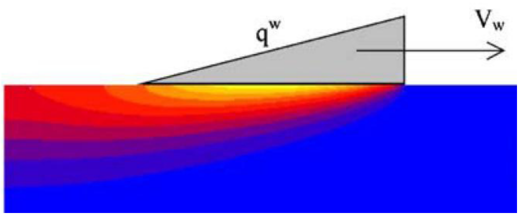

Figure 9: Example for a heat flux distribution along a ground surface [7]

removed material volume $V_{removal}$. The energy which is necessary to heat $V_{removal}$ from 18°C to the mean temperature of 92°C is calculated in **Equation (3.4).** Thus, it is possible to estimate the absolute temperature in the grinding zone by dividing

$$V_{TC} = a_e \cdot b_c \cdot l_g = 0{,}4mm \cdot 11{,}8mm \cdot 6{,}93mm = 32{,}7mm^3 \quad (3.3)$$

$$e_{c,removal} = V_{removal} \cdot \rho_{TiAl} \cdot c_{p,TiAl} \cdot \Delta T_{TC} = 210mm^3 \cdot 4 \cdot 10^{-6} \frac{kg}{mm^3} \cdot 0{,}8 \frac{kJ}{kgK} \cdot 92°K = 62W \quad (3.4)$$

$$T_{TC,abs} = \frac{e_{c,Pnet} \cdot V_{TC}}{e_{c,removal} \cdot t_{gl}} \cdot \Delta T_{TC,mean} = \frac{27{,}16 \frac{J}{mm^3} \cdot 32{,}7mm^3}{62 \frac{J}{s} \cdot 1{,}128s} \cdot 58°C = 736°C \quad (3.5)$$

the grinding removal energy with the material heating energy and multiplying this fraction with the mean temperature $\Delta T_{TC,mean}$. This approach results in a calculated absolute temperature of 736°C which is moderate for γ-TiAl and causes no heating damage. The same result showed also the ground surface where no grinding burn could be detected. It has to be mentioned that this theoretical model has not been tested extensively and further investigations are necessary to determine the boundary of this mathematical analysis.

Conclusion

In this paper an insight into the state of the art temperature measuring technologies has been given. Starting with the thermocouple in a blind hole approach and further to the constantan foil/ workpiece thermocouple junction method. These two technologies have been merged to form a new temperature measurement method which combines the benefit of both presented technologies. The focus was put on an independent workpiece material as well as a variable depth of cut solution. The presented technique enables a repositioning of the thermocouple according to the grinding parameters. Experimental grinding tests have been carried out to obtain the relative temperature in the grinding zone. The mathematical analysis of this investigation showed that the absolute temperature varies up to 600% which is reasonable because no grinding burn could be detected.

For future investigations the current setup is going to be automated to enable relative temperature measurement during swing grinding. In addition a simulation will be carried out that predicts the real grinding zone temperatures regarding to the thermocouple and workpiece thermal inertia.

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