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EFFECTS OF HOT CHIPS IN DRY CUTTING PROCESSES ON THE TEMPERATURE FIELD AND DISPLACEMENT OF THE MACHINE TOOL TABLE

In machining up to 75% of the geometrical variations of work piece, features are caused by thermally induced deformations of machine components [1]. Since in dry cutting up to 80% of the thermal energy is stored in the chips [2], we expected a significant effect of these process-dependent heat sources on the machine accuracy. Based on preliminary simulation results, we systematically applied determined quantities of heated chips to a machine table to understand their impact on the temperature field. Temperature sensors where used to measure the temperature change on the tables surface and in the structure. Length measuring probes measured the corresponding deformations at 24 points distributed over the table. The measurements show a temperature change of 4 K at the surface and 3 K in the structure near the heat source after 6 minutes of exposure to 500°C chips. In this case, the impact on the temperature field is local but causes the bending of the table. We recorded 8 micron of thermo-elastic deformations. The results suggest that high-accuracy processes with large energy input, such as hard turning, require the heat induced into the machine structure by hot chips to be implemented into compensation methods and correction algorithms.

1. INTRODUCTION

Machining of hardened surfaces is often used to produce the final geometry and surface quality of a workpiece. For this reason, these processes are subject to particularly high demands on precision. A high energy input is expected due to the hard surface layer which is machined and glowing chips are often produced, as can be seen in the example in Fig. 1. The heat induced through the process potentially causes deformations at the TCP. Despite broad research activities in this field in recent years, thermally induced errors still account for up to 75% of the total geometric error [1]. While up to now, heat sources from the machine and the environment have been subject of intense research, the future investigations have to

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focus on further influences, such as process conditions. Bryan identified them as influencing variables on thermally induced errors already in 1967 [3].

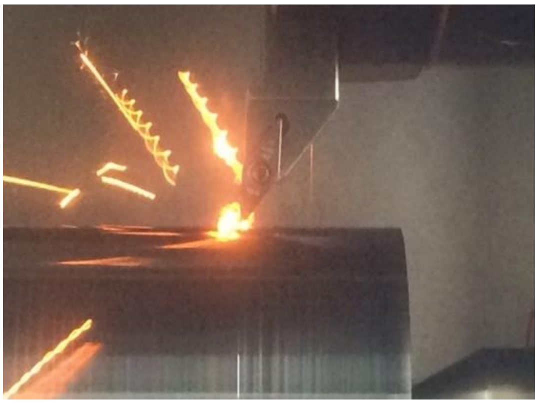

Fig. 1. Dry turning of hardened steel with incandescent chips (copyright A. Hänel, TU Dresden)

The graphic in Fig. 2a shows the power consumption of a machine tool during the cutting process. Approximately one third is lost to motors and drives. The remaining energy is distributed between tool, workpiece and the chips or coolant [4].

Further investigations demonstrated that the distribution of the cutting power strongly depends on the cutting speed. The diagram in Fig. 2b shows that at high cutting speeds up to 80% of the generated heat flows into the chips in continuous cutting processes [2]. In processes, characterized by interrupted cutting, those relations can change.

If cooling lubricant is used, the heat generated by the process can dissipate. First approaches to quantify the influence of cooling lubricants on the thermal behaviour of machine tools [5, 6] and how to correct them [7] already exist. In dry machining, on the other hand, tool and workpiece heat up and the hot chips form of chip nests on the tool table.

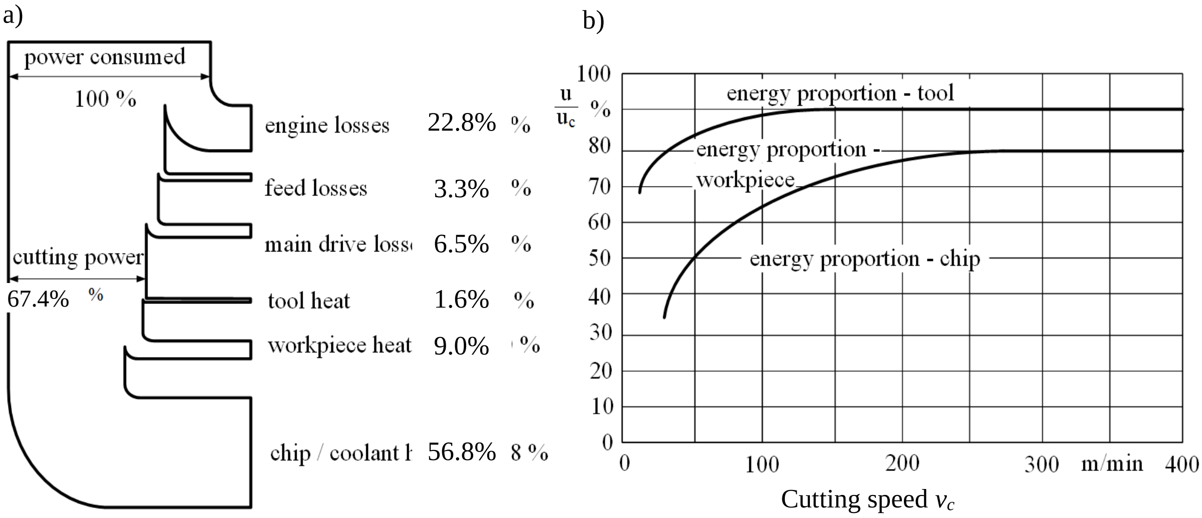

Fig. 2. a) Distribution of the power consumed during machining [4], b) Dependence of the energy distribution between workpiece, tool and continuous chips as a function of the cutting speed [2]

Since this heat cannot dissipate in the cooling lubricant, it affects the machining process. As a result demands on the temperature resistance of the tool materials rise, the workpiece structure is influenced and thermally induced deformations occur [8, 9].

Current research work concerning geometrical errors caused by heat in dry cutting is mainly concerned with approaches for modelling the deformation of the workpiece [10–12] and the tool [13]. Furthermore, there are first approaches to include the cutting process in compensation methods [14].

Although a large part of the process heat dissipates in the chips, these phenomena play a subordinate role in current research. Only design recommendations for the machine interior are to be found, which explain how to avoid chip accumulations and thus minimize the thermal influence on the machine structure [9, 15]. However, there is no numerical or experimental investigation regarding the magnitude of deformation that can actually occur due hot chip deposits. This is a process-related uncertainty for all correction and compensation methods and potentially influences every dry machining process. For improving current simulation, correction, and compensation attempts, it is necessary to analyse, delimit, and quantify this influence. This paper shows an experimental approach to investigate the deformation of a structural machine tool component due to hot chip accumulations. For this purpose, heated chips were applied to a machine table and changes of the temperature field as well as the corresponding deformation were monitored. The investigations contribute to a better characterization of the heat transfer from hot chip accumulations to structural components of machine tools and to a better understanding of the magnitude of the resulting deformation. From the results in section 5, processes and scenarios can be derived which require the influence of hot chips on the displacement of the TCP to be taken into account for more accurate simulations and correction algorithms.

2. OBSERVATIONS OF DRY MACHINING IN THE INDUSTRIAL ENVIRONMENT

We examined exemplary dry machining processes to design an experimental setup that allows us to achieve the most realistic results possible. The dimensions of the chips are small (< 10 mm^3) compared to the size of the structural components (often $> 10^6$ mm^3), as shown in Fig. 3. Although the chips in these processes have a temperature of several hundred degrees, their heat capacity is very small, compared to the machine components.

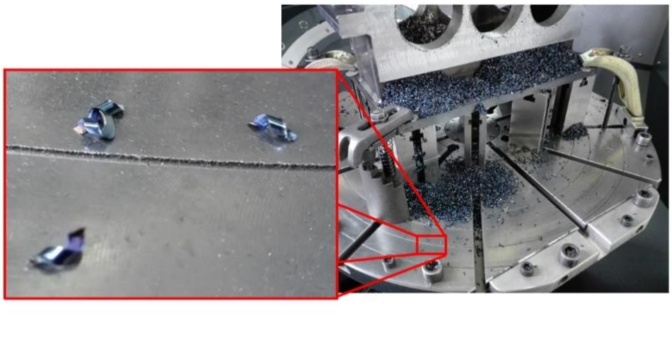

Fig. 3. Dimensional comparison for dry machining of a gearbox housing on a 5-axis milling machine

Therefore, we assume that the thermally induced effects caused by the chips are local and time-limited. The experimental investigation of a single structural component is expected to generate representative results.

The data on the temperature of the chips in machining processes varies greatly and depends on a number of factors, such as material, tool, coating, machining parameters, etc. In addition, the temperature drops considerably with increasing distance from the point of action. From peak temperatures of even up to 1200°C [16] in the machining zone, only a few hundred Celsius degrees can be measured at a short distance [17]. Determining an average temperature is therefore difficult. For the experimental investigations, the temperature of the chips was defined at 500°C.

3. COMPUTING THE EFFECTS OF HOT CHIPS ON A MACHINE COMPONENT

3.1. SIMULATION MODEL

In order to evaluate the assumptions and to support the experimental approach, a preliminary simulation study was carried out.

A loose bulk of hot chips on a machine table was simulated to estimate the changes in the temperature field and deformation of the table. Therefore, a simple model with lumped parameters (node model [18]) was developed (Fig. 4a). Since the temperature field is rotationally symmetric, only the upper half of the bulk and the table is shown in an upright position. The table and the loose bulk of discontinuous chips (200 g) are models with cylindrical elements. At the start of the simulation, the machine table had a temperature of 20°C and the bulk of chips a temperature of 500°C. The environmental temperature is fixed at 20°C. The table is subdivided in three areas: below the bulk of chips, near the bulk and the rest of the table. The material parameters (density, specific heat capacity, temperature dependent conductivity within the bulk) of the chip bulk and the connection to the environment (convection, radiation) and the table (conduction, radiation) are calculated based on approaches published in [19].

3.2. SIMULATION RESULTS

The simulation shows that the temperature below the bulk reaches its maximum after 158 s (Fig. 4a). The simulated temperature field indicates that the bulk is still at around 300°C while the table remains at almost room temperature of approximately 22°C. The plot of average temperatures suggests that the chips have only little to no influence on the table temperature (Fig. 4b). A homogeneous temperature distribution in the table is reached after nearly 30 min. The thermal elongations of the table were estimated (Fig. 5a) based on the temperature field. The free elongation in x direction (Δx in Fig. 4a, Eq. 1) was calculated based on the mean table temperature below the bulk (T_{tbb}), the thickness of the table (h_{table})

and the coefficient of thermal expansion of steel (α_{steel}). The elongation in radial direction was calculated at the outside of the table (Δr in Fig. 4a, Eq. 2).

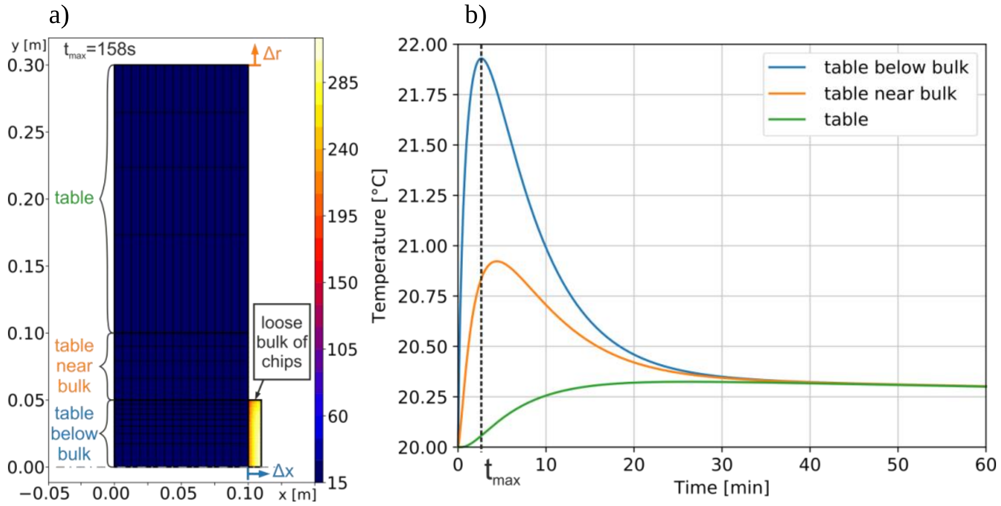

Fig. 4. a) Temperature field at time t_{max}, b) Mean temperature of different areas of the machine table

Therefore, the average temperature over the whole table and an approximate equation [18] for flat circular discs are used (V_{tbb} – volume of table below bulk, V_{tnb} – volume of table near bulk, V_t – volume of outer part of table, T_{tbb}, T_{tnb}, T_t – mean temperature at the corresponding volume, r_{table} – radius of table). The resulting elongations are approximately 2.3 μm in x direction and 1 μm in radial direction. Most of the deformation is reversed after 20 minutes.

$$\Delta x = (T_{tbb} - 20°\mathrm{C})\alpha_{\mathrm{steel}} h_{\mathrm{table}} \tag{1}$$

$$\Delta r = \big((T_{tbb} - 20°\mathrm{C})V_{tbb} + (T_{tnb} - 20°\mathrm{C})V_{tnb} + (T_t - 20°\mathrm{C})V_t\big) \\ 0.5\alpha_{\mathrm{steel}} r_{\mathrm{table}} / (V_{tbb} + V_{tnb} + V_t) \tag{2}$$

The heat flow to the environment is much smaller than to the table (Fig. 5b). In consequence, the heat flow to the environment can be neglected. Most of the heat dissipates in the first 20 min of the simulation.

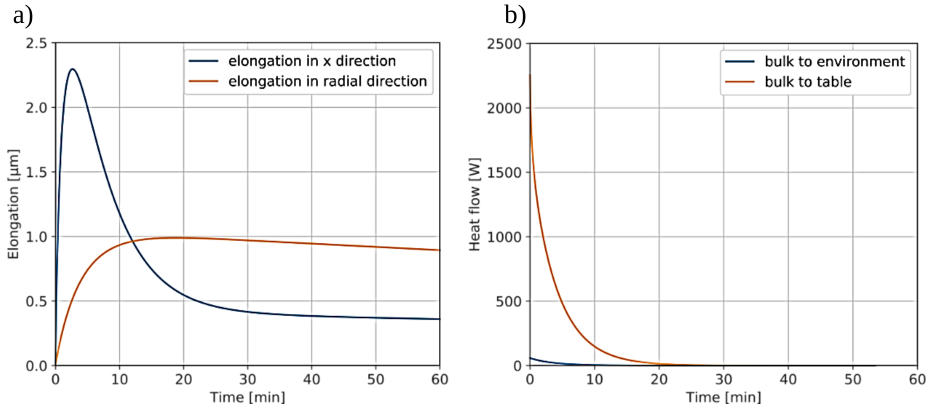

Fig. 5. a) Estimated thermal elongation of table in x and radial direction, b) Heat flow from bulk of chips to environment and table

3.3. DISCUSSION

The results of the simulation show that the influence of the chip accumulation is, as assumed, local and time-limited.

The machine table has a large heat capacity (96069 J/K) and a small heat flow via convection to the environment. Therefore, the resulting thermal time constant (5.72 h) is large and it takes longer than the time period considered in the simulation for the table to reach the original 20°C.

The investigations on a single structural component as a simplified experimental setup are therefore sufficient to carry out the investigations.

4. METHODOLOGY FOR EVALUATING CHIP IMPACT ON TEMPERATURE FIELD

In accordance with the simulation results, we selected a machine table as a representative structural component and equipped the table with sensors (Fig. 6). We used temperature sensors and a thermographic camera to record the temperature field. The sensors were placed on the surface and in holes on the bottom side about 1 cm from the surface to measure the temperature in the structure. We calibrated the camera using the sensor measurements. To capture the spatial deformation of the table, we placed inductive length measuring probes under the table and on the sides. Labels 1, 2 and 3 mark the sensors positions for the surface temperature measurements, which we will present in detail in section 5. I and II indicate the sensor positions for the temperature measurement within the structure. The deformation was evaluated at position A, B and C.

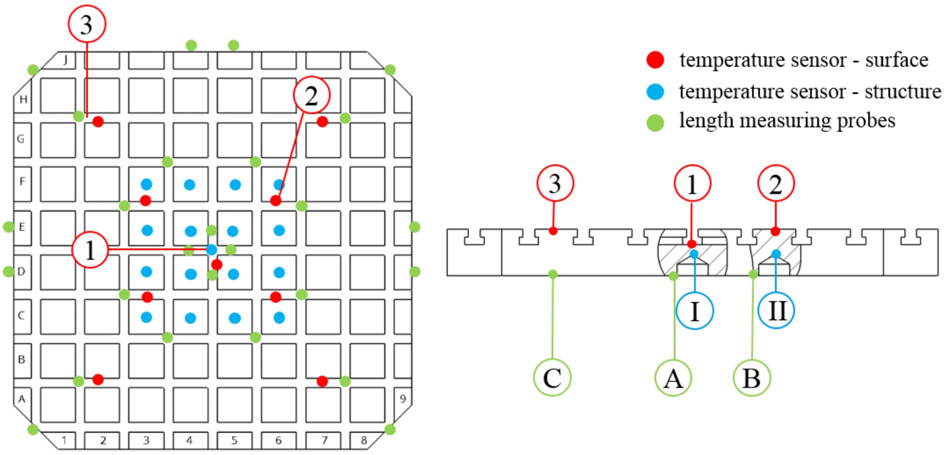

Fig. 6. Schematic sensor positioning on the machine table, left: top view, right: side view

The top of the table is shown in Fig. 7a and the bottom of the table can be seen in Fig. 7b with the corresponding sensors. The temperature sensors of the surface are located at the red marked places. To protect against damage and to prevent the temperature of the chips from being measured incorrectly, they are coated with aluminum around the measuring area. The green marked spots show the positions of the visible inductive length measuring probes.

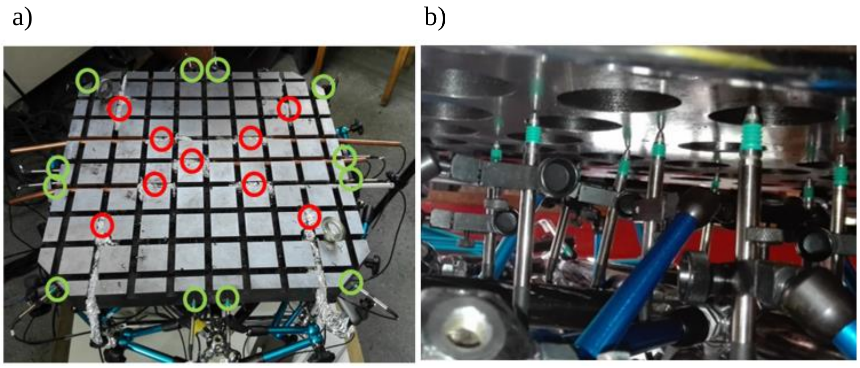

Fig. 7. a) Sensor positions on the upper side of the table, b) Pointing probes on the lower side

For the experiments, we heated the chips in a furnace and then dropped them onto the center of the machine table separately, until we reached a defined mass of 200 g (see Fig. 8). In order to ensure reproducibility of the results, the experiment was repeated several times. Care was taken to leave the chips in the furnace long enough to achieve a uniform temperature distribution. The picture shows the three measuring points at which the surface temperature is evaluated in section 5.

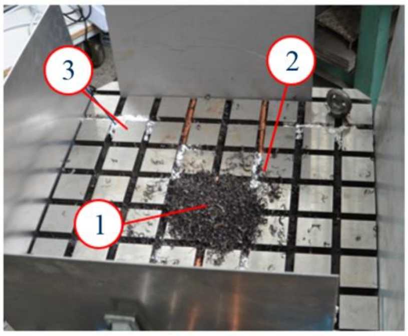

Fig. 8. Chips collected on machine table

The chip quantity corresponds, for example, to machining over a length of 200 mm with the parameters $a_e = 25$ mm, $a_p = 5$ mm and $v_f = 240$ mm/min (material removal rate: $Q = 30$ cm^3/min). Table lists the boundary conditions of the experiment.

Table 1. Experimental specifications

Material – chips	S235JR
Material – machine table	Tool steel
Chip type	Spiral chip fragments
Chip mass	200 g
Chip volume	25.5 cm^3
Chip temperature	500°C
Environmental temperature	26.6°C–27.5°C
Table dimensions	630×630×60

5. RESULTS

To evaluate the influence of the heated chip accumulation on the temperature field and on the deformation of the machine table, we compared the measured values in the marked positions 1, 2 and 3 (surface temperature), I and II (structure temperature) and the deformation at the positions A, B and C (Fig. 6).

5.1. EFFECTS ON TEMPERATURE FIELD

The thermogramms in Fig. 9 show how fast the chips cool down. Due to the high temperature difference, we used different temperature scales for both images. While temperatures above 130°C can still be measured at the beginning (Fig. 9a), the temperature of the chips drops to approx. 27°C only 15 minutes later (Fig. 9b). For comparison, the measuring points 1, 2 and 3 are marked in both pictures.

The measured temperature values on the table surface are shown in Fig. 10a. The diagram in Fig. 10b shows the temperature field plotted over the coordinate system of the machine table at the time of the peak value. At Position 1, the maximum temperature of about 30.5°C is reached after around 6 minutes. While the temporal course at position 2 is equivalent, the maximum value is only 29.5°C. It takes about 45 minutes for the surface temperature to reach a steady state again at positions 1 and 2. Due to the low initial temperature increase at position 3 of only 0.5°C, the measured values reach the ambient temperature level earlier and then begin to rise accordingly.

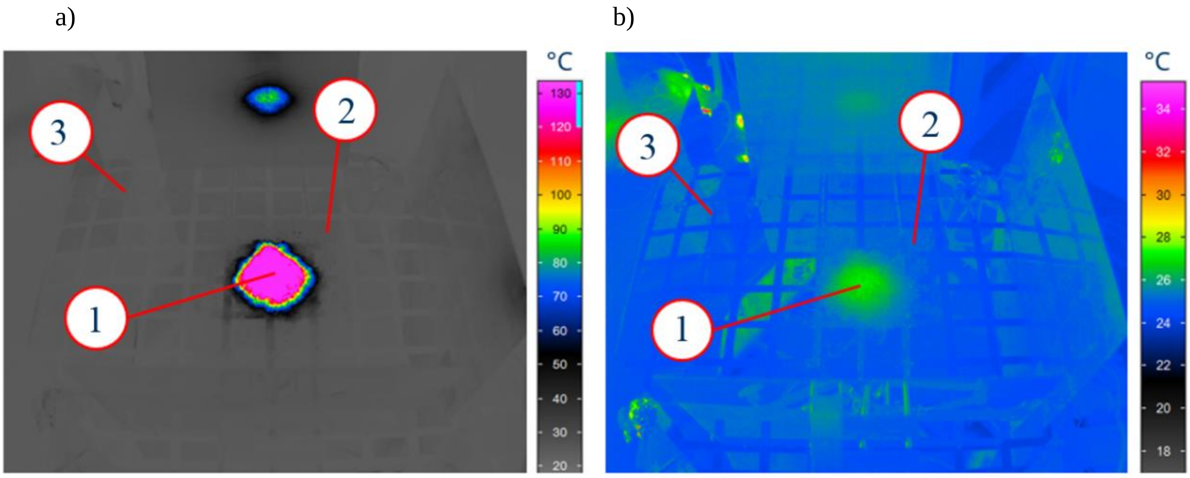
a) b)

Fig. 9. a) Thermographic measurement shortly after applying the chips, b) 15 minutes later

The diagrams of the temperature values measured in the table structure can be found in Fig. 11. At position I approximately the same peak temperature as on the surface is obtained. For position II a difference in the values can be observed. While the maximum temperature at position 2 on the surface is 29.5°C, the internal temperature at position II is 28.5°C.

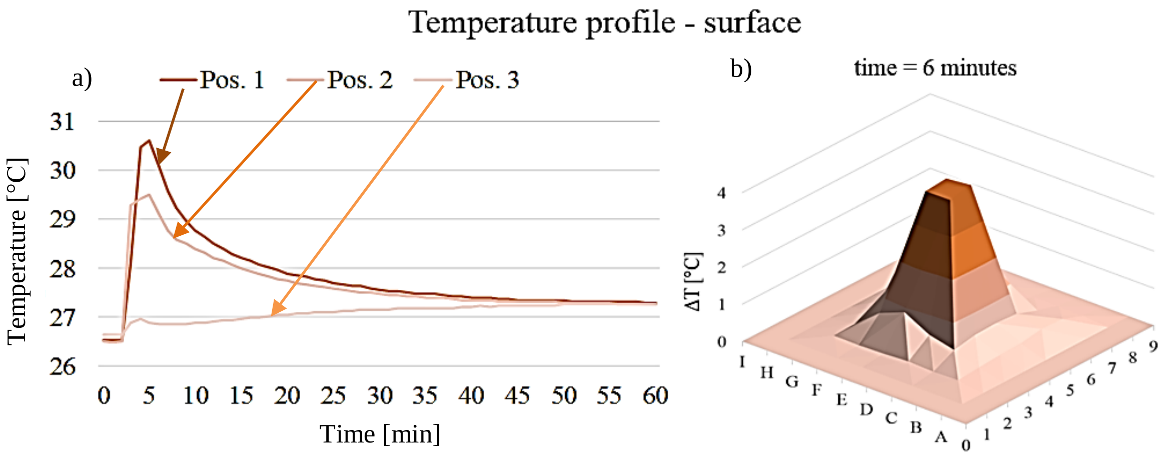

Fig. 10. a) Temporal course of the surface temperature, b) Temperature field at the time of the peak temperature

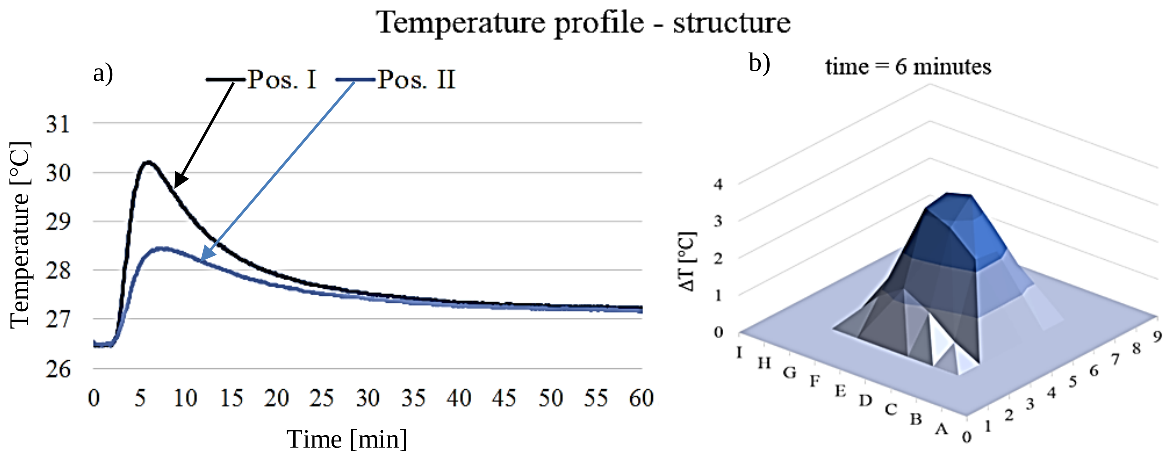

Fig. 11. a) Temporal course of the structure temperature, b) Temperature field at the time of the peak temperature

Over time, both diagrams show a similar course. At position I and II the structure takes about 45 minutes to reach steady state, which is equivalent to the ambient temperature. During the measurement, the ambient temperature rose by 1°C. The temperature profiles on the right side of the images show, that the temperature rise, that is caused by the hot chips is strongly decreasing with increasing distance.

5.2. EFFECTS ON DEFORMATION

The deformation behaviour correlates with the measured temperatures (see Fig. 12). Approximately 6 minutes after the chips touch the surface the maximum deformation is observed. At position A the largest value is 8 µm. At position B, the maximum is only half of it, while at position C a slight negative deformation of 1 µm can be observed. The negative values, on the edge of the table are due to free bending.

After about 10 minutes, vibrations or shocks affected the vicinity of the experimental setup. This lead to the overshooting of the course of position A to negative values. At position

B it lead to a contact loss of the probe to the table, that resulted in a remaining offset of the measurement signal of 2 μm that is not reversed.

The temporal course at the positions A and C shows, that the deformation is reversed after about 45 minutes.

Fig. 12b shows the maximum deformation plotted over the coordinate system of the machine table. As the plot indicates, the largest proportion of deformation is limited to the centre.

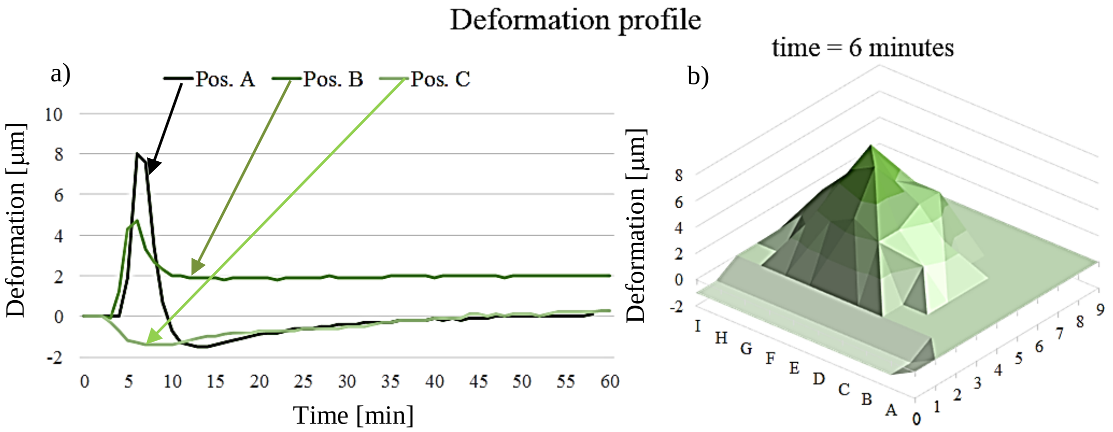

Fig. 12. a) Temporal course of the deformation, b) Deformation of the machine table at the time of the highest peak

6. DISCUSSION OF THE EXPERIMENTAL RESULTS

The measurements at the different positions show that the influence of hot chips on the temperature field and the deformation decreases sharply with growing distance. Beneath the accumulation of chips (position 1), a rise of the temperature by about 4°C and a deformation of 8 μm was measured.

Compared to the simulation, the maximum temperature is twice as high and it takes one and a half times as long to return to steady state again. The time to reach the maximum temperature is nearly the same. The measured maximum deformation is about three times as high as the simulated result. After 20 minutes most of the deformation is reversed, which corresponds to the simulated value. The total time for the deformation to subside is about 45 minutes, which is also the time the temperature needs to reach a steady state again.

The observed effects are limited in time, as presumed. In comparison other heat induced effects in machine tools, for example due to the heat from spindles and motors, often last several hours.

The results indicate that the applied simulation approach is not suitable for the calculation of exact values. Nevertheless, it is useful for preliminary investigation to get an idea of the general temperature behavior and the order of magnitude.

During real cutting processes new hot chips continuously hit the machine structure and will cause higher maximum temperatures and larger deformations. It will also take more time to reach a steady state again.

7. CONCLUSION

Even though it is generally known that chip accumulation in the working area should be avoided, especially during dry machining this goal is not achievable for every type of machine and every machining operation.

The results presented in the paper quantify the previously unknown influence of hot chip deposits on the thermal machine behaviour and the displacement of the TCP in dry cutting. Based on the results presented in section 5 and depending on the required accuracy, an initial estimation can be made as to whether the effects investigated are relevant for a real manufacturing process.

For example, if the required accuracy on a workpiece is less than 20 µm, the resulting deformation of 8 µm can lead to geometric errors of 40% in finishing processes that result in expensive reworking or rejects.

For these cases methods are needed to implement the effects in simulation models for correction purposes. Further investigations on the characterization of the chip distribution in the working area with a special consideration of its tool and workpiece dependencies have to be conducted.

We also recommend to measure the effect of hot chip accumulations in a real machining process with continuous chip feed.

A DOE to capture all relevant scenarios allows for a classification of work piece and process related heat sources and their potential effect on the machine structure. The process planer can then estimate if he needs to implement certain countermeasures in order to guarantee required work piece accuracies.

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