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MILLING TOOL DEFORMATION CAUSED BY HEATING DURING THE CUTTING PROCESS

The presented paper describes an experiment dealing with the deformation of a milling tool caused by heating during the cutting process. Based on the literature review an experimental procedure is designed to simulate heating of the milling tool during machining. The experimental heating of the milling tool is realized using a laser beam. The frequency of laser radiation and the length of each pulse are selected in order to simulate the real cutting process. The output power of the laser radiation is 10W or 20W. During the experiment deformation and temperature of the tool are measured. In the second part of the presented article an experiment is carried out investigating the heating and deformation of the milling tool during real machining of an aluminium alloy. The experiment consists of several test cycles, when a different amount of material is removed. Deformations of the tool and also of the machine tool are measured immediately after milling, and during cooling to ambient temperature. The results clearly show that there is a significant temperature rise of the milling tool during the cutting process, which mainly causes milling tool extension in the axial direction. The conclusion of the experiment is that the thermal deformation of the milling tool during machining cannot be neglected, as it can also be a source of certain errors.

1. INTRODUCTION

The heat produced by the cutting process is transferred to the tool, the workpiece, the machine tool itself and also to its environment. Temperature change of machine parts causes material thermal expansion, which is undesirable for the precision work of the machine tool. This fact applies not only to machine tools, but also to the cutting tool and workpiece. Measuring the temperature and deformation of the milling tool near the cutting edge during machining is complicated. This problem has been partially solved by several authors in the past. In one part of the reviewed articles the heating of the cutting tool is simulated in a variety of ways. The second part of the reviewed articles uses various methods for measuring temperature directly during machining.

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Suprock et al [1] used a solder tip for heating the replaceable inserts of the milling tool. This method represents a relatively efficient source of heat (up to 500°C), reduced to a small area. Temperature is measured using a thermocouple placed in a cavity underneath the insert. Heating of the cutting tool with a solder was also used by Konvicka et al [2]. Their work deals with the thermal deformations of a modular tooling system. Besides heating the tool tip, the heat source in the form of electrical heaters on the spindle shaft in the position of bearings is applied. The spindle shaft, the tool holder and the hydraulic clamping together form a test stand. The authors noted that hot air guns were first used for heating the tool tip. This method is inefficient because it greatly affects the entire cutting tool and its surroundings, including deformation sensors. Dewes et al [3] used an oxy-acetylene torch instead of a hot air gun for heating the tool tip. Unfortunately, the authors did not note more information about the achieved temperatures. Heating of the tools at a very high temperature and large thermal influence on the surrounding area are expected. Hayashi et al [4] used a silicon oil bath in their work for heating the turning tool equipped with a resistive temperature sensor. The authors assume the use of tools for fine finishing, so it is not necessary to achieve high temperatures. Tool was heated only to a temperature of approximately 45°C. Kato and Fujii [5] studied the spreading of heat in the steel solid body. They used a laser beam for heating of the solid body. The surface of the solid body was covered with a radiation-absorbing coating to prevent the reflection of the laser beam. A laser cutting machine was used for irradiating the solid body surface. Irradiation time was chosen between 0.1 and 1 second. It was a continuous CO_2 laser radiation with a wavelength of 10.6 micron and power 0.2kW, beam diameter 5mm, the average heat flux $10.2 W/mm^2$. The laser beam seems to be very suitable for heating the cutting tool tip.

A comprehensive literature review [6] devoted to measuring the temperature during machining mainly lists resistive sensors and the thermocouple methods. Below are the methods based on the thermophysical processes and temperature measurements based on the spectral radiation of the solid body. Methods based on the fact that high temperatures cause a change in the material hardness, metallurgical changes and changes in chemical composition, are mentioned by Li and Shin [7]. These include the method of micro-hardness measurement, scanning using electron microscopy, energy dispersion by X-ray scanning, or the use of temperature-sensitive coatings on tools. For the workshop environment only thermocouple and RTD are practicable. It is possible to use an infrared camera, only in the case of dry machining and correct emissivity setting of the scanned body. Although the camera records the temperature at the surface of the cutting tool, the maximum temperature is achieved on the lower side of the chip, at the point of contact with the tool.

2. EXPERIMENTAL HEATING OF A MILLING TOOL USING A LASER BEAM

The heat load of the milling tool during operation was simulated by heating with a laser beam. During heating and subsequent cooling, temperature near the cutting edge and axial deformation of the tool were measured. The whole process was also scanned by an infrared camera to capture the heat transfer from the point of heat sources to the surrounding area.

2. 1. EXPERIMENTAL SET-UP

Experimental measuring of deformation depending on the temperature of the milling tool was carried out on the Lumonics JK701H machine equipped with a solid-state Nd:YAG laser. The machine is designed for cutting, drilling, welding and cladding. Laser wavelength is 1064nm; output power is adjustable from 0 to 550W. Pulse width is adjustable from 0.5 to 20ms and pulse energy from 0.1 to 70J. The frequency of radiation is selectable in the range of 0.2 to 500Hz. By adjusting the mentioned parameters of laser radiation, real cutting conditions can be simulated. The frequency of laser radiation corresponds to the frequency of the milling tool rotation. The width of a pulse can then be compared to the time of contact of the blade with the material during one revolution. The experimental stand was arranged on the laser machine´s table (Fig. 1).

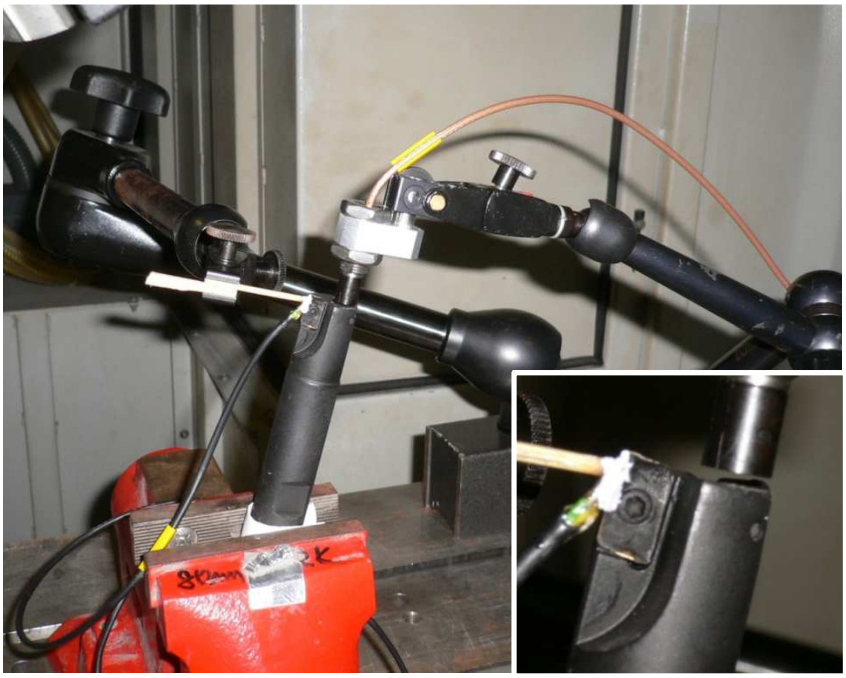

Fig. 1. Arrangement of the experimental stand

The measurement was carried out on double-edged cutter with a length of 100mm and a diameter of 20mm (AMS Alpha Mill 2020s). The beam radiation was focussed close to the cutting edge of one of the inserts on an area of 1.3mm in diameter. Two tests were conducted at laser output power 10W and 20W. The frequency of radiation was set to 16.6Hz, which corresponds approximately to a 1000rpm milling tool. The selected width of a pulse of 7ms and a frequency of 16.6Hz correspond to the fact that the insert is in the cutting contact about 12% of the time during one revolution of the tool. One pulse supplies

0.6J to the inserts in the case of laser power 10W, or 1.2J at 20W output. The tool was heated for 10 minutes, and then cooling back to room temperature (approx. 20°C) followed. During the entire cycle of heating and cooling the temperature was measured near the cutting edge of the insert and the axial deformation of the tools was measured (Fig. 1). The temperature was measured using resistance temperature sensor Pt100. For better heat transfer between the sensor surface and insert, special heat conductive paste was applied. Axial deformation was measured using a contactless "eddy current" probe. The entire experiment was in addition scanned by an infrared camera, to record the temperature fields of the tool and its surroundings. For this purpose, the tool was covered with a special coating of known emissivity of radiation.

2. 2. RESULTS OF THE EXPERIMENT

Measurement of milling tools axial deformation in response to temperature changes showed that the progression is nonlinear. Fig. 2 shows the progression of milling tool axial deformation depending on the temperature during heating and subsequent cooling.

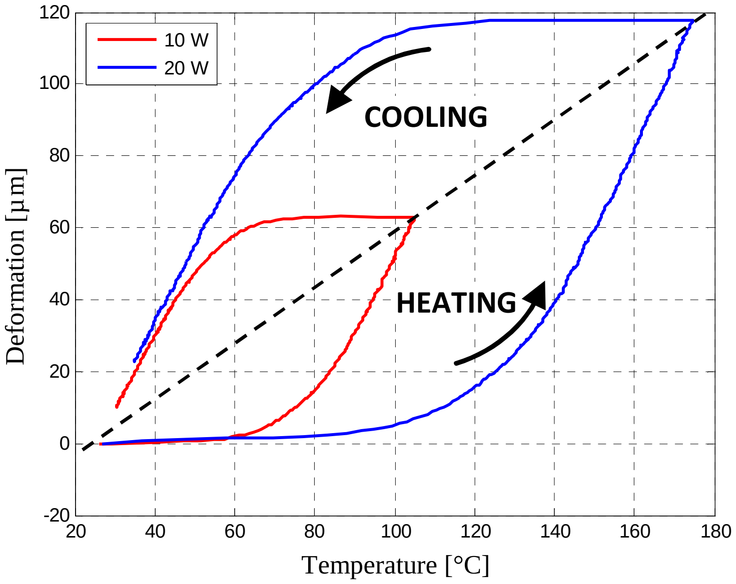

Fig. 2. Milling tool axial deformation in response to temperature changes

It is an apparent hysteresis caused by the uneven heating of the tool body. After the start of heating, temperature starts to rise sharply, while the deformation is almost unchanged. The same thing occurred after the end of heating. The temperature decreased sharply, without causing a change in deflection. This effect is caused by the gradual spread of heat in the material, which happens with a certain time lag. It should also be noted that the sharp increase or decrease in temperature happens in a very short period of time (see

Fig. 3a), and only close to the cutting edge of the insert where a heat source was also applied. The progression of milling tool deformation is relatively fluent during heating and cooling (see Fig. 3b), due to a time lag of heat transfer in the material. Comparison of measured values for the heating laser power 10W and 20W shows a linear relationship between the heat source and the deformation caused by temperature change.

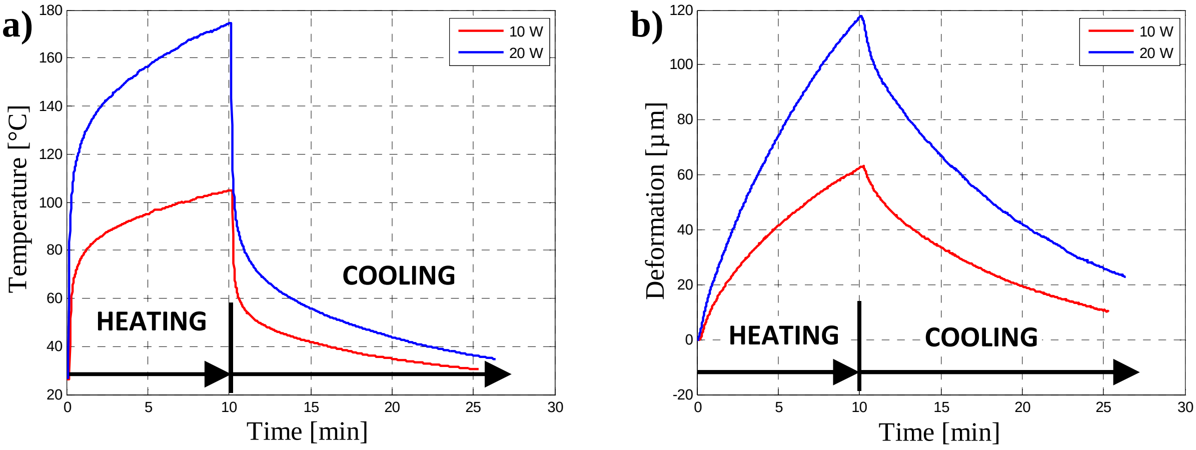

Fig. 3. The temperature at the cutting edge of the insert according to the time of heating and cooling - a), axial deformation of the tool depending on the time of heating and cooling - b)

A ten-minute heating by 10W power caused a tool extension of 63µm. Heating by 20W power extended the tool by 118µm. In the case of dependent performance of the heat source and tool temperature, linearity does not apply, mainly due to heat transfer from the instrument to a cooler surrounding area. When the power was 10W, after ten minutes of heating the cutting edge temperature was 105°C. With the power of 20W the temperature was 175°C.

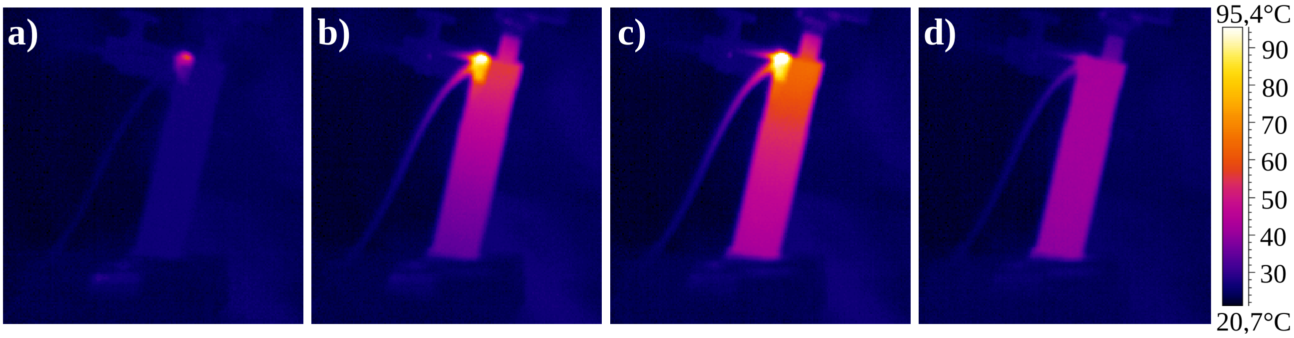

Fig. 4. Heating of the milling tool by laser beam with 10W output power: a) initiating of heating, b) after 5min of heating, c) after 10min of heating, d) after 5 min of cooling

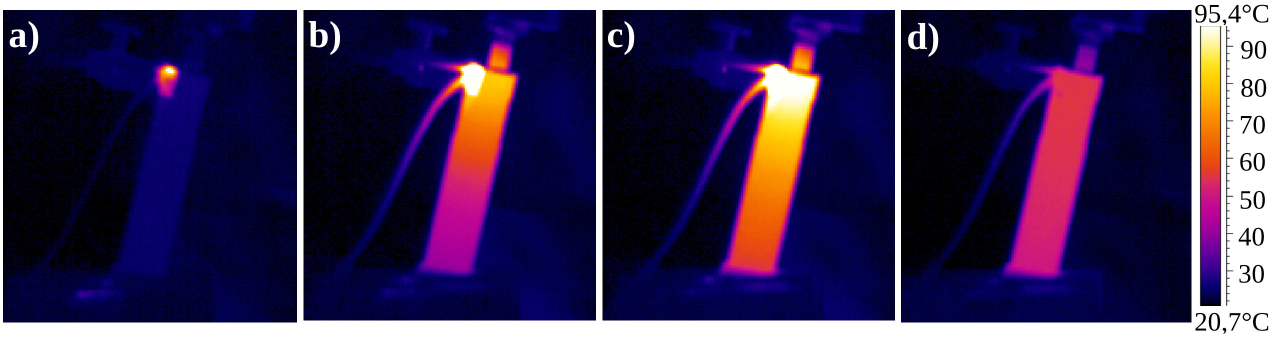

Fig. 5. Heating of the milling tool by laser beam with 20W output power: a) initiating of heating, b) after 5min of heating, c) after 10min of heating, d) after 5min of cooling

The entire experiment was also scanned by an infrared camera. Fig. 4 and Fig. 5 show the pictures taken when the thermal source started to work, after five and after ten minutes of heating and after five minutes of cooling down. From these images it is easy to see heat transfer in the material from the point of the laser beam.

3. MILLING TOOL DEFORMATION CAUSED BY HEATING DURING MILLING

The experiment was based on measuring the deformation of the machine tool and milling tool induced by warming from the heat produced during the cutting process. The aim was to detect the effect of the amount of material removed, or more precisely, of the machining time on tool warming, or its deformation.

3.1. EXPERIMENTAL SET-UP

The experiment was performed on a vertical three-axis milling centre. The machine was not equipped with covers, allowing easier access for placement of sensors and scanning by infrared camera (see Fig. 6a). The working space of the machine was divided into machining area and measuring area. In the measuring area seven proximity sensors were placed for measuring deformation at selected positions on the machine tool so that deformation of the tool could be obtained, without the intervention of machine tool deformation. The milling tool deformation was measured in the X, Y and Z direction; the machine tool deformation was measured on the spindle also in the X, Y and Z direction, and on the table in the Z direction of the machine tool coordinate system (see Fig. 6b). The milling tool with three replaceable inserts and Ø32mm was used. Tool length including tool holder from the spindle nose was 175mm, length of the protruding part of the tool from the tool holder was 67mm.

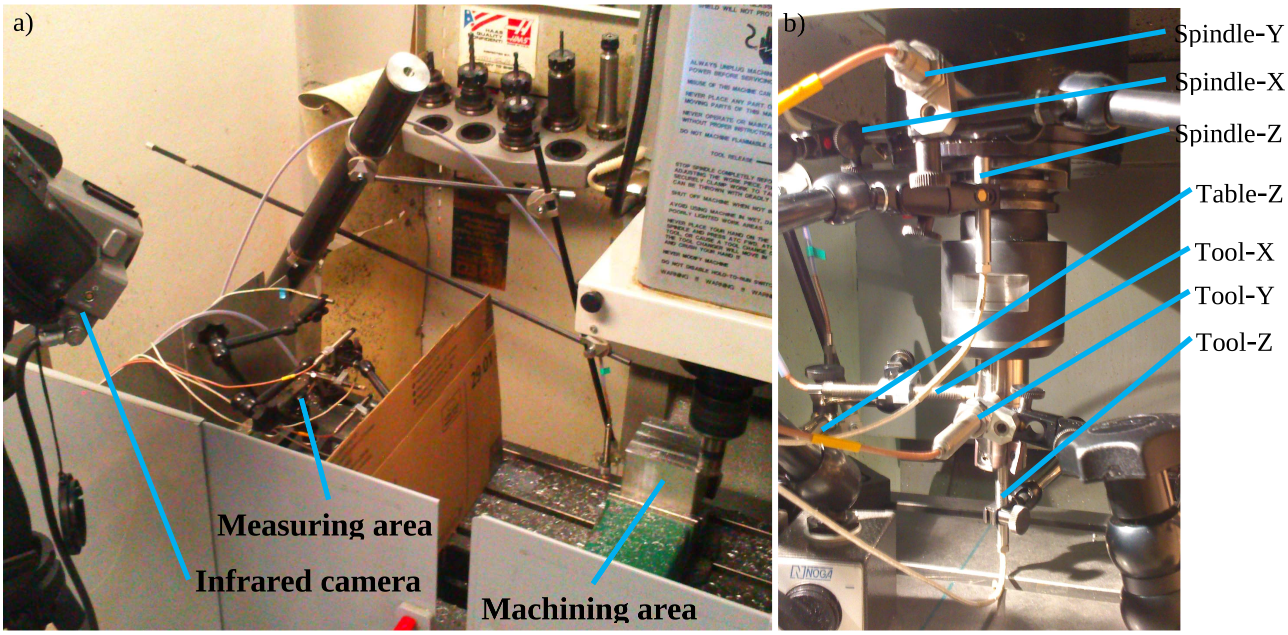

Fig. 6. Experimental set-up

An aluminium rod with dimensions of 100x100mm was machined, from which individual layers were successively taken. The spindle speed was 2000rpm, axial depth of cut was 2 mm and feed rate was 300mm/min (i.e. 0.15mm per revolution, 0.05mm per tooth). Machining was carried out in the absence of coolant. After each machining cycle the machine was positioned to the measuring position and deformation was measured. It stayed in the measurement position until the tool cooled down to ambient temperature, or more precisely, until the deformation of the milling tool returned to values close to zero. During cooling in the measuring position the spindle still rotated at 2000 min. The parameters of the individual machining cycles are summarized in Table 1.

Table 1. Machining cycle parameters

Machining cycle [-]	Layers removed [-]	Amount of material removed [cm^3]	Machining time [min:sec]
1	1	20	1:49
2	2	40	3:38
3	4	80	7:16
4	8	160	14:32
5	16	320	29:04

The process of machining and milling tool cooling was scanned by an infrared camera with a period of 5 seconds. Pictures taken with an infrared camera can be considered as indicative only, as it is very difficult to accurately set the emissivity of the scanned material, if not directly known. Acquired images therefore only provide information about temperature change, not its absolute value.

3.2. EVALUATION OF MEASURED RESULTS

The evaluation of the axial deformation of the milling tool, or more precisely of the tool with the tool holder is the most important information from the set of the obtained data. Furthermore, the data provide information on mutual distortion of the machine tool structure. Pictures taken with an infrared camera show the process of heating the tool during machining and the process of cooling to ambient temperature in the measuring position.

The values of milling tool axial deformation were obtained by subtracting the deformations measured at the head of the spindle and deformation measured at the tool tip. The result is the extension of the milling tool including a tool holder with a total length of 175mm. The results are shown in the graph in Fig. 7. The graph shows that while the machining time at each machine cycle increases twice, the tool increases more gradually.

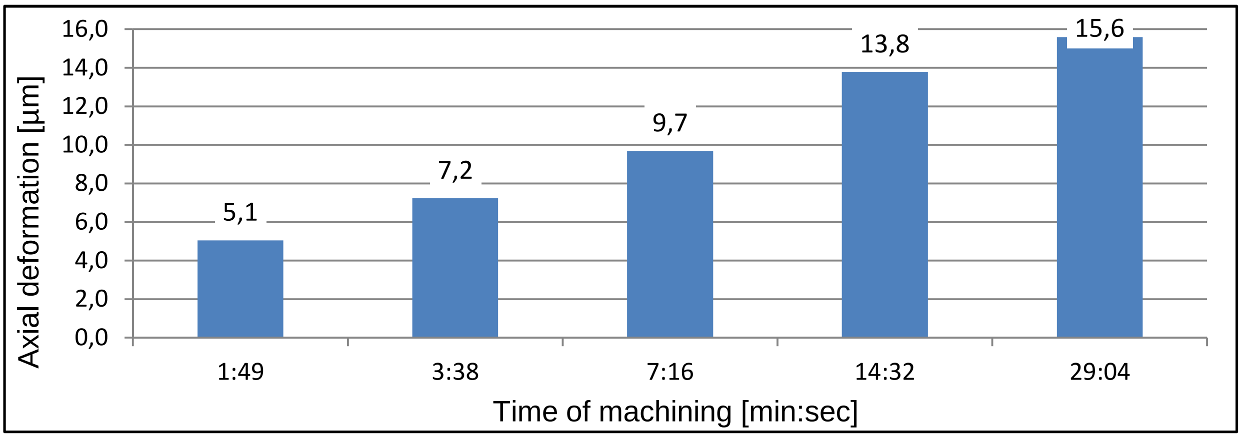

Fig. 7. Axial deformation of the milling tool after milling in individual cycles

Axial deformation during cooling of the milling tool is shown in Fig. 8. It should be noted that the results may be affected by the angular deformation of the machine tool structure. Prior to the test the machine was not perfectly heated, and therefore it was still heating up during the experiment, which caused its deformation. A thermally unbalanced condition of the machine tool during the experiment most probably caused the phenomenon shown Fig. 8. The deformation during cooling, after machining the last cycle (16 layers, 320cm^3), decreases more steeply than the previous characteristic during solidification. While the tool has been cooled after each machining cycle, the machine warmed throughout the whole experiment. Heating was mainly from the spindle, which is constantly rotated throughout the whole experiment.

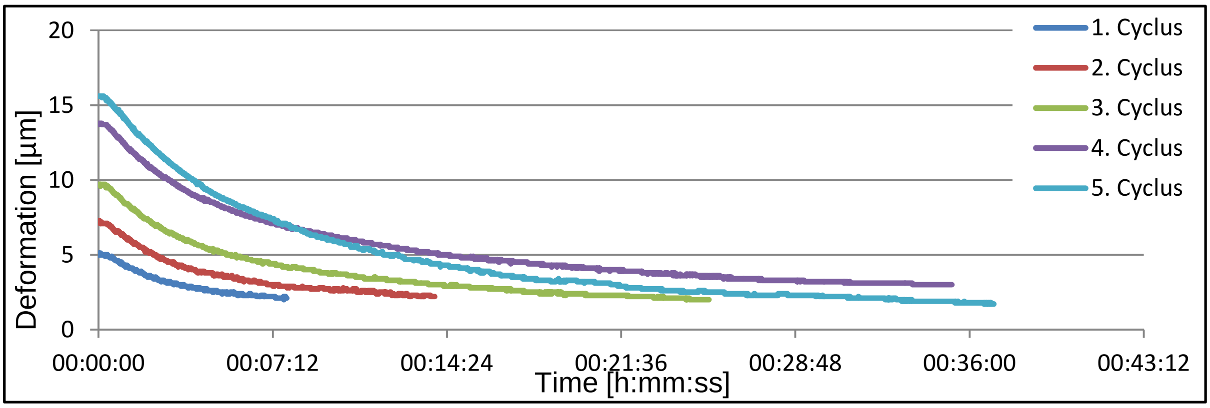

Fig. 8. Milling tool axial deformation during cooling in measuring position

The considerable angular deformation of the machine tool structure does not sufficiently accurately evaluate the deformation of the tool in the radial direction. Due to the dimensions of the tool the detected deformation of the tool in the axial direction can be assumed as an enlargement of the tool diameter by approximately 2 to 3µm. This value may not be completely negligible, but at the same time it cannot be considered as critical.

Temperature during the whole experiment, divided into five cycles, is shown in Fig. 9. The graph shows the temperature curve for each machining cycle, always before the start of machining, at the last cut of each machining cycle, just after completion of each machining cycle and after cooling to a temperature close to ambient temperature.

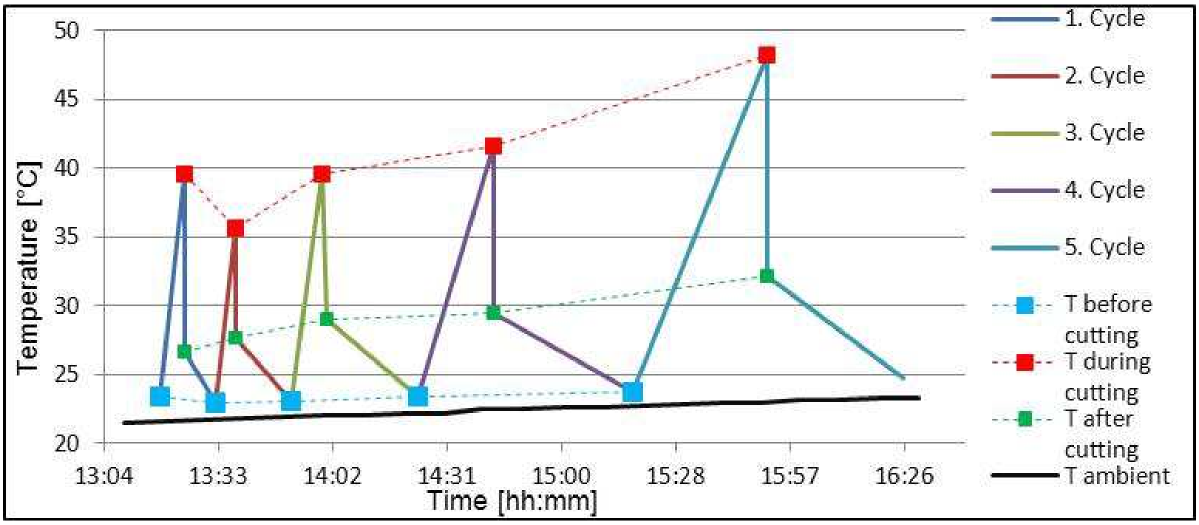

Fig. 9. Milling tool temperature during experiment

The ambient temperature in the measuring area is also plotted in the graph for comparison. As expected, it was confirmed that the temperature of the tools increases depending on the machining time. Function is not directly proportional, which is mainly due to the fact that heat produced during the cutting process is transmitted to the tool and continues to spread around from the tool. Temperatures at the milling tool end in the cut cannot be considered as absolutely accurate through resolution of the infrared camera. As is known, the temperature at the cutting edge can be moved even in the order of hundreds of degrees Celsius. When the experiment was measured, temperature exceeded a value in the range of 35 - 48°C. The measured temperature is the temperature of the bottom of the tool body, rather than the value in the cut. The method of measuring temperature using an infrared camera depends on the camera resolution. A temperature value is recorded for each pixel. This value corresponds to the average temperature on the surface of the pixel. Therefore, large thermal gradients taking place on a small area cannot be identified with sufficient precision. This fact is most likely responsible for the difference in the temperatures in the tool tip section (Fig.) when the temperature during the second machine cycle is significantly different from the expected characteristic. A comparison of the temperature of the milling tool during machining and temperature immediately after shows how rapidly the temperature at the tool tip decreases. This is also evident from the images taken by infrared camera (see Figs 10 -14).

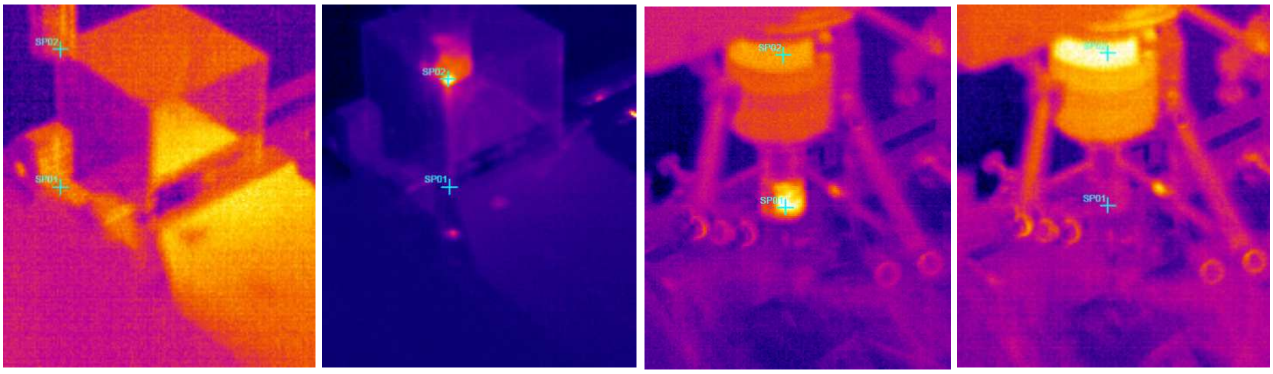

Fig. 10. Infrared images taken during 1st machining cycle and following cooling

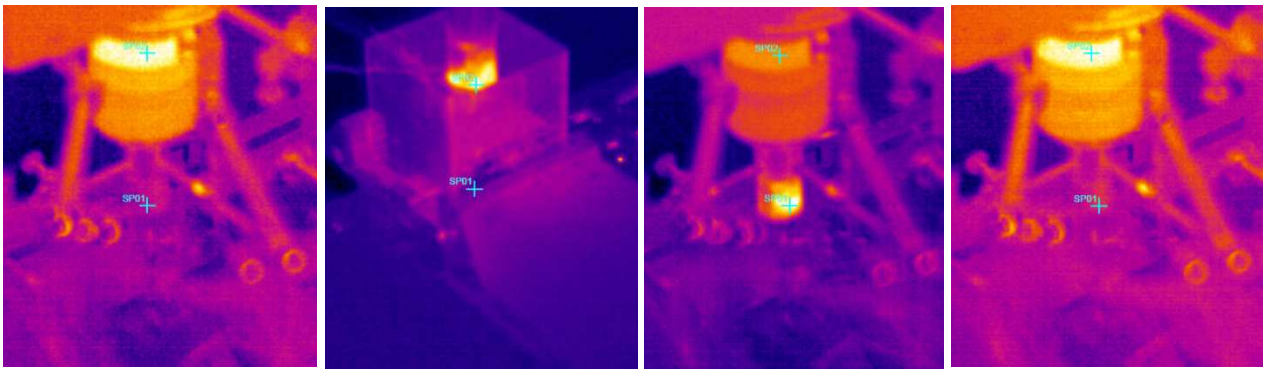

Fig. 11. Infrared images taken during 2nd machining cycle and following cooling

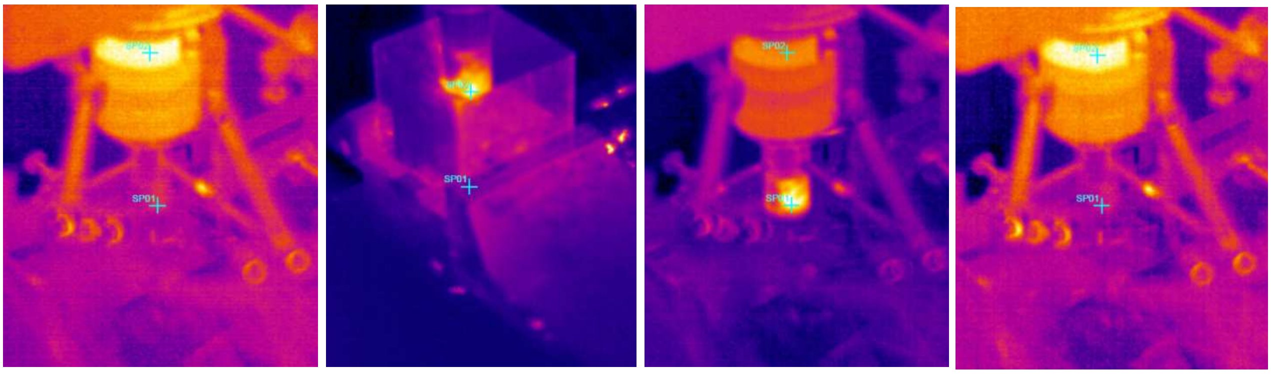

Fig. 12. Infrared images taken during 3rd machining cycle and following cooling

Fig. 13. Infrared images taken during 4th machining cycle and following cooling

Fig. 14. Infrared images taken during 5th machining cycle and following cooling

4. CONCLUSION

The experiments clearly showed that the deformation caused by the heating of the tool during the cutting process cannot be neglected because it can be a source of errors. The maximum temperature is not pivotal for the axial deformation of the milling tool because it only occurs in a very small area. It is the temperature change around the whole tool body caused by the heat transferred into the tool during machining that is significant. This is only influenced by machining time if the cutting conditions are constant.

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