In process temperature and tool wear for the machining of aeronautic aluminum under different lubrication conditions

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ABSTRACT

The use of aluminum-lithium alloys in aeronautics is an efficient solution for lightweight structures, but its machinability can cause increased tool wear. The cutting temperature is one of the most important parameters controlling the tool wear and the quality of machined surfaces. Therefore, its measurement is of great interest to analyze the heat generation during the cut and then being able to limit it in the cutting edge. This article presents an original experimental study of the cutting temperature of two aluminum alloys (7000 series and Li-containing 2000 series), for dry, MQL: Minimum Quantity of Lubrication and wet machining conditions. The interactions between tool wear and cutting temperature are also investigated. To be able to observe tool wear, the milling of very large volumes of aluminum alloys has been necessary since the tool lifetime is several hours when machining this kind of material. To measure temperature as close as possible the cutting zone, an original set-up with machinable thermocouples was used, enabling measurements on a large frequency bandwidth. Complementary investigations by Second Ion Mass Spectroscopy revealed a diffusion of lithium in the cutting insert, which can reduce its lifetime (divided by 8, with the Li-containing 2000 series compared to the 7000 series).

KEYWORDS

Cutting temperature; lubrication; machinable thermocouples; tool wear

Introduction

In the industry, innovative aluminum alloys are developed such as aluminum-lithium. Indeed, they have very interesting properties such as lower density, high mechanical strength and high stiffness. However, the machining of these new alloys can lead to premature tool wear, compared to classical aluminum alloys. One solution consists in reducing the cutting conditions which results in lower productivity and quality.

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The heat generation and the plastic deformation induced during machining affect the machined surface. In particular, the heat generated induces residual stresses and activates the tool wear mechanisms. Therefore, it is of great interest to analyze and identify the heat generation during the milling of aluminum alloy for different lubrication conditions of lubrication.

Different studies have been conducted to determine cutting temperature when machining, particularly in turning.

A very common method is the use of a pyrometer or infrared camera to observe the contact between the tool and the workpiece. In that way, Kuzcmaszewski and Zagòrski (2013) used data collected from thermal image sequences to analyze the face milling of magnesium alloy. They observe that changing the cutting speed does not cause a significant increase in the temperature in the cutting area. Nevertheless, this method can entail dealing with inaccuracy due to changing emissivity coefficient and is inapplicable with lubricant.

Then a very reliable temperature measurement method in machining is the use of a thermocouple; either embedded in the workpiece, or in the tool depending if it is turning or milling. Kerrigan and O'Donnell (2013), for example, used a Wireless Tool-Integrated sensor (developed by ACTARUS) to measure temperature in CFRP: Carbon Fiber Reinforced Polymer Milling. The review of Davies et al. (2007) on the temperature measurement in material removal processes demonstrates a very good time resolution and a weak uncertainty for the thermocouple. Kitagawa et al. (1997) (Kitagawa, Kubo et Maekawa 1997)provide quantitative data on tool temperature with increasing cutting speed and were interested in tool wear characteristics in high-speed machining from a thermal point of view. Measurements of cutting temperatures were made (by an embedded thermocouple in the tool) during intermittent turning a titanium disk, which was supposed to simulate a milling process. Thanks to this device, the authors observe that the maximum rake temperature is lower for intermittent cutting than for continuous cutting by approximately 15%. They also show that wet cutting led to a decrease in the maximum temperature and in the temperature in the non-cutting period in comparison to dry conditions.

However, temperature measurements during intermittent turning do not consider the change in the chip thickness while cutting which occur in milling. That's why other authors such as (Hou, Zhao et Zhu 2011) Hou et al. (2011) used in their work an embedded thermocouple inside the workpiece to measure the temperature profile while face milling a magnesium alloy. During milling, the thermocouple is heated by the shear plane until the top of the thermocouple is cut off. Authors show that the temperature increases slightly when the cutting speed is less than 1,507 m/min.

However, because only one part of the sensor is cut off during the milling, the authors observe only 3 °C of temperature rise. Kesrikioglu and Pfefferkorn (2018) also used embedded thermocouples in milling.

To obtain a more precise temperature on the cutting edge, Dewez et al. (1999) propose a machinable thermocouple. The authors implant a suitable insulated thermocouple wire into a workpiece. When the workpiece is sheared during the machining process, the insulation is broken, and an instantaneous hot junction is formed between the wire and the workpiece material in the cutting zone. Thanks to this method, authors observe that temperature increased with cutting speed and no reduction at higher speeds occurred. Moreover, machining with a worn tool generated higher temperatures when using new tools. Hirao (1989) with this method was able to determine the temperature distribution on the flank face of the cutting tool. He demonstrated that with a small enough wire, very fast response time (about 100 kHz) may be reached. This machinable device is also very useful to measure temperature in the contact zone in grinding processes (Lefebvre et al., 2012).

Le Coz and Dudzinski (2014) also studied temperature variation in the workpiece and in the cutting tool when dry milling Inconel 718. A similar measurement method as Dewez et al. (1999) was employed. Indeed, a specially developed machinable thermocouple was used. The hot junction was realized by the action of the cutting edge. It consisted of two dissimilar thermocouple materials, iron and constantan, to form a standardized and calibrated J-type thermocouple combination insulated from the workpiece by using mica. During the cutting test, as soon as the cutting edge of the tool cut off the sensor, a smearing of one material upon the other was produced, creating the first hot junction of the thermocouple. This junction allowed the measurement of the temperature at the tool-workpiece interface. The authors also measured the subsurface temperature by using an embedded thermocouple. Then they defined what they called a gradient temperature from the surface to the subsurface. A large temperature gradient was observed from the surface to the subsurface, especially for the higher cutting speed values.

Because of the promising results of Le Coz and Dudzinski (2014), the same type of machinable thermocouple was used in the present study. Therefore, the temperature in the contact area of a milling process was measured on two different aluminum alloys (a Li-containing 2000 series alloy and a 7000 series alloy). First, a frequency analysis was performed to determine the contact time between the tool and the workpiece. The temperature profiles for three different cooling conditions (dry, MQL and wet lubrication) and for different tool wear rates were analyzed. Finally, Second

Ion Mass Spectroscopy (SIMS) cartographies were done on the tool after machining Li-containing 2000 series to better understand the tool wear.

Experimental setup

Materials used

The sample was composed of two pieces of aluminum alloy of 100 mm height, 30 mm length and 200 mm width. 10 300 µm section channels were machined in a lonely aluminum piece to insert thermocouples.

Two types of aluminum alloy A (Li-containing 2000 series alloy) and B (7000 series alloy) were used. The A alloy was slightly less dense than the B alloy (−5%) and it was also less able to evacuate the heat. Indeed at 20 °C the thermal diffusivity of the B alloy was 50% higher than for the A alloy and 34% higher at 300 °C.

Cutting conditions and temperature measurement

Table 1 present the cutting conditions that were chosen for the experiments. They are common ones in the High-Speed Machining of aluminum alloys in the aeronautic industry (Wang et al., 2020).

The machine-tool was a Huron KX30 equipped with a Fischer spindle MFW2310 (24kRPM, 70 kW). The tool was a 40 mm-diameter R4 bull-nose tool with four uncoated Kennametal inserts, which is typically used for rough milling operations in the aeronautic industry.

Experiments under different lubrication conditions were carried out: dry machining, wet machining and MQL machining. For the wet machining, a Blaser emulsion lubricant type was used. Moreover, all along the study, cutting conditions were identical. The stability of the cut has been verified during all the experiments, by vibration measurement with EmmaTools device (Godreau et al., 2019).

An original setup for thermal measurement in milling was developed, as presented in Figure 1. The temperature of the aluminum sample was measured by a sequence of five thermocouples (K type) along the height of the workpiece. They were inserted in the sample perpendicularly to the toolpath (Figure 2). The first thermocouple was placed 3 mm below the top of the sample. The other thermocouples were separated by 5 mm between each other. The diameter of each wire of the thermocouples was 125 µm

TABLE 1. Cutting conditions of the milling process.

a_e (mm)	a_p (mm)	N (rpm)	f_z (mm/tooth)
30	5 mm	24,000	0.1

a_e is the width of cut, a_p the depth of cut, N the spindle speed and f_z the feed per tooth.

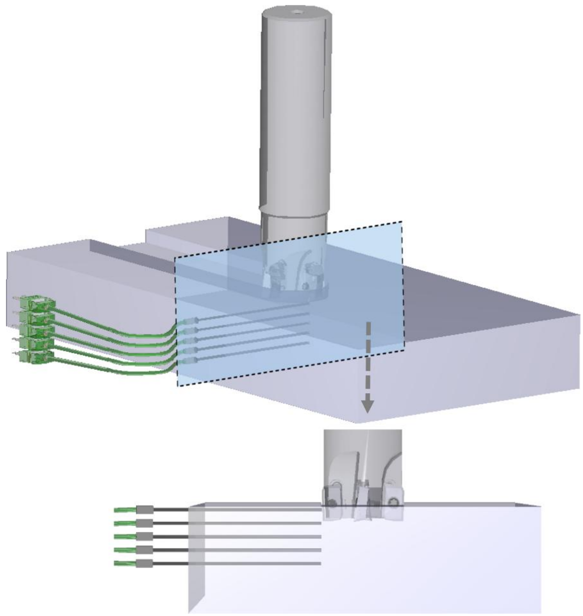

FIGURE 1. Temperature measurement set up. Schematic view of one face before milling.

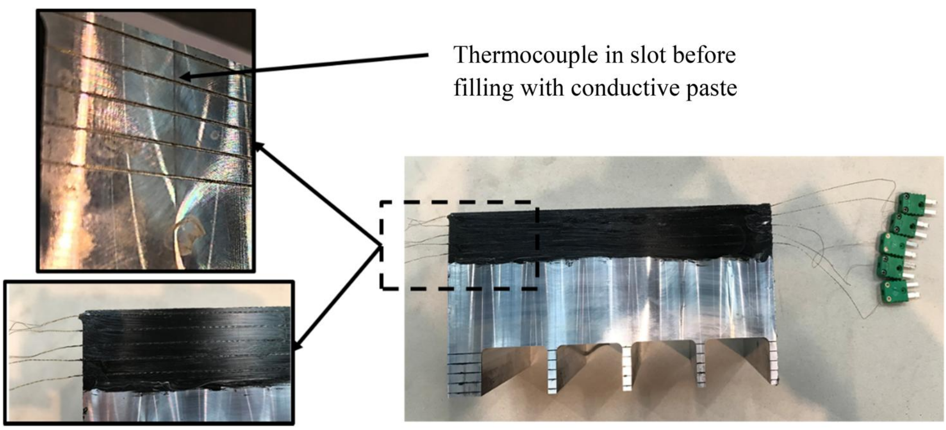

FIGURE 2. Experimental setup for thermal measurement.

and was surrounded by a 10 µm isolating polyimide coating. The two wires of the thermocouples were twisted together to make the couple stiffer and to insert it properly in the channel of 300 µm width and 300 µm depth. The thermocouple channels were then filled by an electrically conductive paste and the thermocouples were then inserted in the channels.

The temperature was measured during the milling. Indeed, each time the tool is cutting the thermocouples a hot junction was created thanks to the contact between the tool and the two wires of the thermocouple. Therefore, the temperature was measured as close as possible to the surface of the sample. The electrical contact between the two wires of the thermocouples was also guaranteed by the conductive paste. In this case, the conductive paste was considered as an isothermal intermediate media which does not influence the temperature measurement. This hypothesis was made by Le Coz and Dudzinski (2014) and validated by the review of Bhirud and Gawande (2017).

The temperature was studied during a pocket machining operation of the two aluminum alloys under three lubrication conditions: dry, wet or MQL. The pocket got a parallelepiped shape and corresponded to a metal removal of 0.19 dm^3. Several pockets were machined until respectively a 0.06 mm and a 0.2 mm VB: Tool Flank Wear. The effect of the tool wear on the temperature in the contact area was then investigated in the TC: Thermocouple-instrumented sample, for its two wear levels VB of 0.06 and 0.2 mm.

The temperature recording was performed by an HBM quantum MX840 device. The sample frequency was 19,200 Hz and a low-pass filter with a 2,000 Hz cutoff frequency was applied. This cutoff frequency has been chosen to observe the teeth passing frequency at 1,600 Hz. The recording of the temperature signal was triggered by a machine's signal to automate the measurement.

Results and discussions

Based on the cutting conditions and tool dimension, the contact time t was determined and was 0.125 s (Equation (1)).

$$t = R_{\text{tool}}/(Z.f_z.f_s) \tag{1}$$

where R_{tool} was the radius of the tool in mm, f_z the feed per tooth in mm, Z the number of teeth and f_s the spindle frequency with $f_s = N/60$.

The tooth passing frequency f_t was also calculated from Equation (2) (1,600 Hz in the cutting tests).

$$f_t = Z.f_s \tag{2}$$

Figure 3 is an example of a temperature profile during a dry-cutting path. Before the tool reaches the thermocouple, the temperature measured by the thermocouple is the sample temperature. When the tool reaches the thermocouple, the measured temperature increases very quickly, stays high, and finally decreases to the initial temperature. The measured temperature appears to be noisy (numbers of peaks can be seen in Figure 3), but a closer look at the evolution of temperature enabled the understanding of the occurrence of these peaks.

In the following parts, a frequency analysis was first made to link the obtained signal to the milling conditions. Then the signal has been processed to determine a coherent milling temperature and to be able to observe the effect of dry MQL and wet conditions on the tool wear in a thermal point of view.

Frequency analysis of the temperature profile

Figure 4 presents three different time windows (from Figure 3), to observe more accurately the evolution of the temperature during the machining of the toolpath. The temperature is plotted between 0 s and 0.05 s in the

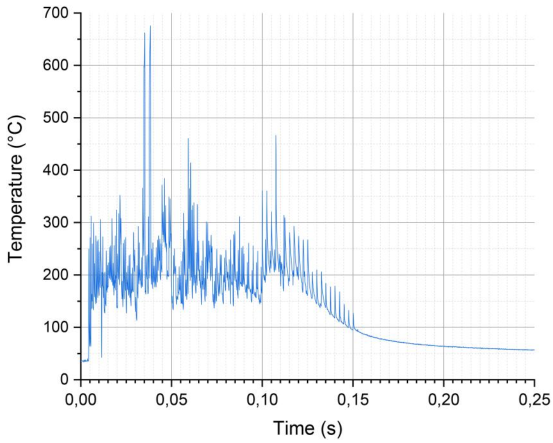

FIGURE 3. Temperature profile of the dry machining of a 7000 series aluminum sample.

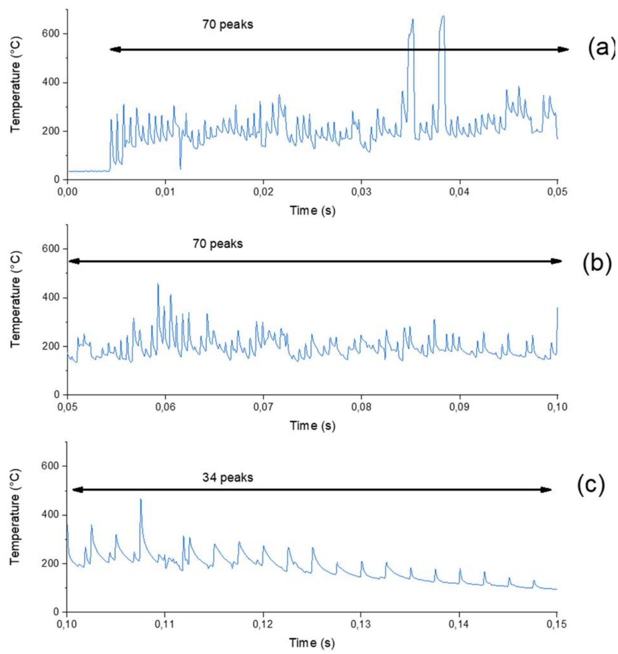

FIGURE 4. Temperature profile during dry milling divided into three parts (a, b, c).

subgraph (a); the temperature is then plotted between 0.05 s and 0.1 s in the subgraph (b); the temperature is finally plotted between 0.1 s and 0.15 s in the subgraph (c). The “noisy” appearance of the signal is due to temperature peaks, which seem to occur periodically (Figure 4).

Hence, the time between two peaks in Figure 5 has been measured. Figure 6 presents the evolution of temperature between 0.085 s and 0.095 s. The temperature peaks are easily observable and the duration between two peaks is generally close to 0.65 ms, which corresponds to the tooth passing frequency at 1,600 Hz. However, in some cases, this duration is significantly longer and corresponds to an 800 Hz frequency. These figures demonstrate that the peaks were due to the passing of the teeth of the cutting tool on the sensor. The higher frequency was related to the cutting frequency (four teeth at 400 Hz). The lower frequencies at 400 Hz are explained by the slight differences in the radial eccentricity of the inserts of the tool, of which the largest one passes periodically at the spindle frequency f_s (Ritou et al., 2014) (Ritou, et al. 2014). Indeed, each insert cannot be mounted exactly in the radial position on the tool. The difference between one tooth and the next one may be about 20 µm. This difference had a very limited

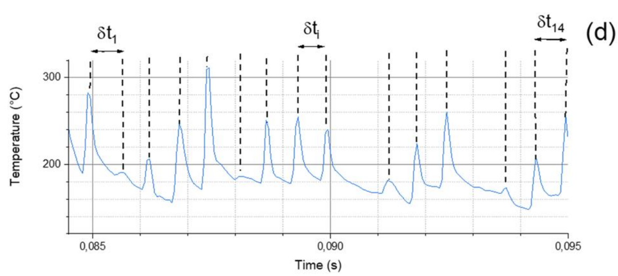

FIGURE 5. Temperature profile for dry machining (between 0.85 s and 0.95 s).

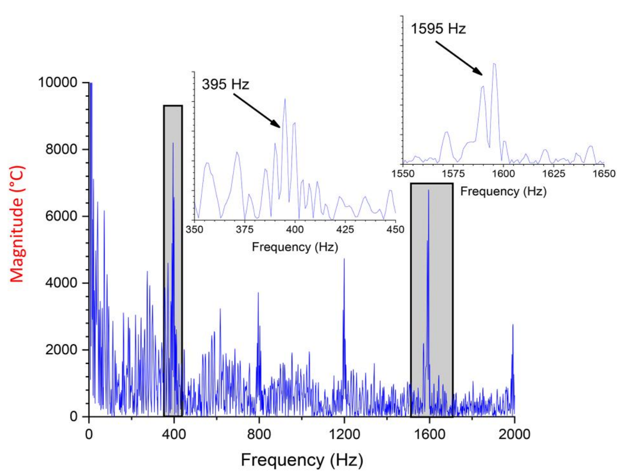

FIGURE 6. Frequency spectrum of the temperature during the toolpath.

impact on the signal at the beginning of the measurement. However, at the end, when the thermocouple is almost perpendicular to the tool path, this is only the longer tooth which may cut the thermocouple. The other teeth are not long enough to touch the hot junction and to provoke any temperature peaks, the signal frequency is therefore 400 Hz.

To confirm the relation between the teeth of the tool and the temperature peaks from the signal, a spectrum analysis was performed on the temperature signal thanks to an FFT: Fast Fourier Transform algorithm. Figure 6 presents the magnitude of the frequency spectrum of the temperature signal during the dry cut. The magnitude of signal is high at very low frequency (due to slow evolution of signal shape in Figure 3). Two contributions at 395 Hz and 1,595 Hz are clearly noticeable, which corresponds respectively to the spindle frequency (400 Hz) and the tooth passing frequency (1,600 Hz).

Signal processing and determination of the cutting temperature in the ending contact zone

The frequency analysis revealed a consistent relation between the cutting speed and the occurrence of temperature peaks. However, it was also essential to obtain a coherent workpiece temperature from these peaks.

In their work, Le Coz and Dudzinski (2014) (Le Coz et Dudzinski 2014) explained that during milling, as soon as the cutting edge of the tool cut the thermocouple, a first hot junction was created. As a result, the created junction allowed the measurement of the temperature at the tool-workpiece interface. The entire tool was moving linearly depending on the feed direction and on the feed per tooth amplitude. Then a succession of hot junctions was created until the last intersection of the tool at the final junction. The thermocouple observed a peak temperature when a tooth was crossing the sensor, then a decrease of temperature when the tooth was gone. These peaks successions were defining the gradient of temperature in the cutting edge. However, those temperature variations were very quick and occurred in the extreme surface of the sample. Indeed, in their work (Le Coz and Dudzinski, 2014) with an embedded thermocouple sensor placed at only 0.5 mm of the contact zone were unable to observe the same variations. Therefore, these peaks seem to be related to a very quick localized heating which does not affect the workpiece integrity. To get rid of these peaks, in the grinding process, Rowe et al. (1995) defined the background temperature whose maximum must not overcome a threshold hereafter grinding burns will occur.

In this article, the signal of the thermocouple was processed to obtain the background temperature to define the temperature profile absorbed by the workpiece. Batako et al. (2005) in their study removed the temperature

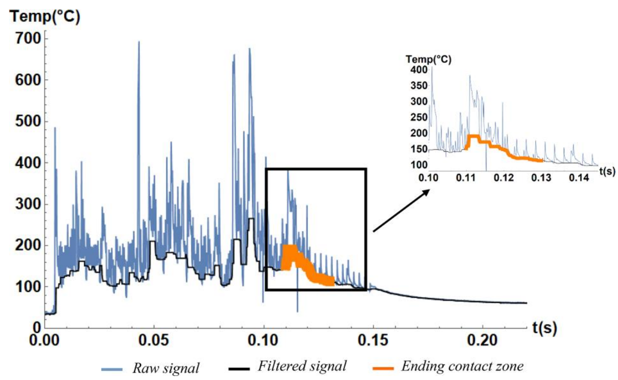

FIGURE 7. Background temperature profile of the dry cutting of a 7000 series sample.

peaks after using a grindable thermocouple. To remove the temperature flashes Lefebvre et al. (2012) developed a method based on the finding of local minima inside the signal. In our study, we adapted this approach. Indeed, to process the raw signal, local minima was obtained by using a minimum filter, which replaced every value by the minimum value in the range of 10 neighborhoods. To avoid the measurement artifacts and to smooth the curve a median filter on a range of 10 data is then applied.

A comparison of raw data, the background temperature as defined by Rowe et al. (1995) and the local minimum is presented in Figure 7. It shows a very good correlation (temperature difference $< 10\,^{\circ}\mathrm{C}$) between the background temperature of the raw signal and the envelope curve. This method of determining the background temperature was used throughout our study. Since earlier studies found that the temperature distribution is very sensitive to filter parameters (Xu and Malkin, 2001; Fang et al., 2008), the same filter characteristics were kept constant for the analysis.

To compare each test the temperature at the end of the contact time was used. Considering the workpiece speed, the end of the contact was defined by averaging all the data of the background signal located between 0.115 s and 0.135 s (orange line on Figure 7 after the beginning of the cutting.)

To enhance the chance to get a signal at the end of the contact and to minimize the variability of the results each temperature when machining a pocket (equal to the removed volume of $0.19\,\mathrm{dm}^3$) has been averaged over the five thermocouples measurements. This hypothesis was made since the measuring range of the five temperatures (given by the five thermocouples) was quite small (about $10\,^{\circ}\mathrm{C}$).

Cutting temperature in the ending contact zone after one path

The temperature in the ending contact zone for dry, MQL and wet conditions after machining of 1.86×10^{-1} dm^3 for the two aluminum alloys

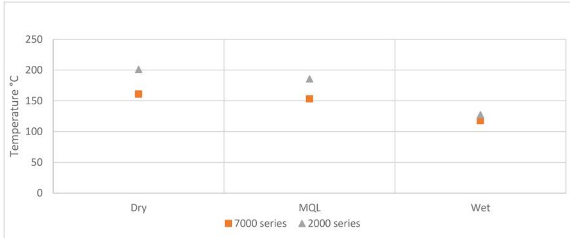

FIGURE 8. Temperature at the ending contact zone for dry, MQL and wet conditions on 7000 series and 2000 series samples.

(7000 and Li-containing 2000 series) has been presented on Figure 8. The obtained temperatures between 130 °C and 210 °C are consistent with the work of Ming et al. (2003).

It is interesting to point out that the 7000 series always present lower temperature than the Li-containing 2000 series. Indeed, for this last material, temperature is around 9–25% higher. It may be explained by the fact that the 7000 series has a higher thermal diffusivity than the Li-containing 2000 series (about 50% higher at 20 °C as previously explained.

Moreover, as expected the wet conditions enabled the contact temperature to be decreased by more than 30% compared to the MQL. This observation applies for both the 7000 and Li-containing 2000 series, as the presence of the coolant impacts the heat generation by reducing friction and by absorbing and removing heat from the cutting area thanks to the conduction and the cooling effects (Klocke and Eisenblätter, 1997; Weinert et al., 2004). For example, in their work Kalidas et al. (2001) investigated the effect of drill coatings on hole quality under dry and wet cutting conditions. By using many thermocouples located at different positions inside the workpiece, they observed for every thermocouple temperature 50% lower under wet conditions than under dry conditions. Weinert et al. (2004) explained in their work that the oil used in MQL mostly contributes to reducing friction and adhesion between the workpiece and the tool. However, in case of MQL the direct cooling effect of oil/air mix is of minor importance compared to full wet conditions. For these reasons, it made sense to observe only a little drop in the temperature by using MQL instead of dry conditions. Indeed, the drop of about 6% for the 7000 series and 7.5% for the Li-containing 2000 was outlined.

It was also observed that the difference between the 7000 series and Li-containing 2000 series alloy in terms of contact temperature is strongly reduced under the wet conditions. It revealed that the ratio of heat flux absorbed by the workpiece out of the total cutting power is reduced thanks to the heat flux absorbed by the cutting fluid. Indeed, under the wet conditions the convection heat transfer coefficient may reach more than 100 kW/m^{2}K while machining (Jin et al., 2003). We suppose that a large part of the heat is absorbed by the fluid under the wet conditions. The temperature in the tool-workpiece contact area is then stabilized and depends more on the boiling fluid temperature than on the heat properties of the machined material.

Tool wear effect on the cutting temperature

The effect of the tool wear was also studied, and the results are presented on Figure 9. It is obtained that the rise in the machined volume has led to the growth of tool wear. The increase of the tool wear is also depended on the cutting and on the coolant conditions. As we can observe on Figure 9, for the two aluminum alloys, that the dry conditions led to a quicker tool wear than with MQL or under wet conditions.

For the Li-containing 2000 series scattered results were obtained under wet conditions (2000 Li Wet 1 and 2000 Li Wet 2, Figure 9). An average of these two series of results was considered for the following of the study.

It is supposed to impact the temperature of the ending contact zone by contributing to the friction mechanism between the tool and the machined part. Thus, this temperature has been reported into Figure 10 graph after machining each pocket (0.19 dm^{-3} of material removal). Figure 10(a) presents the temperature on the 7000 series and Figure 10(b) stands for the 2000 Li-containing series. On Figure 10(a) the values corresponding to a 0.06 mm flank wear (for MQL and wet conditions) are highlighted and Figure 10(b) illustrates the evolution of temperature for both 0.06 mm and 0.2 mm flank wear.

One can observe that the increase in the machined volume, which involves an increase in the tool cutting time and thus an increase in the tool wear, led to a gradual increase of the ending contact zone temperature. This behavior seems to be realistic for MQL and dry conditions on the 7000 and Li-containing 2000 series both. Indeed, the temperature passed

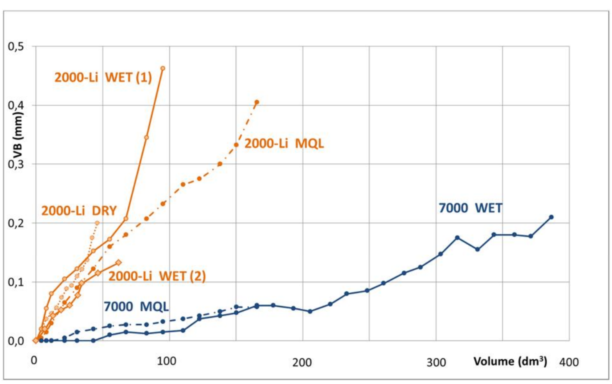

FIGURE 9. Evolution of tool wear, in relation to the lubrication conditions and the alloy.

(a)

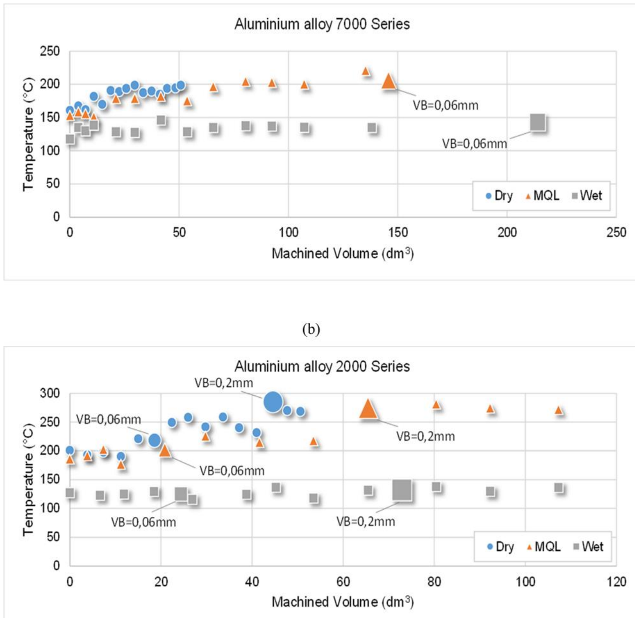

FIGURE 10. (a) Evolution of the end milling temperature and the tool wear versus the volume removed in the 7000 series; (b) in the 2000 series.

from 155 °C to 195 °C for the 7000 series and from 190 °C to 270 °C for the 2000 series. This increase of temperature linked to the tool wear was also observed by O'Sullivan and Cotterell (2001)(O'Sullivan et Cotterell 2001). They studied the effect of tool wear on the temperature in single point turning and showed a 15% increase in the temperature between a sharp tool and a tool with 0.35 mm flank wear. They explained this phenomenon by the fact that when the tool was wearing there was an increase in the contact area at the tool chip and tool work interface due to the presence of the flank and crater wear mechanisms. The overall efficiency of the cutting process was therefore reduced and an excess of amount of energy was required to perform the cutting process. This excess of energy led to higher cutting forces and temperatures. Similar observation of raised temperature after tool wear was also detailed in many other studies (Young, 1996; Ay and Yang, 1998; Chu and Wallbank, 1998).

On Figure 9, the evolution of the temperature is more substantial for Li-containing 2000 alloys under MQL and dry conditions (+80 °C after 65 dm^3 removed) than for the 7000 alloys (+40 °C after 65 dm^3 removed). Young (1996) demonstrate that the tool wear phenomenon is strongly temperature dependent. Then as the machining of Li-containing 2000 series led to a higher milling temperature than the 7000 without any tool wear. This initial higher temperature will boost the increase of the tool wear after each pocket machining and will further increase the temperature.

At last, it was interesting to observe that under the wet conditions, the ending contact zone temperature was similar to the two alloys and was stable even after machining more than 1,000 dm^3 (approximately 303 kg of metal removal). It is well known that the lubricant enables the tool wear to be reduced and its life expectancy to be improved (El-Hossainy 2001). Therefore, the first explanation to this no-increase in the temperature after a large number of machining was the ability of the coolant to avoid the tool wear.

However, to better understand the tool wear phenomenon on the ending contact zone temperature, the temperature for a given flank wear was investigated as shown with Figure 10. On this figure, the temperatures for the 7000 series under MQL and wet conditions after a 0.06 mm flank wear but also the temperature of the Li-containing 2000 series under dry MQL and wet conditions for the same flank wear were reported. It is important to explain that unfortunately we were unable to get any flank wear measurements for the 7000 series dry tests. Indeed, under this dry condition with this alloy a lot of chip adhesion (built up edge) was observed on the flank face and it was impossible to obtain a precise value of the flank wear with the adhered chip. This phenomenon is detailed by List et al. (2005) who observed a lot of adhesion after dry machining of an aluminum alloy. The considered flank wear is weak. However, it needed to remove about 150 dm^3 and 200 dm^3 for the MQL and wet conditions with the 7000 series to get the 0.06 mm flank wear (Figure 9). For material saving considerations, we were not able to get a bigger wear for the 7000 series MQL.

The temperature under MQL conditions was quasi similar after the same flank wear for the 7000 alloy and the 2000 (respectively 206 °C for the first one and 202 °C for the second). The same observation was done under wet conditions. Indeed, the ending contact zone temperature for the 7000 series was about 140 °C and 130 °C for the Li-containing 2000 series. We can deduce that even with a worn tool, a large amount of cooling (if we compare wet and MQL conditions) enabled to a large part of the heat in the cutting contact area to be evacuated. Therefore, for a limited tool wear, the trend of temperature increase related to greater tool flank wear was completely annihilated by the cooling efficiency of the lubricant.

However, it was interesting to observe that the lubrication also enabled the tool wear for the Li-containing 2000 series to be limited. Indeed, under dry cutting conditions for this material, an amount of 18.6 dm^3 (about 53 kg) of metal was machined to get the 0.06 mm flank wear. And for the wet condition, it was possible to remove 6 dm^3 (17 kg) more before observing the same level of wear. Nevertheless, even with those wet conditions this volume removed for the Li-containing 2000 series for given flank wear is about ten times lower than with the 7000 series. However, a work on the lubricating condition (use of high-pressure jet for example) could certainly improve the tool life expectancy while machining the Li-containing 2000 series as in the study of Ayed and Germain (2018).

To analyze the effect of a more pronounced flank wear, end milling temperature of the Li-containing 2000 series after a 0.2 mm tool flank wear were reported in Figure 11. As in Figure 10, temperature and volume removed are compared with the same flank wear under respectively dry, MQL and wet conditions.

For this wear there were no results for the 7000 series. Indeed, it was already noticed for a weak flank wear (0.06 mm) that about ten times more material removal was needed to get the same wear as with the Li-containing 2000 series (Figure 9). Then the same thing happened for a bigger wear, for example more than 270 dm^3 (760 kg) had to be removed for the 7000 under wet conditions just to get only 0.11 mm flank wear when 90 kg of the Li-containing 2000 series under wet conditions were sufficient for the same wear. For material saving reasons, it was therefore decided to study the bigger flank wear on the Li-containing 2000 alloy only, as shown with Figure 11.

For the 0.2 mm wear, the observation is quite similar in terms of temperature: the amount of lubricant under MQL is not sufficient to substantially reduce the end milling temperature compared to dry conditions (275 °C vs. 285 °C). However, the wet conditions enable the same temperature as with no wear to be obtained (140 °C). Once again, it demonstrates that the ability of the coolant to evacuate heat is predominant compared to the rise in friction due to the tool wear. Then, it prevents any temperature runaway as long as the flank wear remains reasonable (<0.3 mm) (Figure 12).

The observation that the lubrication improved the tool life expectancy for the Li-containing 2000 series is even more striking after a 0.2 mm flank wear. Indeed, passing from dry to MQL conditions enables a 50% increase in the volume of the alloy to be milled before reaching 0.2 mm tool wear.

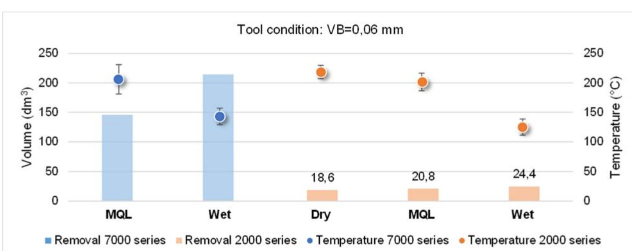

FIGURE 11. Cutting temperature (at the ending contact zone) and the corresponding volume of alloy removed for 0.06 mm flank wear.

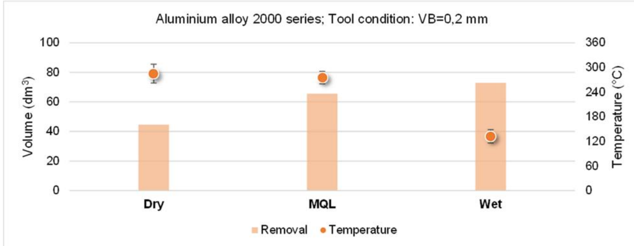

FIGURE 12. Cutting temperature (at the ending contact zone) and the corresponding volume of alloy removed for 0.2 mm flank wear.

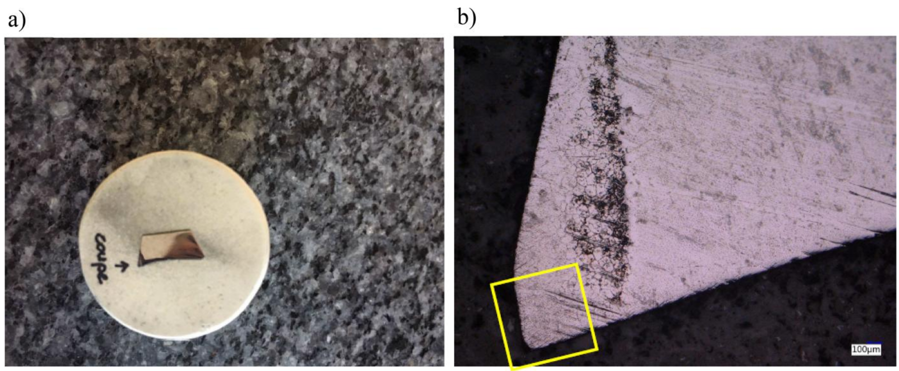

FIGURE 13. (a) Picture of the slice of the carbide insert (cutting edge on the left). (b) Cutting edge analyzed by SIMS (yellow square).

It was an only 20% improvement between dry and MQL for the 0.06 mm flank wear.

In wet conditions, a volume of alloy removed 15% bigger than in MQL conditions is needed to get also 0.2 mm flank wear. This 15% increase was also observed for a 0.06 mm flank wear.

However, the big dispersion in the wet wear results (Figure 9) makes difficult to conclude to a real improvement of the wear reducing effect under wet conditions compared to MQL ones.

Analysis of the cutting tool

To understand the important tool wear observed after machining Li-containing 2000 alloy (under dry, MQL and wet conditions) compared with those after machining the 7000 series a SIMS was done on the tool (Figure 13).

The target of this physicochemical technic was to make a qualitative analysis of the cutting tool, to detect the potential diffusion of the elements of the aluminum alloy or of the cutting tool (especially Li, Cu, Mg, W, Co and Cr). The detection was made from 10 ppm to hundreds of ppm.

Set-up conditions

Instrumental measurements of SIMS:

- depth of measurements (100 nm to 500µm)
- electron beam (Bi keV)
- abrasion beam (Cs + for the negative polarity and O_2 for the positive polarity +)

A slice of the carbide insert was cut by wire EDM: electrical discharge machining and polished. In Figure 13, the yellow square around the cutting edge was analyzed by SIMS. The dimension of the area was 500 µm × 500 µm with a lateral resolution of 2 µm.

Results

The following significant ionic elements were investigated: Li^+, C^+, Mg^+, Al^+, V^+, Cr^+, Co^+ and W^+. Figure 14 displays the results for Li^+, Mg^+ and Al^+, the major components of the alloy (Figure 14).

The cutting insert is at the right-hand side of the 110 µm abscissa. On its left, an adhesive layer of aluminum alloy is sticking on the cutting insert. It can be observed that there is no diffusion of Al or Mg (from the alloy), into the cutting tool. Peaks are due to some little impurities generated during the preparation of the sample. To the contrary, a diffusion of lithium inside the cutting tool is clearly observable (Figure 14, Li^+). Indeed, the amount of lithium is high in a thin band where some aluminum alloy is sticking on the flank face of the cutting insert. Then it slowly decreases into the tool, which reveals a phenomenon of diffusion. The lithium is

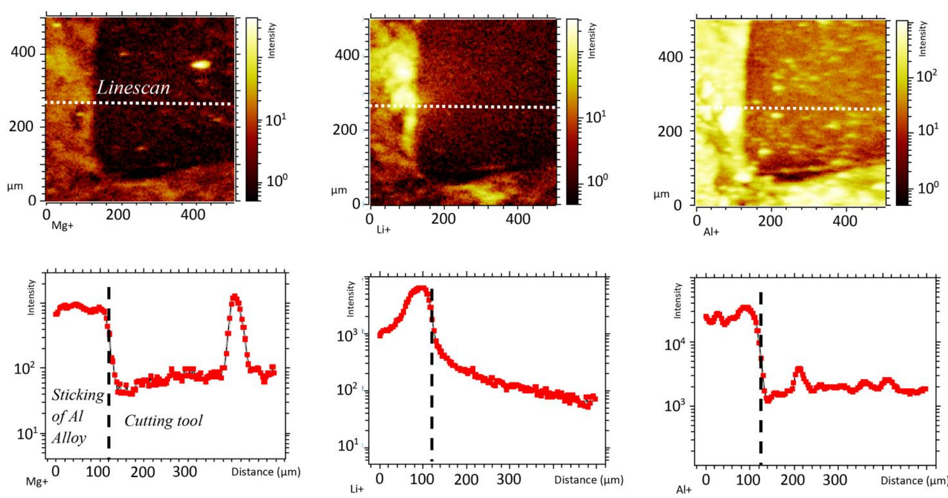

FIGURE 14. Chemical cartography and linescan (Li^+, Mg^+ and Al^+) in logarithmic scale.

highly reactive during thermo-mechanical processing (Ahmad, 1987). Therefore, during milling of Li-containing aluminum alloy, a loss of lithium is often observed in the chip (Wagner et al., 2016). For the other elements, no diffusion inside the tool was observed.

The diffusion of Li is activated by the thermo-mechanical loads occurring during the machining the Li-containing 2000 aluminum alloy. The atoms that are diffused from the tool to the chip are carried away by the flow of work material along the tool surface (List et al., 2005). The increasing flank wear and the atoms that are diffused from the chip to the tool deteriorate the tool surface finish. It leads to the occurrence of an adhesion layer and a build-up edge or to the formation of a crater on the tool. It may consequently lead to significant increase in the tool wear and a reduced tool lifetime.

Conclusion

In this work, an experimental study of the milling temperature of two aluminum alloys (7000 series and Li-containing 2000 series) was made for dry, MQL and wet machining. To be able to observe the effect of the tool wear on the temperature, the milling of very large volumes of aluminum alloys has been necessary.

The original experimental device of temperature measurement (machinable thermocouples settled on a large frequency bandwidth) revealed, after a spectrum analysis, contributions at the tooth passing frequency.

The 7000 series, because of is better ability to conduct heat, presented lower cutting temperature in the ending contact zone than the Li-containing 2000 alloy. Indeed, under dry and MQL condition, the temperature was about 150 °C versus 190 °C for new uncoated inserts.

It was shown that tool wear has clearly an effect on the temperature for dry and MQL conditions. Indeed, for the two alloys, an increase of about 50% of the temperature was observed. However, for identical flank wear level, no difference of cutting temperature was noticed between the two alloys.

Wet condition provides the best results in terms of temperature. Indeed, with that lubrication condition, the cutting temperatures for the 7000 and Li-containing 2000 series were identical at about 130 °C and were constant even after the machining of large volumes of material. The cooling effect of the lubricant was therefore predominant, compared to the increase of friction due to the tool flank wear. Moreover, the use of lubricant was clearly responsible for an increase of the tool lifetime. For a given level of flank wear, the volume of material removed was bigger under wet conditions than for dry conditions. Considering the scattered results obtained with the wet conditions in terms of tool wear, the difference observed with MQL conditions was not significant enough to conclude to an improvement in the tool life. However, for all lubrication conditions of our study, the tool flank wear appears earlier for the Li-containing 2000 alloy than for the 7000. Indeed, under wet conditions and despite similar cutting temperatures, the flank wear observed while machining a Li-containing 2000 series is still larger than while machining the 7000 series. The SIMS cartography revealed an important Li diffusion inside the cutting tool after machining Li-containing 2000 series, which may be the source of the reduced lifetime of the tool.

On the contrary, MQL conditions (with quasi no effects on the contact temperature) led to a relatively similar decrease of the flank wear (compared to wet conditions). It demonstrates that these conditions are hardly less efficient than the wet one, whereas it is less expensive and more eco-friendly. Hence, it highlights the high potential of MQL for the machining of these aluminum alloys in industry.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Ahmad, M. (1987). Thermal oxidation behavior of an Al-Li-Cu-Mg-Zr alloy. *Metallurgical Transactions A* 18(4): 681–689. 10.1007/BF02649484

Ay, H.; Yang, W.J. (1998) Heat transfer and life of metal cutting tools in turning. *International Journal of Heat and Mass Transfer*, 41(3): 613–623. 10.1016/S0017-9310(97)00105-1

Ayed, Y.; Germain, G. 2018, High-pressure water-jet-assisted machining of Ti555-3 titanium alloy: investigation of tool wear mechanisms. *The International Journal of Advanced Manufacturing Technology*, 96(1–4): 845–856. 10.1007/s00170-018-1661-2

Batako, A.D.; Rowe, W.B.; Morgan, M.N. (2005) Temperature measurement in high efficiency deep grinding. *International Journal of Machine Tools and Manufacture*, 45(11): 1231–1245. 10.1016/j.ijmachtools.2005.01.013

Bhirud, N.L.; Gawande, R.R. (2017) Measurement and prediction of cutting temperatures during dry milling: review and discussions. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 39(12): 5135–5158. 10.1007/s40430-017-0869-7

Chu, T.H.; Wallbank, J. (1998) Determination of the temperature of a machined surface. *Journal of Manufacturing Science and Engineering*, 120(2): 259–263. 10.1115/1.2830122

Davies, M.A.; Ueda, T.; M'Saoubi, R.; Mullany, B.; Cooke, A.L. (2007) On the measurement of temperature in material removal processes. *CIRP Annals*, 56(2): 581–604. 10.1016/j.cirp.2007.10.009

Dewes, R.C.; Ng, E.; Chua, K.S.; Newton, P.G.; Aspinwall, D.K. (1999) Temperature measurement when high speed machining hardened mould/die steel. *Journal of Materials Processing Technology*, 92–93: 293–301. 10.1016/S0924-0136(99)00116-8

El-Hossainy, T.M. (2001) Tool wear monitoring under dry and wet machining. *Materials and Manufacturing Processes*, 16(2): 165–176. 10.1081/AMP-100104298

Fang, C.; Huang, H.; Xu, X. (2008) The influence of thermocouples on the measurement of grinding temperatures. *Key Engineering Materials*, 375–376: 549–552. 10.4028/www.scientific.net/KEM.375-376.549

Godreau, V.; Ritou, M.; Chové, E.; Furet, B.; Dumur, D. 2019, Continuous improvement of HSM process by datamining. *Journal of Intelligent Manufacturing*, 30(7): 2781–2788. 10.1007/s10845-018-1426-7

Hirao, M. (1989) Determining temperature distribution on flank face of cutting tool. *Journal of Materials Shaping Technology*, 6(3): 143–148. 10.1007/BF02833765

Hou, J.; Zhao, N.; Zhu, S. (2011) Influence of cutting speed on flank temperature during face milling of magnesium alloy. *Materials and Manufacturing Processes*, 26(8): 1059–1063. 10.1080/10426914.2010.536927

Jin, T.; Stephenson, D.J.; Rowe, W.B. (2003) Estimation of the convection heat transfer coefficient of coolant within the grinding zone. *Journal of Engineering Manufacture*, 217(3): 397–407. 10.1243/095440503321590550

Kalidas, S.; DeVor, R.E.; Kapoor, S.G. (2001) Experimental investigation of the effect of drill coatings on hole quality under dry and wet drilling conditions. *Surface and Coatings Technology*, 148(2–3): 117–128. 10.1016/S0257-8972(01)01349-4

Kerrigan, K.; O'Donnell, G.E, (2013) Temperature measurement in CFRP milling using a wireless tool-integrated process monitoring sensor. *International Journal of Automation Technology*, 7(6): 742–750. 10.20965/ijat.2013.p0742

Kesriklioglu, S.; Pfefferkorn, F.E. (2018) Real time temperature measurement with embedded thin-film. *Procedia CIRP*, 77: 618–621. 10.1016/j.procir.2018.08.193

Kitagawa, T.; Kubo, A.; Maekawa, K. (1997) Temperature and wear of cutting tools in high-speed machining of Incone1718 and Ti-6A1-6V-2Sn. *Wear*, 202(2): 142–148. 10.1016/S0043-1648(96)07255-9

Klocke, F.; Eisenblätter, G. (1997) Dry cutting. *CIRP Annals*, 46(2): 519–526. 10.1016/S0007-8506(07)60877-4

Kuzcmaszewski, J.; Zagòrski, I. (2013) Methodological problems of temperature measurement in the cutting area during milling magnesium alloys. *Management and Production Engineering Review*, 4: 26–33.

Le Coz, G.; Dudzinski, D. (2014) Temperature variation in the workpiece and in the cutting. *The International Journal of Advanced Manufacturing Technology*, 74(5–8): 1133–1139. 10.1007/s00170-014-6006-1

Lefebvre, A.; Lanzetta, F.; Lipinski, P.; Torrance, A.A. (2012) Measurement of grinding temperatures using a foil/workpiece thermocouple. *International Journal of Machine Tools and Manufacture*, 58: 1–10. 10.1016/j.ijmachtools.2012.02.006

List, G.; Nouari, M.; Géhin, D.; Gomez, S.; Manaud, J.P.; Le Petitcorps, Y.; Girot, F. (2005) Wear behaviour of cemented carbide tools in dry machining of aluminium alloy. *Wear*, 259(7–12): 1177–1189. 10.1016/j.wear.2005.02.056

Ming, C.; Fanghong, S.; Haili, W.; Renwei, Y.; Zhenghong, Q.; Shuqiao, Z. (2003) Experimental research on the dynamic characteristics of the cutting temperature in the process of high-speed milling. *Journal of Materials Processing Technology*, 138(1–3): 468–471. 10.1016/S0924-0136(03)00120-1

O'Sullivan, D.; Cotterell, M. (2001) Temperature measurement in single point turning. *Journal of Materials Processing Technology*, 118(1–3): 301–308. 10.1016/S0924-0136(01)00853-6

Ritou, M.; Garnier, S.; Furet, B.; Hascoet, J.Y. (2014) Angular approach combined to mechanical model for tool breakage detection by Eddy current sensors. *Mechanical Systems and Signal Processing*, 44(1–2): 211–220. 10.1016/j.ymssp.2013.02.004

Rowe, W.B.; Black, S.C.; Mills, B.; Qi, H.S.; Morgan, M.N. (1995) Experimental investigation of heat transfer in grinding. *CIRP Annals*, 44(1): 329–332. 10.1016/S0007-8506(07)62336-1

Wagner, V.; Vissio, A.; Duc, E.; Pijolat, M. (2016) Relationship between cutting conditions and chips morphology during milling of aluminium Al-2050. *The International Journal of Advanced Manufacturing Technology*, 82(9–12): 1881–1897. 10.1007/s00170-015-7490-7

Wang, Z.; Ritou, M.; Da Cunha, C.; Furet, B. (2020) Contextual classification for smart machining based on unsupervised machine learning by Gaussian mixture model. *International Journal of Computer Integrated Manufacturing*, 33(10–11): 1042–1054. 10.1080/0951192X.2020.1775302

Weinert, K.; Inasaki, I.; Sutherland, J.W.; Wakabayashi, T. (2004) Dry machining and minimum quantity lubrication. *CIRP Annals*, 53(2): 511–537. 10.1016/S0007-8506(07)60027-4

Xu, X.; Malkin, S. (2001) Comparison of methods to measure grinding temperatures. *Journal of Manufacturing Science and Engineering*, 123(2): 191–195. 10.1115/1.1369358

Young, H.T. 1996, Cutting temperature response to flank wear. *Wear*, 201(1–2): 117–120. 10.1016/S0043-1648(96)07227-4