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An experimental investigation of hot machining with induction to improve Ti-5553 machinability

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Abstract. The manufacturing of aeronautic parts with high mechanical properties requires the use of high performance materials. That's why; new materials are used for landing gears such as the titanium alloy Ti-5553. The machining of this material leads to high cutting forces and temperatures, and poor machinability which requires the use of low cutting conditions.

In order to increase the productivity rate, one solution could be to raise the workpiece initial temperature. Assisted hot machining consists in heating the workpiece material before the material removal takes place, in order to weaken the material mechanical properties, and thus reducing at least the cutting forces.

First, a bibliography review has been done in order to determine all heating instruments used and the thermal alleviation that exists on conventional materials.

An induction assisted hot machining was chosen and a system capable to maintain a constant temperature into the workpiece during machining (turning) was designed.

Trails permit to identify the variation of cutting forces according to the initial temperature of the workpiece, with fixed cutting conditions according to the TMP (Tool-Material-Pair) methodology at ambient temperature. Tool life and deterioration mode are identified notably.

The results analysis shows a low reduction of specific cutting forces for a temperature area compatible with industrial process. The reduction is more important at elevated temperature. However, it has consequences on quality of the workpiece surface and tool wear.

Introduction

For aeronautic field, new high performance materials are used because of their low density, their excellent properties at room and elevated temperature, such as resistance to fatigue and corrosion and specific strength. Indeed, for the manufacture of their landing gears, *Messier-Dowty* uses a new titanium alloy: Ti-5Al-5Mo-5V-3Cr (Ti-5553). However, this new refractory material presents a poor machinability compared to steel or the more known titanium alloy: Ti-6Al-4V (Ti-64) [1]. When machining Ti-5553, the cutting speed is low and the tool life is short. So, this results increase cycle time and manufacturing cost becomes a major problem.

Proposing improved solutions is possible only by understanding the cutting Ti-5553 alloy phenomena and the degradation modes of cutting tool, according to the assistants allowing increasing machinability.

The aim of this paper is to study the impact of the initial temperature of the material being machined about the evolution of cutting forces and modes of degradation of tool. This is based on hypothesis that a potential gain in cutting force will positively affect the machinability. The methodology of the approach is based on Tool-Material Pair (AFNOR: COM [2]). For this approach, the representative criterion of the optimization is the specific cutting energy Kc. Indeed, heating the workpiece material reduces plastic flow stress of the material, thereby, causing the thermal softening phenomenon (well known in high speed machining), which leads to the reduction of Kc. However, this temperature will affect the tool life (increasing of thermal stresses, flank wear, abrasion of the coating ...). This heating can cause a microstructural transformation of the material and generates a reduction in mechanical properties of the workpiece surface. Therefore, it's necessary to analyze the gains and limitations of hot machining approach.

State of the art for hot machining

The low machinability of titanium alloys is mainly due to its mechanical properties. Indeed, its poor thermal conductivity concentrates more heat at the tool-workpiece interface. This creates a high temperature tool-material contact. In addition to that, by high temperatures, titanium alloys react chemically with many materials of cutting tools.

With increasing temperature, mechanical properties of all materials decrease (figure 1). So, heating lowers the plastic flow stress of metals.

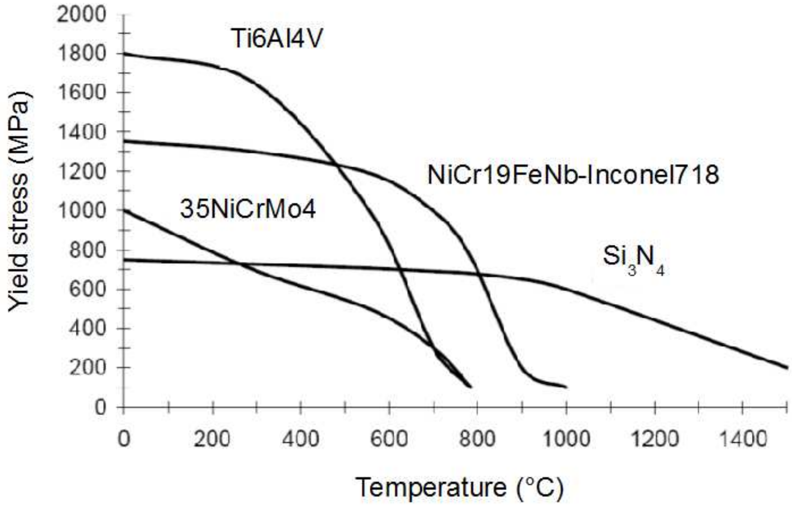


Figure 1 Evolution of tensile strength as a function of temperature for different materials [3]

The principle of assisted hot machining consists in taking advantage of the material mechanical properties decrease due to the increase in the workpiece initial temperature. Since the 70s, many studies have been conducted on this topic. Moore [4] carried researches on different metallic materials and ceramics. He noted the improved machinability of aerospace materials such as titanium and nickel alloys. Gains generally observed are lower cutting forces, vibration and tool wear and improved surface finish. Studies have been conducted by Ozler [5] on the tool life when hot machining of austenitic-manganese steel. It was concluded that the tool life is proportional to the workpiece temperature to 600°C. However, it's inversely proportional to cutting speed. These results show that hot machining allows the use of higher cutting speeds for a given tool life. Melhaoui's researches [6] also confirm the interest of heating the workpiece in order to increase the tool life. In fact, with thermal assistance, he showed that 80% of the flank wear and 60% of the crater wear have been reduced.

For hot machining of Ti-64, Sun [7] have observed that the plasma assistance degrades the tool life, despite the reduction of cutting forces. Bi [8] explains that the thermal assistance does not necessarily reduce wear of the tool. As depicted in figure 2, we note that at low temperature, adhesion and abrasion are preponderant. However, at high temperature, diffusion, corrosion and plastic deformation occur. According to machined materials and cutting parameters, thermal assistance has contrasting effects on the wear of cutting tools. Depending on the temperature, the wear may have mechanical origins (abrasion) or chemical ones (diffusion). In addition to that, the physico-chemical properties of materials play an important role. Indeed, the high temperature reduces the material stress, but it activates the chemical reactions between tool and material.

To raise the temperature of the machined material, several methods are possible: the piece is entirety heated before being machined or local heating techniques are used. The plasma heating technique allows increasing the local workpiece temperature upstream of the tool path with a plasma torch. This method has been used in [9] to heat Inconel 718.

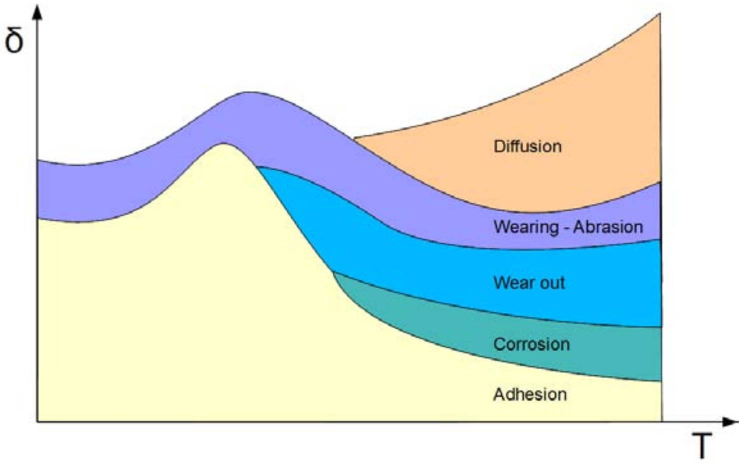


Figure 2 Tool wear depending on temperature

Another heating method that can be used: the laser heating [10]. The principle of this method is similar to that of plasma method one. However, the power density obtained is much greater. The last heating method used is the induction heating one. Indeed, the workpiece is immersed in a magnetic field. So, the heating is done without any contact with the workpiece and can easily be compatible with the machining. It allows increasing a titanium alloy temperature at 1000°C in only 2 minutes. Moreover, it does not cause any danger because only the workpiece is heated and the thermal radiation remains very low.

If increasing temperature of the machined material decreases its resistance and improves its machinability, it has a bad impact on the material surface integrity: microstructural changes and residual stresses ([11,12]). Indeed, Germain [13] observed microstructural changes due to heat treatment caused by surface heating. Thus, α and β material phases change their structures. Thereby, rapid cooling of the surface generates stresses and cracks appear. Their presence affects the fatigue strength of the workpiece during its use. Jones [14] studied the impact of temperature on the Ti-5553 structure. At room temperature, the titanium alloy has a β metastable structure. This structure evolves into (α + β) structure since crossing the β-transus at around of 845°C. The mechanical and thermal stresses caused by machining generate dilation of the superficial layer of the machined material. The difference of expansion between the material layers creates residual stresses. Mastered residual stresses (excessive value ones generate a fractured surface) improves the mechanical properties of the material. By heating the Ti-64, Germain [13] presents relation between the surface residual stresses and the temperature reached. Indeed, the residual stresses due to tension increases at the expense of those due to compression.

About cutting forces, all research carried out with laser assistance show a significant reduction of the specific cutting force. By turning a hard steel (AISI 4130), Ding [11] obtained a reduction of Kc about 20%. For a metal matrix composite material, Wang [15] shows a significant reduction from 30 up to 50% of cutting forces while the tool life is improved.

Braham-Bouchnak [16] studied two assistance methods to machining the Ti-5553 material: laser assistance and high pressure water jet assistance. For the first method, it shows a reduction for specific cutting force of 35% with low cutting speeds (outside the area of usual $V_{c,min}$ according to TMP Method) to 19% for high speeds. His researches also show an increasing $V_{c,min}$ from 50 to 70 m/min through the laser assistance. Moreover, the roughness does not seem affected, but he noted increasing residual stresses to tensile strength and a reduction of strain hardening as the local heating caused by the laser only generates an expansion in a plastic surface layer.

Nowadays, researches carried out are limited to study the influence of increased temperature on the cutting forces, tool life, ductility, and surface integrity of the material independently. However, they don't reach an overall and industrial conclusion by comparing contributions of this technology on the machinability compared to its disadvantages. The goal of our work is to complete the literature in order to affirm if the heating of Ti-5553 represents a path of improvement and optimization of machinability and if it can find an industrial application.

Experimental set-up

The experimental set-up allows performing turning tests of Ti-5553 with stabilized temperature of the workpiece. In a first approach, the cutting parameters and the tool are settled down and only the temperature varies. We note the cutting force, roughness, wear of the cutting tool and the micro-hardness of the machined surface. The procedure consists in getting the workpiece at a controlled temperature, to carry the machining and to recover the measured information.

The machinied workpiece is constituted of a piece of material at the initial state changed at each machining test. The choice of cutting tools and cutting conditions is determined by a previous study detailed in [17] giving an optimal result at room temperature presented as following:

- cutting speed Vc: 35 m/min (the cutting speed was selected according to the TMP (Tool-Material-Pair) methodology at ambient temperature),
- feedrate f : 0.15 mm/rev,
- depth of cut Ap: 3 mm,
- machining time: 10 s,
- tool insert: Sandvik CNMG 16 06 12 – QM 1105 (Rake angle = 13 °, backing edge of 0.12mm at 13 ° combined with a honing of 0.02mm),
- dry machining.

However, these conditions are not critical since the goal is to observe a differential of cutting forces and not to seek an optimum.

If we observe the heat treatment cycle of Ti-5553 depicted in figure 3, and in terms of temperature, the material behavior can be divided into three clearly zones: the first zone corresponds to temperatures below 300°C, hot machining should not alter the effects of heat treatment as the Ti-5553 is in its stable area. Between 300 and 640°C, the stress relaxation zone seems particularly interesting. Indeed, it is in this zone that the prospects for reducing cutting forces and tool wear are expected. The last zone corresponds to temperatures above 640°C. In this case, there are irreversible microstructural changes affecting the mechanical properties of the material. Therefore, all heated material above 580°C must be removed from the cutting operation, in order to avoid a reduction in mechanical properties.

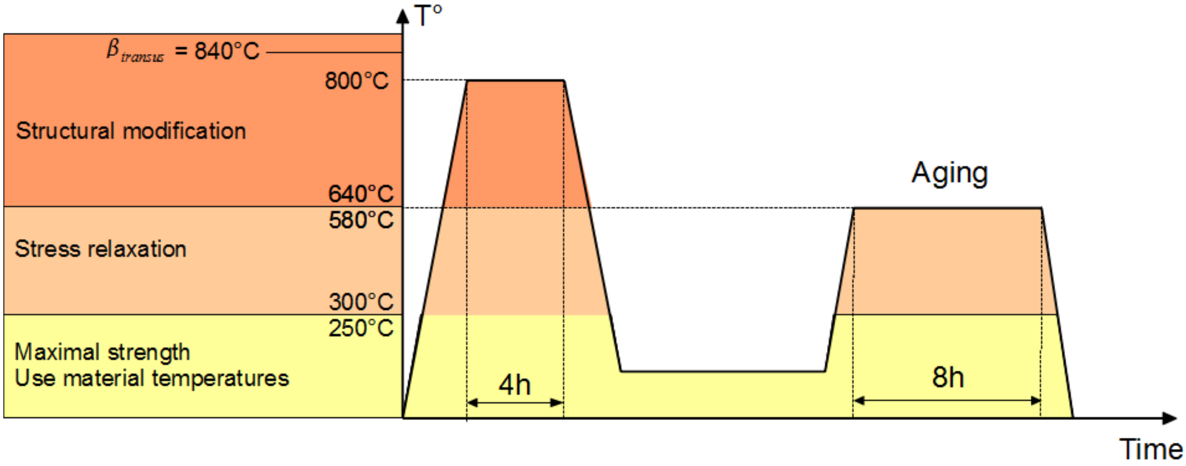


Figure 3 Range of heat treatment of Ti-5553

As specified previously, the best heating mean compatible with machining, allowing reaching quickly high, controlled, and stabilized temperatures is induction assisted hot machining method. The trials to be performed are turning tests under high temperature; this temperature must be maintained during machining. Thus, the experimental device consists of a semi-circular "pancake" inductor partially enveloping the workpiece during the turning, specifically designed for our tests (figure 4).

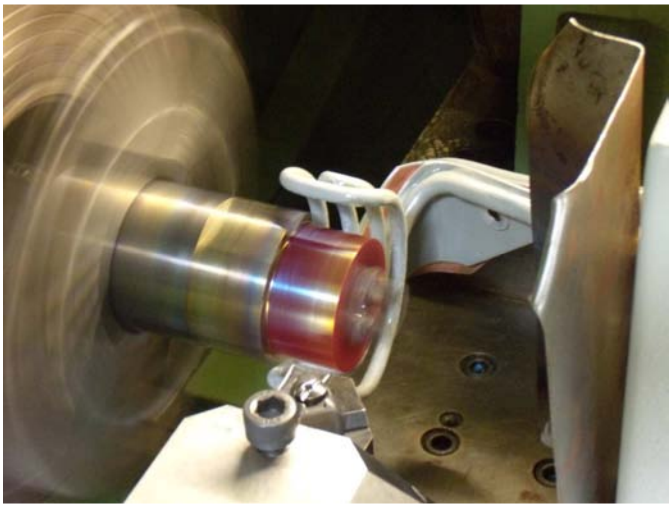


Figure 4 Material heating by semi-circular inductor

The geometry of the rotating workpiece was designed to integrate thermocouples inside and closer to the cutting zone. During the machining, the signal recoveries from thermocouples are carried through a rotating collector across the chuck of the lathe. Furthermore, a thermal camera was used to compare its temperature measurements to those provided by thermocouples.

A dynamometer platform has been used for the cutting forces measurements (Kistler 9263-A). Figure 5 illustrates the device used for machining. For machining, a protocol for raising and maintaining the temperature of the rotating workpiece in the inductor, with temperature measurement by both thermocouples and thermal imaging camera determines the heating process. So, it ensures the stabilization at the desired temperature workpiece. We note that the delay of temperature rising is under 3 seconds.

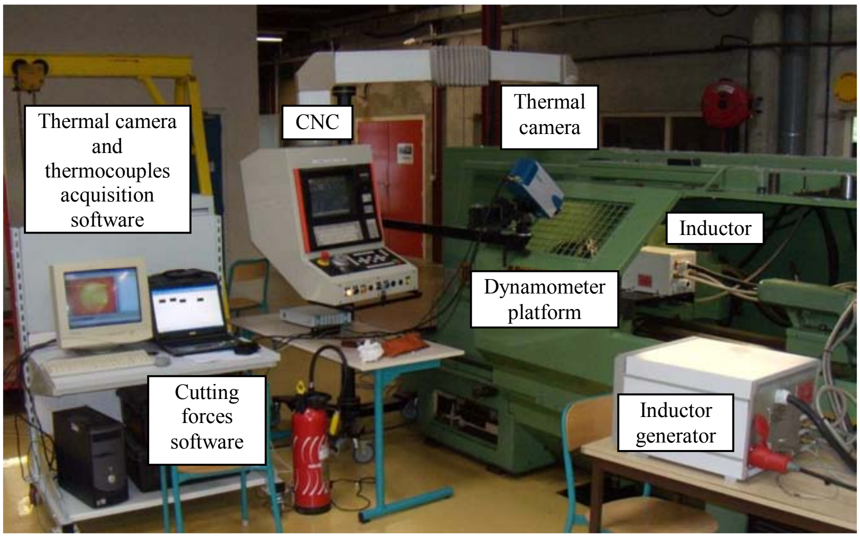


Figure 5 Experimental set-up

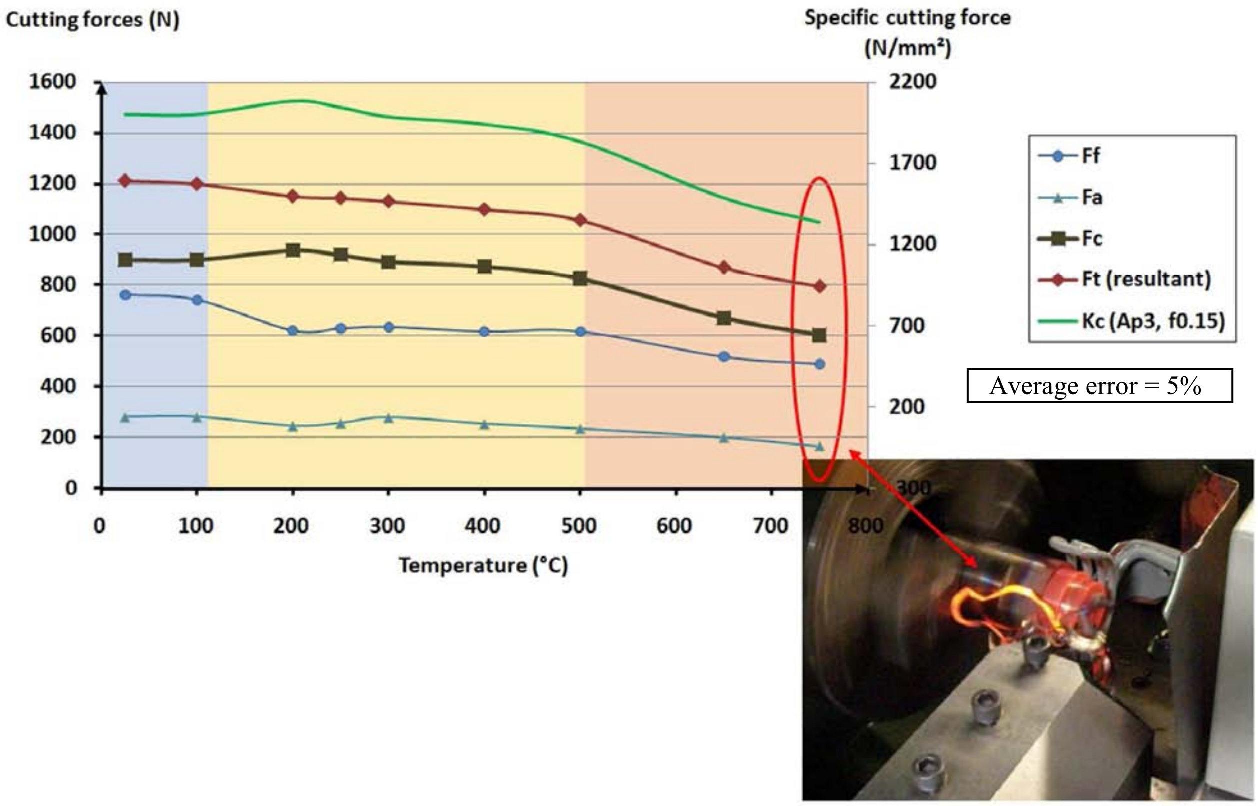
Experimental results and discussion

Cutting forces.

Table 1 shows the evolution of the cutting forces and the specific cutting energy based on the initial temperature of the workpiece before machining. By observing figure 6, we can see that the evolution of cutting forces and specific cutting force Kc presents 3 phases: at temperatures lower than 100°C, the effort remains constant. When the heating temperature is between 100°C and 500°C, cutting force reducing is poor (about 10%). This reduction became significant only when heating temperature exceeds 500°C. Consequently, if we consider only the specific cutting force parameter, this domain would be of interest to optimize machinability (right picture on figure 6).

Temperature [°C]	25	100	200	250	300	400	500	650	750
Cutting force Ff [N]	760	740	620	628	634	616	616	517	489
Cutting force Fa [N]	280	280	245	256	278	253	234	200	166
Cutting force Fc [N]	900	900	937	919	893	873	825	670	603
Cutting force Ft [N]	1211	1198	1150	1142	1130	1098	1056	870	794
Specific cutting force Kc [N/mm^2]	2000	2000	2082	2042	1984	1940	1833	1489	1340
Resultant cutting force [N]	1211	1198	1150	1142	1130	1098	1056	870	794
Variation of resultant force	Reference	-1%	-5%	-6%	-7%	-9%	-13%	-28%	-34%

Table 1 Experimental set-up



Average error = 5%

Figure 6 Evolution of cutting forces and Kc depending on the temperature

In this interesting domain, reduction values of specific cutting force correspond to the bibliography results. Indeed, Kc reduction values reach from 13 to 34% for a temperature range of 500 to 750°C. Compared to heating laser technique on Ti-5553 [16] where the heating zone remains superficial in the cut thickness, the Kc reduction is here significantly higher (figure 6: approximately 30% against 19% with laser) since in our configuration all machined thickness is at the elevated temperature. However, thermal stresses supported by tool are also higher than in laser heating case.

The decrease observed in cutting forces caused by the high initial temperature of workpiece is mainly due to thermal softening of the material. For the Johnson-Cook law (presented in equation 1) that can characterize the material behavior in context heating machining [18], the third term of this law illustrates this trend.

$$\bar{\sigma} = \left[A + B\left(\bar{\varepsilon}\right)^{n} \right] . \left[1 + C \ln \frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0} \right] . \left[1 - \left(\frac{T - T_0}{T_f - T_0} \right)^{m} \right] \tag{1}$$

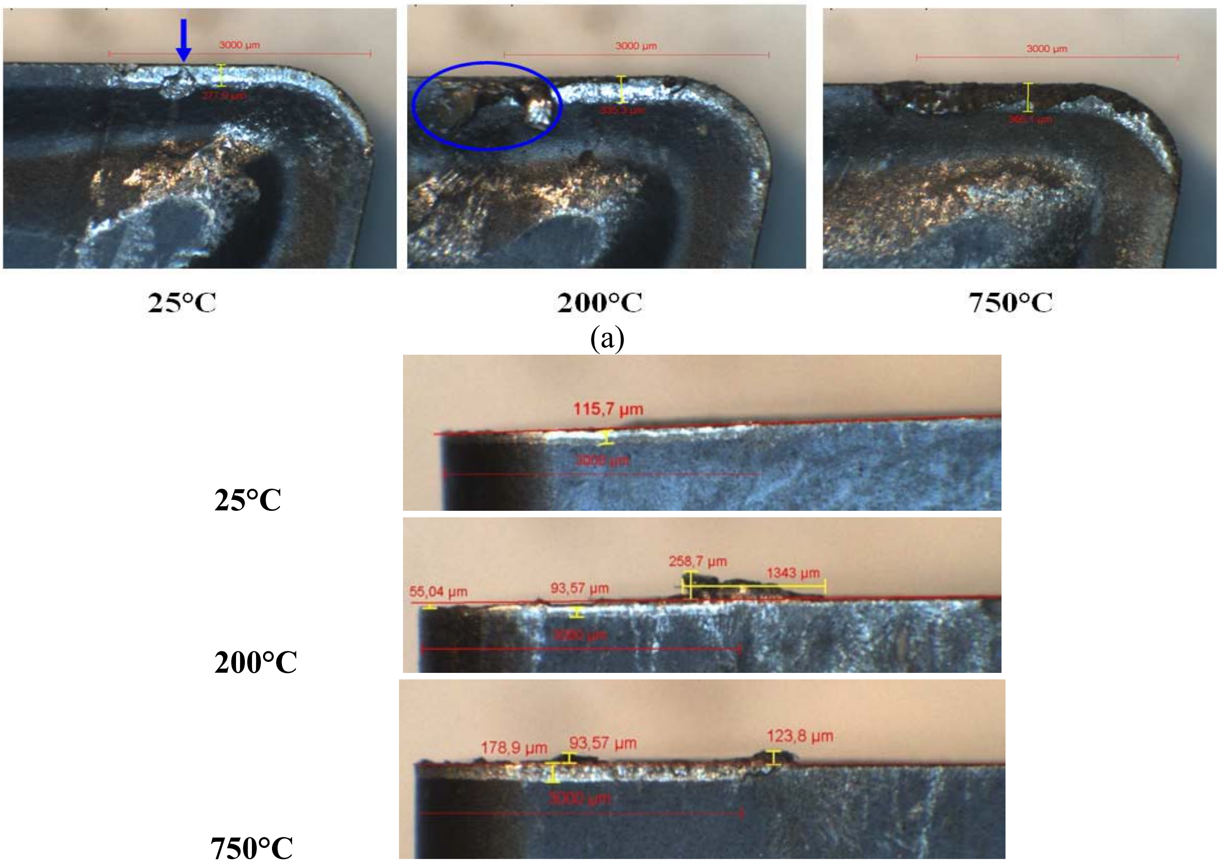
With: $\bar{\sigma}$: Von Mises flow stress, $\bar{\varepsilon}$: deformation, $\dot{\bar{\varepsilon}}/\dot{\bar{\varepsilon}}_0$: plastic strain rate, T_0 : room temperature, T_f : melting temperature and A, B, C, n et m: constants.

In Johnson-Cook law, m> 1. Consequently, if the temperature T of the material increases, the stress σ and hence the cutting force decreases, and vice versa.

However, all tests were carried at constant cutting speed. It would be interesting on future experimental campaign to check the influence of workpiece temperature on the optimum cutting speed according to the COM approach [2]. It would quantify the potential effect of temperature elevation on the cycle time.

Tool wear.

For the three temperature phases identified above, wear tests for quasi-orthogonal cutting were performed. At room temperature (workpiece at 25°C), there was a slight cutting edge chipping at limit the depth of cut. This degradation mode is resulted from various factors: severe abrasion on the rake face, effort and pressure on the workpiece caused by chip friction, difference of pressure on the free zone of the tool (cracking appearing in this zone) and possibility of inclusion in the material. When the temperature increases, a second degradation mode is observed: a built-up edge grows. It becomes more relevant as the workpiece temperature increases (figure 7).



(b)

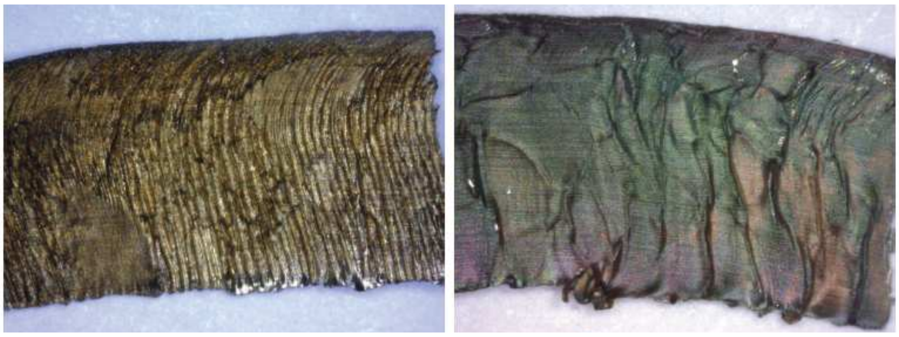
Figure 7 Rake wear (a) and flank wear (b)

This mode reflects a very high temperature at tool-chip interface and a lower pressure in this zone. At high heating temperature (750°C), built-up edge is present across whole width of cut and a flank wear appears.

Unlike the results depicted in literature about tool wear when hot machining of different materials, the influence of Ti-5553 initial temperature on tool wear is predominant. If the cutting forces are reduced, chipping and flank wear becomes significant as the temperature increases.

Relationship between chip morphology and temperature.

Machining Ti-5553 generates long and continuous chip. This chip morphology is an aggravating factor on tool life. The heat machining may be a means of segmentation of the chips [7]. The chips obtained without thermal assistance are wavy with a high strain rate. For machining with laser assistance, the material is less resistant to shear forces. However, for the Ti-5553 and whatever the workpiece temperature, the chip does not remain segmented. This is due to poor thermal softening effect compared with hardening induced in the primary shear plane. In figure 8, we observe different chip morphology. At low temperature, shear bands are more pronounced. However, for high cutting temperature, the chip does not seem formed by shearing but seems repulsed.



(a) (b)

Figure 8 Chip morphology at 250°C (a) and 750°C (b)

Surface integrity.

The micro-hardness depicted in figure 9 is representative of the surface integrity of machined material. This micro-hardness tends to increase with heating temperature, but very weakly (about 40 Hv on average). Beyond 500°C, the structure is modified, resulting from significant changes at micro-hardness of the surface. The peak at 250°C is not significant.

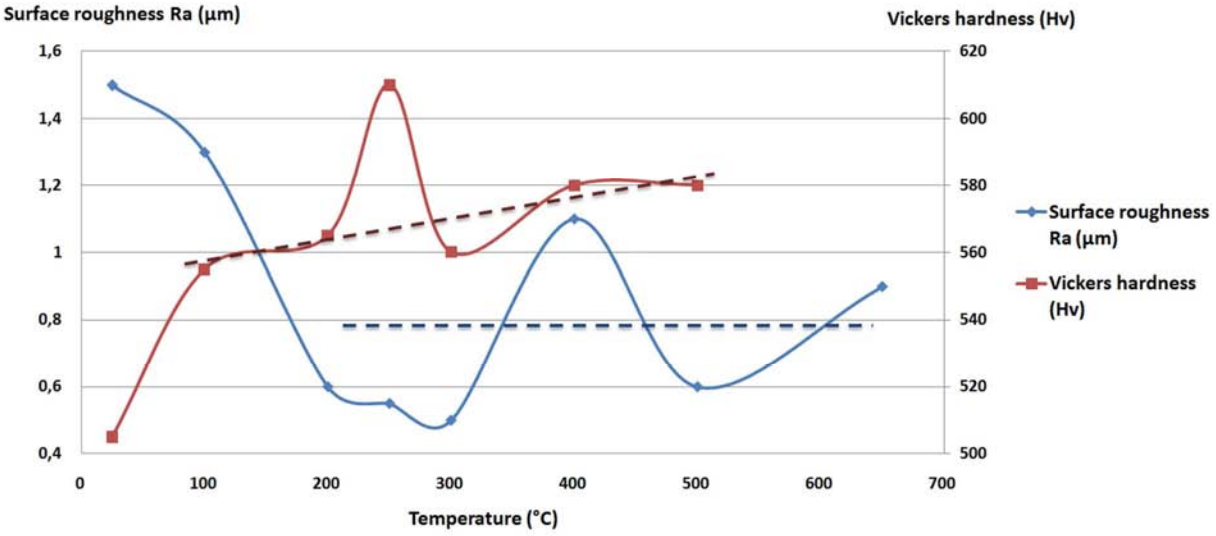


Figure 9 Influence of the temperature on the Vickers hardness and surface roughness

Residual stresses in surface of machined material are the result of a competition between mechanical phenomena and thermal phenomena. In turning, cutting forces (mechanical phenomena) generate compressive residual stress. However, the heat flux (thermal phenomena) caused by the machining, i.e. plastic expansion of the heated and cooled superficial layer, generates tensile residual stresses. In laser heating, Germain [13] and Braham-Bouchnak [16] note a trend towards the tensile residual stresses that can be explained by the localized heating of the beam. By heating all the workpiece (as in induction assisted hot machining method), this phenomenon does not appear and the difference between temperature caused by cutting and initial heating temperature is lower. So, we can imagine, even if supplementary residual stress measurements have to be made to reinforce this analysis, that either we should get a stress relaxation, either a tendency toward compressive residual stresses. The increase of micro-hardness according to initial temperature of the material seems to correlate with this analysis; since the micro-hardness increases depending on temperature (the machined surface undergoes compression or strain hardening).

Figure 9 shows too the evolution of roughness as a function of temperature. As depicted, roughness varies from Ra 1.6 μm to Ra 0.8 μm for the machining carried at temperatures above 200°C. It's difficult to explain the peak at 400°C, maybe due to a chip adhering. As shown in [11] on hard materials and unlike laser assistance on the Ti-5553 [13], we see a significant improvement in the roughness of the surface material around 50%. This decrease can be explained by the higher ductility of the material machined at high temperatures. Furthermore, the reduction of cutting forces involved in the limitation of the disturbing phenomena of the surface such as bending or vibration cutting. Reducing the frequency of the shear plane on the chip (as illustrated in figure 8) leads to an improvement of surface roughness, because cutting force variations are reduced with a more flexible and repulsed chip.

Summary

The aim of this paper is to study the influence of temperature on the machinability of Ti-5553. In this work, a induction assisted hot machining system was designed. Based on cutting conditions defined in a previous study, the impact of temperature on specific cutting force, wear of the tool and surface integrity was studied. The Ti-5553 is a brittle material. So, heating it can bring closer its behavior of more conventional materials such as hardened steels. Compared to room temperature, a 13% reduction of specific cutting force for a temperature of 500°C was measured. For a temperature of 750°C, the decrease reaches 34%. However, the material structure is irreversibly changed and the tool life is reduced. To overcome this problem, a cooling system of the cutting edge (cryogenic machining) will be tested using the results of [19]. Another optimization track is possible: varying the cutting speed, which was fixed during this study (equal to $V_{c,min}$ determined at room temperature). Indeed, $V_{c,min}$ varies according to temperature and seems to be higher at high temperature, thereby this may reduce cycle time. In addition, assistance by high pressure lubrication [20] is also an interesting mean to improve the Ti-5553 machinability. Indeed, this approach leads to chip fragmentation, low friction and the tendency is to obtain residual stresses in compression. But, this approach may be incompatible with some processes (dry machining required or milling case with a pilot on the cutting zone is very difficult to achieve).

Finally, this research was foccused to the surface micro-hardness xith regards to surface integrity issues. Thus, in future work, more detailed study of surface integrity (residual stresses, strain hardening) has to be conducted.

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