Design, manufacturing and validation of chip breakers in ceramic inserts for the machining of aeronautic nickel-based superalloys Inconel® 718

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Abstract: In a world where reducing manufacturing times of components is primordial, achieving not only increased cutting tool life but also the capacity to machine faster is a great advance in the technique. Furthermore, sectors, such as the aeronautical engine one, work with very low machinability materials as heat-resistant superalloys. The nature of these kinds of alloys prevents machining from high cutting speeds. There is only one way to do it by using ceramic tools that are harder than the traditional cemented carbide tools, but much more fragile, with a shorter tool life and too expensive. This work involves the design, the manufacturing and the validation of a chipbreaker in an alumina reinforced with whiskers of SiC turning insert for the machining of these heat-resistant superalloys (Inconel® 718), so used in sectors like the aeronautic. In view of the lack of chipbreakers in ceramic turning inserts, something unthinkable in nowadays-cemented carbide inserts, this works is intended to open a gate to a new generation of cutting tools.

Keywords: Turning, Inconel® 718, Ceramic tool, Chipbreaker, Laser engraving.

1. Introduction

The turbomachinery components required by the aeronautical industry are subjected to extreme working conditions. Therefore, these components are made of alloys that can withstand high cyclical loads at very high temperatures such as Ti6Al4V or Inconel® 718. However, due to their excellent mechanical and physical properties, this kind of alloys presents a challenge when manufacturing them.

Turning is a stable process in which the cutting forces generated during the process are constant or with a slight inclination due to tool wear and, therefore, it is a process that generates fewer vibration problems in the workpieces. However, this stability presents a problem compared to other cutting processes. As it is an uninterrupted cutting process in which the same cutting edge is continuously cutting, the chips generated tend to be continuous and not to break, leading to possible problems in the surface quality of the final component or in the useful life of the tool [1].

Furthermore, the chip plays a fundamental role in extracting the heat generated during the cutting process. In an ideal process in which the cutting would be perfectly adiabatic, the chip would carry away all the heat generated during the cutting process. However, as it is not an ideal process, the aim must be
to get as close as possible to it and, to do so, two things must be achieved. Firstly, the chip must break up to take most of the heat with it and it must not pass to the workpiece or the tool. Secondly, it must be done as quickly as possible. Consequently, chip breaking in turning operations is fundamental and, in fact, to ensure optimum process conditions, chip morphology is a critical variable [2].

Difficult to cut materials are more common in nowadays industry. Machining these materials results in an increase of the tool wear decreasing manufacturing productivity, requiring more set-ups and machining time. To increase tool life, cutting speed, and therefore the productivity its necessary improve the tools materials. Ceramics are harder and stable than the traditional cemented carbide tools, but much more fragile, what can result in shorter tool life and costs per cut insert. Nevertheless, in contrast with the cemented carbide tools, ceramic tools do not have chipbreakers in their geometry due to the high pressures and temperatures required in the manufacturing process prevent the generation of complex geometries [3].

In order to deal with this issue and to further increase productivity, manufacturers of turning inserts have advanced along the lines of generating new chipbreakers that take care of directing the chips in such a way as to obtain a short chip lengths and thus achieve productive turning processes. Yilmaz et al. presented a new design of a mechanical chipbreaker which has a small gear at its end that breaks the chip [4].

There are also chipbreakers such as the one presented in Zou et al. where, with a simple notch in the tip radius of the insert, it is possible to modify the form of chip-tool contact by reducing the thermo-mechanical load and, therefore, extending tool life [5]. However, this kind of notching on turning tools does not achieve chip breaking, which is imperative when machining superalloys. For this reason, there are developments where laser texturing is combined with the chipbreaker itself near the cutting edge on the side of the cutting face.

In Xing et al. various textures, including those filled with molybdenum disulphide which is a solid lubricant, are presented, which achieved reduced temperature during cutting due to reduced tool-chip contact [6]. This is of great interest to the possibility of further increasing cutting speed and further increasing productivity by using these advanced substrates without the need to modify their chemical composition.

With texturing as shown by Sharma et al. in their research, the temperature during cutting is reduced compared to a non-textured insert. This is because, by texturing the rake face, the contact length between chip and tool decreases and, with it, the coefficient of friction between the two. In addition, the cutting forces are also reduced, thus increasing the tool life [7].

Therefore, in this work, a new chipbreaker is designed to break Inconel® 718 chip. Afterwards, it is manufactured with laser engraving technique and, finally, it is compared in a turning process with a ceramic tool without a chipbreaker.

2. Laser grooving manufacturing
In order to manufacture the chipbreaker on the rake face of the tool, a Trumpf® Trumark 5000 station was used. This station is equipped with a pulsed Nd: YAG fiber laser of average output power of 50 W. The pulse frequency range goes from 1 to 1000 kHz with minimum pulse duration of 7 nanoseconds. The laser beam quality is characterized with a M² value of 1.6. The 2D scanner responsible for the beam movement has a 110×110 mm workspace, as it can be seen in figure 1, and a laser spot size, when focused, of 50 μm. The maximum speed of the scanning unit is 10,000 mm∙s⁻¹.

Firstly, a characterization of the ceramic insert was made. The aim of this characterization is to determine the best suited parameters in order to establish the depth of the manufactured tool when processed. The insert material was alumina reinforced with silicon carbides whiskers. The tested laser parameters for the alumina were a radial step of 0.05 mm, a scan speed of 400 mm/s a pulse frequency of 50,000 Hz, a pulse duration of 250 nanoseconds and 100% of the laser power. With these parameters, the evolution of the depth was analysed increasing the number of hatchings (repetitions) represented in figure 2. As it can be seen in the figure, the depth measurement has a parabolic tendency.
Once the characterization was made, it was decided to divide the chipbreaker geometry through different planes separated one from each other 10 μm in the normal direction to the rake face of the tool due to the limitations of the laser machine. Thus, the laser was progressively removing material from the rake face of the tool until the final chipbreaker shape was achieved. Figure 3(a) and figure 3(b) show the final shape of the insert after the laser engraving process. Figure 3(c) shows a section of the chipbreaker manufactured in the alumina tool. This tool shape was determined by the experience of tool manufacturers.

3. Experimental set-up
To validate the performance of the chipbreaker in comparison with a non-modified tool, a battery of turning tests in Inconel® 718 was carried out. In table 1, chemical composition and mechanical properties of the alloy used are shown.

The tests were carried out in a CMZ TC25BTY turning centre with 35 kW of spindle power and integral spindle. Cutting forces were registered with a triaxial Kistler® 9129A piezoelectric dynamometer and an OROS® OR35 real-time multi-analyser with a sample frequency of
The inserts were TNGN 160408 of alumina reinforced with silicon carbides whiskers provided by NTK cutting tools. The cutting conditions used were the recommended by the manufacturer for roughing machining. In particular, a cutting speed of 275 m/min, feed of 0.15 mm/rev, a depth of cut of 1 mm and a cutting edge angle of 95°. The tests were carried out in dry conditions. Finally, chips were collected after each test with the aim of verifying the suitability of the chipbreaker.

4. Results and Discussion

4.1. Tool wear
The tool with chipbreaker was worn more slowly than the reference one. The tool life´s end criteria was
different in each tool. While in the reference tool both the notch and the average flank wear limits were overtaken, the tool with the chipbreaker only overtook the average flank wear. Figure 4 shows the average flank wear for both tools. Even so, there was also notch wear, but this stopped after two passes and prevented the tool from breaking.

![Figure 4. Tool wear comparison.](image)

The tool without the chipbreaker machined 8.14 cm³ in a time of 12.05 seconds, while the insert with the chipbreaker managed to remove 40.69 cm³ of material in 60.57 seconds. In terms of tool life, the inclusion of the chipbreaker has extended tool life by 400%.

4.2. Cutting forces
The results obtained from the tool life are closely related with the cutting forces. Therefore, in figure 5, the average of the cutting forces components from each test is shown. Ff corresponds to feed force, Ft to tangential force, Fb to binormal force, and, finally, the Modulus corresponds to the modulus of the components of the three forces.

![Figure 5. Average cutting forces.](image)

It can be shown that the inclusion of the chipbreaker in the ceramic insert reduces the total
machining force by approximately 27%. In particular, there is a clear decrease in the feed force, which suggests that there has been a clear reduction in chip-to-tool friction. Therefore, with the chipbreaker the flow of the chip has been modified. Moreover, the reduction of the friction between tool and chip could lead to it a reduction in the heat produced during the cutting process as Xing et al. showed in their study [6]. All these theories are in accordance with the increment of the tool life achieved by using the chipbreaker tool.

4.3. Chip analysis
Chips obtained from the tests can be seen in figure 6(a) and figure 6(b), which corresponds to chip generated by the reference tool and the modified tool respectively.

![Figure 6. Chip morphology. (a) Reference tool. (b) Chipbreaker tool.](image)

On the one hand, according to ISO 3685:1993, reference tool generated a tubular and short chip. However, it had a chipping appearance, which seems to come from an unstable cutting process. On the other hand, the chip that came from the modified tool’s cut is also tubular and short, but without chipping appearance.

Moreover, figure 6(b) chip presents higher degree of chip curling than chip generated with the reference tool. According to some researches, this high chip curling is an effect not only of higher tool-tip temperature, but also of higher chip evacuation from the cutting zone and, hence, less heat flow to the workpiece, approaching the ideal adiabatic model [8,9].

For all these reasons, including a chipbreaker in ceramic tools is essential to improve tool life and, hence, increase processes productivity and, in this way, continue to move on robust, stable and optimized processes.

5. Conclusions
In this work, an analysis of a manufactured chipbreaker performance in comparison with a plane tool has been made. After carrying out the tests and the different measurements, the following conclusions have been reached:

- The inclusion of the chipbreaker in the alumina reinforced insert has delayed the onset of flank wear so that tool life has been increased. In addition, after a few seconds of machining, the development of notch wear is slowed down, which means that the tool does not fracture.
- With the new chipbreaker, it is possible to reduce in approximately 27% the forces generated during cutting, due to the improved chip sliding on the cutting face of the tool. As a result, the friction between tool and chip is reduced. This results in more stable machining processes.
- In terms of the extracted chip, from the appearance of them it can be concluded that the chip during the cutting process with the modified tool reached more temperature, but it was evacuated faster than with the reference tool. Therefore, the inclusion of the chipbreaker in the rake face of the tool, brings the process to the ideal adiabatic one.
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