Materials Research Proceedings 28 (2023) 1347-1356 https://doi.org/10.21741/9781644902479-146

Evolution of contact lengths during the turning of treated Ti64β

WAGNER Vincent[1,a *] and DESSEIN Gilles[1,b]

[1]Laboratoire Génie de Production, Ecole Nationale d'Ingénieurs de Tarbes, Université de Toulouse, Tarbes Cedex, France

[a]vincent.wagner@enit.fr, [b]gilles.dessein@enit.fr

Keywords: Contact Length, Ti64β, Tool Wear

Abstract. One of the main ways to increase productivity during the machining of titanium alloy parts is to control the wear mechanisms and consequently the life of the cutting tools. The state-of-the-art shows wear phenomena generated mainly by diffusion. The latter is due to the intrinsic physical properties of titanium generating high temperatures on the cutting and relief faces. Concerning the secondary cutting zone, the wear phenomena result from thermomechanical actions induced by the contact between the secondary zone of the chip and the cutting face of the tool. The analysis of the contact lengths, divided into two parts (sliding contact and sticking contact), is then a strong indicator to be privileged in order to allow the understanding of the present mechanisms. This analysis is even more important when machining processed Ti64 β in which chip formation is no longer periodic but a function of the angle between the primary shear band and the orientation of the individual colonies comprising the titanium. The purpose of this article is the analysis of the contact lengths during the machining of Ti64 treated β . After having presented the experimental device allowing visualising the evolution of the contact length between the chip and the cutting face, a statistical analysis based on the collected images makes it possible to put forward the differences of sliding behaviour on the cutting face. It appears that the distribution of the collected values allows explaining and extrapolating the wear appearing on the cutting face.

Introduction

When machining titanium alloys, two types of tool wear occur. Because of their high mechanical properties and low thermal properties, the wear encountered is flank wear and edge collapse. Tool wear has been studied for many years [1] and [2]. To avoid or limit tool wear, one of the solutions is then to define an optimal tool geometry and reduce the cutting conditions. The aim is to reduce the phenomena of diffusion. These phenomena appear mainly on the rake face and result from the high thermomechanical stresses applied to the cutting face over a distance called the contact length. Some studies concern the analysis of the parameter but it is always considered as constant and function of the cutting conditions, the cutting tool geometry and the workpiece behaviour. For example, Lee and Shaffer [3] and Abdulaze and al. [4] some pioneers in this filed developed an analytical tool-chip contact length models for standard steel. With this model, they link the geometrical aspect such as rake angle, uncut chip thickness or shear angle. Zhang et al. introduced the effect of cutting speed on the model of these lengths and in application for low-carbon steel [5]. Oxley provide a model based on coefficients traducing the strain hardening of the material [6]. Moufki et al attempt to take into account the effect of temperature of the friction law between the chip and the tool, where most of the studies use a Coulomb contact [7]. Moreover, it is commonly accepted that the contact length decreases with increasing cutting speed and rake angle and decreases with the feed rate [8]. A major part of these models are dedicated to a sharp cutting edge. However, when machining with chamfered tools, the cutting process is relatively different. Indeed, the chamfered edge will often lead to the formation of a dead metal zone under itself. This dead metal zone will replace the missing nose of the tool and form a small edge radius, changing the

shear angle. With this specific shape will appear a stagnation point around which the material will flow. Recently, Barelli and al. [9] showed there is a particular evolution of contact lengths during machining. They show from a statistical analysis of the contact lengths over a short period of time that the contact evolves and generates more or less significant deposits. However, this analysis, although accurate, is limited to a single alloy.
Wagner and al. [10] shows that chip formation during the machining of Ti64 β does not follow the cutting process introduced by [11]. It then appears that chip formation is not constant over time but is a function of the orientation of the structure encountered during the creation of the shear band. The morphology of the harvested chips is then very variable.

The objective of this study is to provide an analysis of the contact lengths during the machining of Ti64 β in order to identify if the particular process of chip formation, which is not constant, impacts the contact lengths. After having presented the alloy and the chip formation process, this study is based on an experimental device allowing measuring at each moment the contact lengths during machining. The images collected and analysed allow correlating the contact lengths with the cutting conditions and to compare their variability with the more common structure.

Studied Material

The objective of this part is to present the machined material as well as the experimental device. The alloy used is a Ti64 composed of titanium, 6% aluminium and 4% vanadium. The recrystallisation process is defined by different steps (Fig. 1). The difference between this structure and the more common structure results in the addition of a solution phase in the βdomain between the forging and tempering phases. Indeed, the microstructure of Ti64 is a function of the different stages of the recrystallisation process. The heat treatment is divided in four steps. The first one corresponds to the homogenisation of the structure. The second step is the forging carried out only in the domain α +β . This is followed by solution heat treatment starting in the β range and followed by a long cooling phase. Ultimately, a tempering is performed at a temperature below β transus.

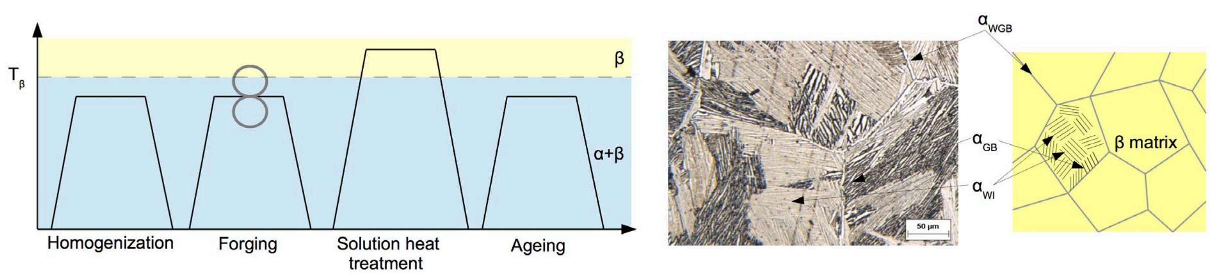


Fig. 1. Heat treatment (left) and structure of Ti64β (two figures on the right).

In contrast to the classical Ti64 structure (with nodular grain [11]), the structure of the alloy studied is fully lamellar (Fig. 2). The α phase is transformed into an acicular phase α ' in the matrix β. It is also possible to observe the α_{BG} phase near the grain boundaries. It appears as the continuous line around the old grains β. Concerning the α_{WBG} phase, it germinates from the grain boundary to the centre and appears as lamellae. Finally, the α_{W1} phase germinates inside the old grain β. The whole phases are immersed in the matrix β.

Materials Research Proceedings 28 (2023) 1347-1356 https://doi.org/10.21741/9781644902479-146

Experimental Device

For these tests, Genymab 900 turning lathe was used. The inserts used were CCMX 120408 with TiN PVD coating, the rake angle was 20° and inserts had a chamfer edge preparation of 0.02 mm. The tests were carried out on tubes in order to be in simple, generalisable cutting conditions. The chip flow will not be unidirectional insofar as a slight angle of inclination of the edge appears. These tests were carried out without lubrication in order not to disturb the image acquisition. The tubes used for these tests have a thickness of 3 mm. Force measurements during machining were performed using a Kistler 9129A dynamometer, a 5019A amplifier and Dynoware software.

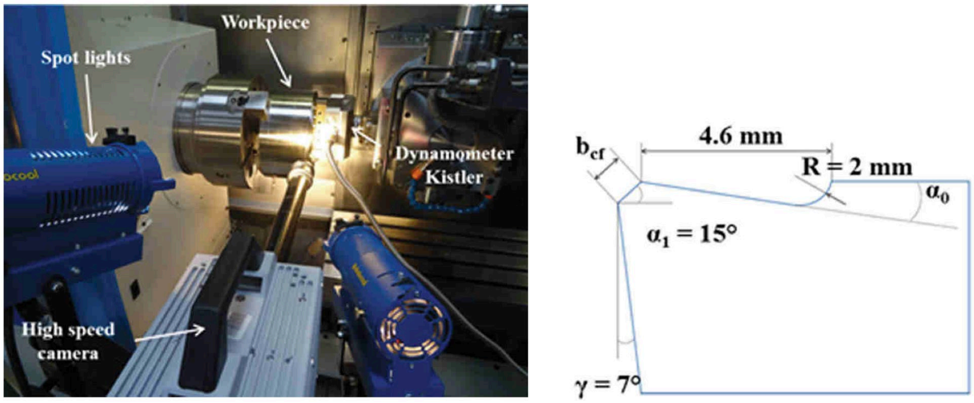


Fig. 2. Experimental setup.

The observations of the chip flow during the machining process were carried out with the help of the PhotronFastcam SA1 high-speed camera whose acquisition characteristics of 5000 images/s^{-1} is chosen. The resolution used is 1024x1024 pixels2 allowing an acquisition time of about 1s. For these tests, two cold light projectors were used to limit their influence on the cutting temperature. Definitely, rings were added between the cell and the x100 zoom lens. The resolution obtained is 5μ m. The experimental setup is shown in Fig. 2.

Chip Formation

For this alloy, the study shows that chip formation does not follow the classical process developed in many works [11-1]. Indeed, the chip formation is not only due to shears generated between the tool tip and the root of the chip. Several phenomena mainly due to the structure composed of lamellar colonies α +β oriented whose orientation varies appear (Fig. 3). The purpose of this section is to highlight these phenomena in order to explain, subsequently, the evolution of the contact lengths.

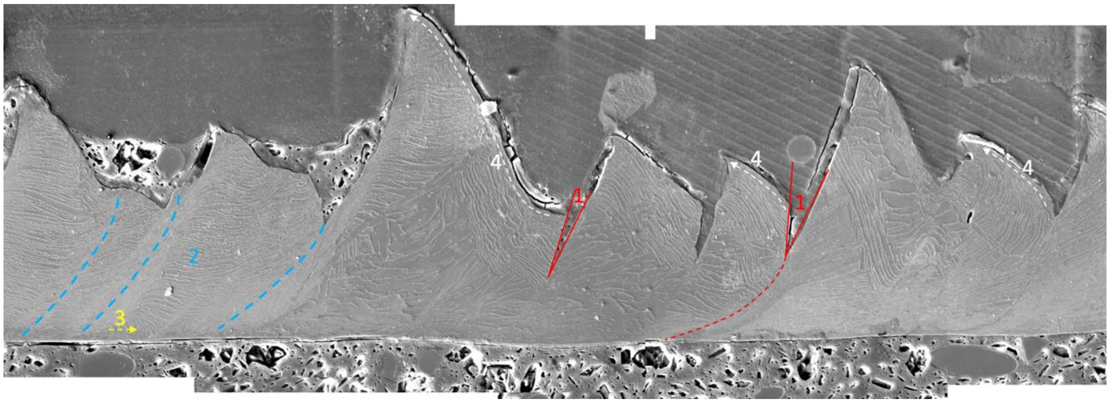


Fig. 3. Example of a micrograph of a Ti64 β chip.

The study of the chip formation allowed to put forward 4 configurations (Table 1).

Configuration 1

Whatever the cutting conditions, cracks can appear near the primary shear bands. There are two possible causes. The first one is similar to the one observed on more classical structures. The crack is then explained by intense shears. The second cause is specific to this alloy. The crack is then explained by a strong accumulation of plastic deformation at the interface of two strongly disoriented colonies (Colony 3 compared to Colony 4 and Colony 1 compared to Colony 2) (Table 1). In this case, the stress accumulation is explained by the difficulty of providing dislocations between two differently oriented colonies.

Configuration 2

The shear bands will appear in a privileged way in colonies whose orientation is transverse to the shear propagation. If the interfacesα /β are not a brake to the propagation of dislocations, a stress gradient exists between the different lamellaeβ going towards an increase of the stress near the interface. Consequently, the strain required to shear the interfaces is greater than that required to shear the laminae α .

Configuration 3

It appears that colonies relatively collinear to the main shear direction can be sheared transversely. The latter is initiated by the movement between the various colonies surrounding it.

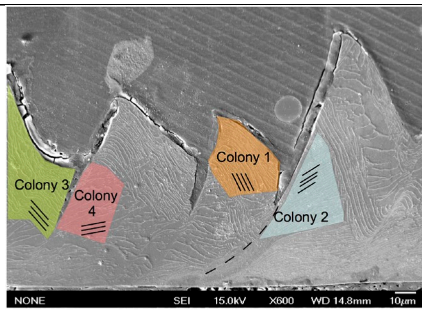
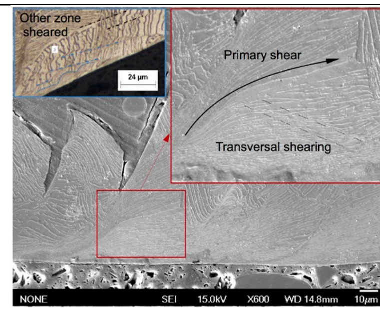
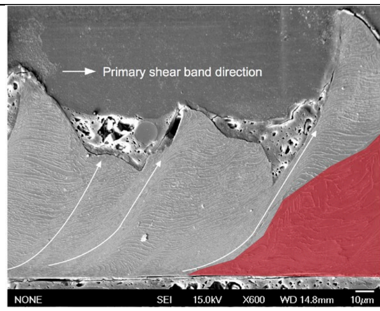
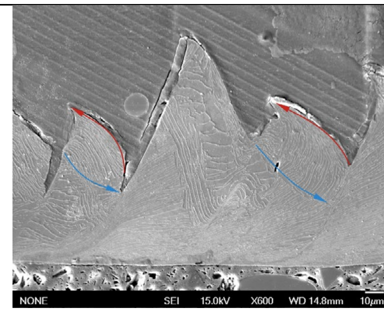
Configuration 4

In this configuration, it appears that a continuous shearing of the colony takes place near the free edges of the chip. The chip thus follows the movement imposed between the end and the interface of the closest colony.

This initial study thus shows the randomness of chip formation. A study from [10] concerning the influence of cutting conditions on chip formation then shows that adiabatic shear and cracking become regular when the feed rate and therefore the shear forces are high enough to generate them despite the orientation of the colonies.

The objective of the next part is then to observe the effect of this particular chip formation on the chip flow length.

Table 1. Summary of the different configurations found.

<table>
<tr><th>Configuration 1</th><th>Configuration 2</th></tr>
<tr><td></td><td></td></tr>
<tr><th>Configuration 3</th><th>Configuration 4</th></tr>
<tr><td></td><td></td></tr>
</table>

Cutting Length Measurements

The images are then processed using Matlab © software following an algorithm detailed in Fig. 4. The first step consists in locating the cutting edge by defining in X and from the left of the image, the last black pixel (grey level 0). This same operation is performed in Y. From the coordinates of the cutting edge, the algorithm recreates the cutting edge. For this and for each column, the program defines the last pixel with gray levels equal to 255 (white). Then, the chip being one of the elements reflecting the lightest, it is easy to determine a threshold value of gray level delimiting the lower surface of the chip in the background. This value is specific to each serie of images, the algorithm artificially defined that all gray levels below this threshold value are equal to 0. From the points belonging to the edge, the algorithm searches column by column, in the direction of the positive Y, for the last pixel with a gray level of 0. These pixels then belong to the lower surface of the chip. The set of coordinates of the edge and the cutting face being known, it is then possible by difference to calculate the contact lengths between the chip and the cutting face.

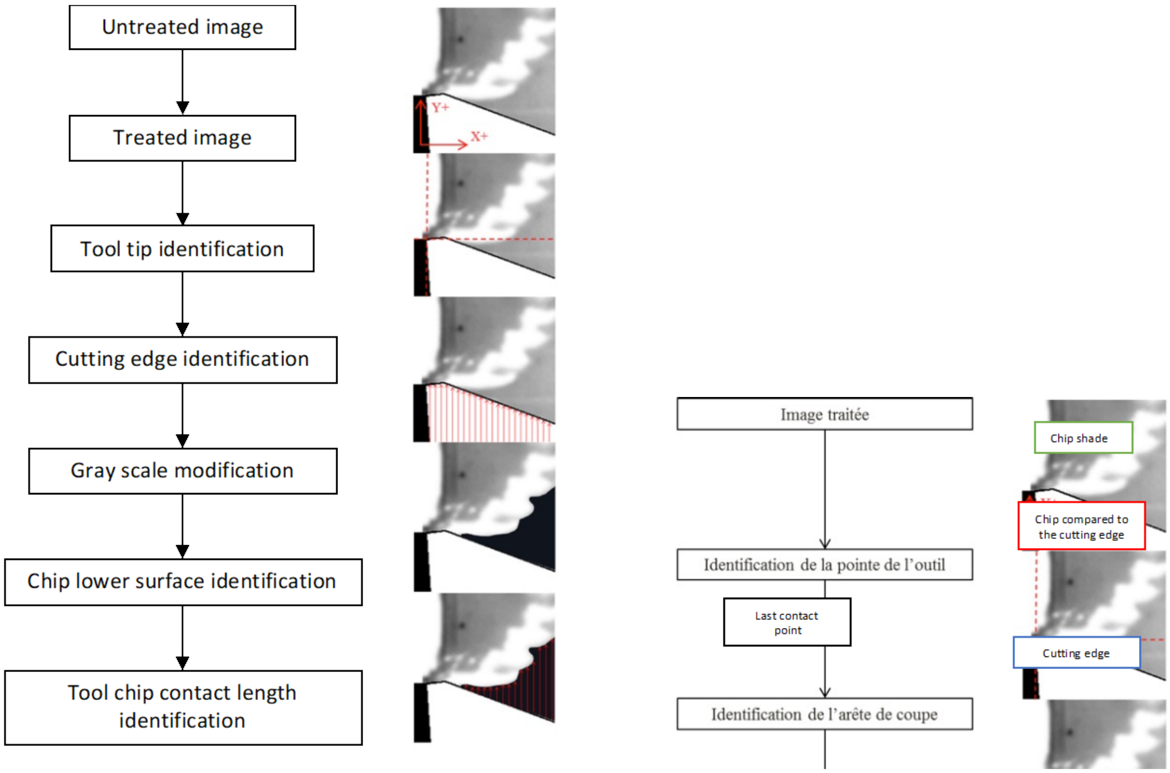


Fig. 4. Image processing.

Given the large number of values obtained, a statistical analysis was carried out. The results obtained are presented in the form of a moustache box (Fig. 5). This choice makes it possible to highlight the distribution of the data and the preferred values taken by the contact lengths. On the representations exposed in this article will be exposed the 5th percentile (the low end of the segment), the 1 st quartile (the low part of the box), the median (the line in the middle of the box), the 3rd quartile (the high part of the box) and finally the 95th percentile (the end of the segment). Each result sums up measurements made on 1000 images of tool-chip contact lengths within cutting process.

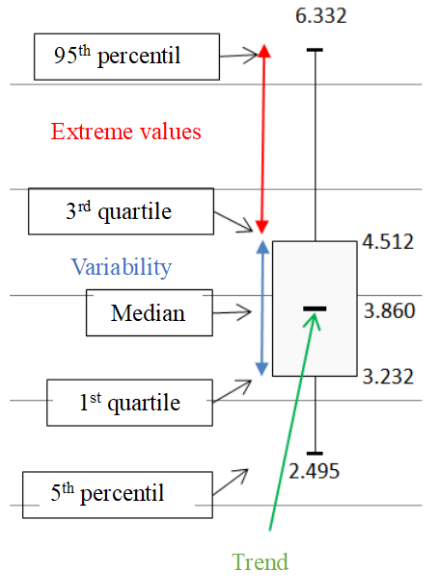


Fig. 5. Moustache box.

When machining Ti64 with a classical structure, the general trend observed is a quasi-linear increase in contact lengths with the feed rate. The increase of the cutting speed has the effect of slightly reducing the contact lengths but in lesser proportions compared to the feed rate.
For this microstructure, the trends are slightly different (Fig. 6). The classical relationship between contact length and feed rate does not appear. For all three cutting speeds tested, increasing the feed rate results in an increase in contact length. From these tests, it is not possible to define the conditions giving the greatest contact length. Concerning their extent, the most variable conditions appear for Vc=30 m/min. Indeed, whatever the quantile or the percentile observed, the greatest differences appear for Vc=30 m/min.

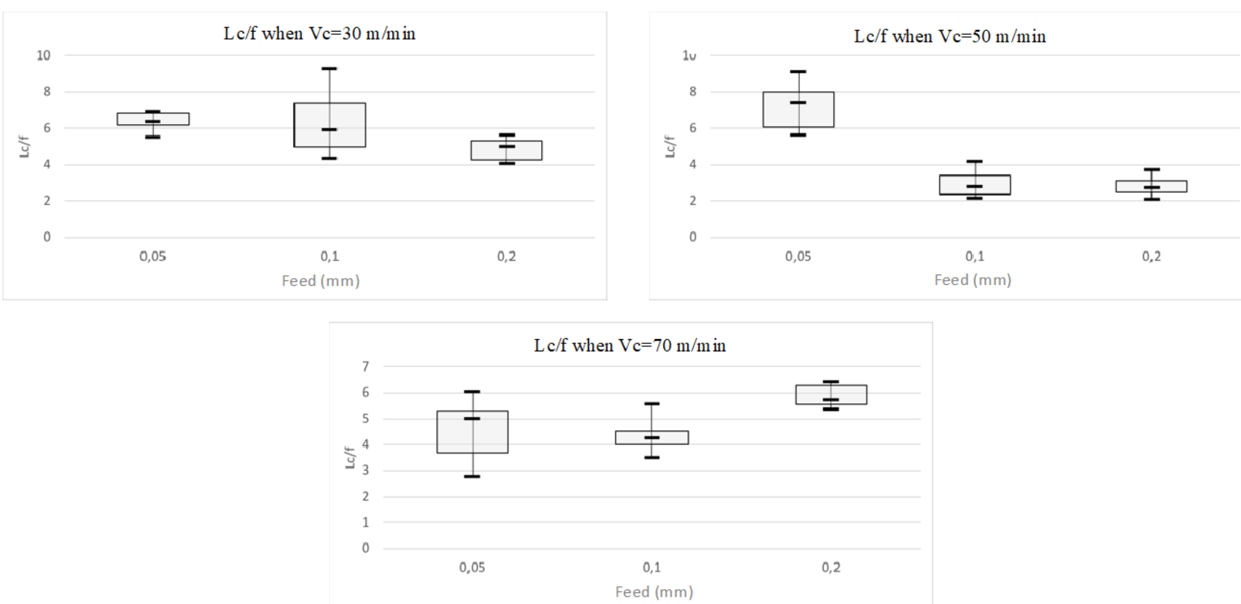
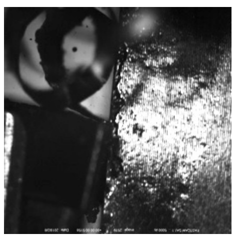


Fig. 6. Evolution of contact lengths for Vc=30 m/min, Vc=50 m/min and Vc=70 m/min.

Materials Research Proceedings 28 (2023) 1347-1356 https://doi.org/10.21741/9781644902479-146

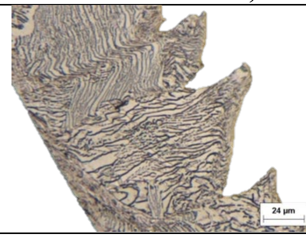
This trend appears to follow the cutting process and chip formation developed earlier. The variability also seems to correlate with the effect of cutting conditions on chip formation.
Contrary to the analysis made on the more classical structure, it appears that whatever the analysis time, the radius of curvature is not impacted. Table 2 shows the chip formation observed at different times (at the beginning of the analysis, in the first quarter, in the middle, in the third quarter and at the end). It appears that the chip never touches the chip breaker, never segments and because of the edge inclination never meets the machined face (in this example out of the field). Moreover, the tests showed that over the recording period, the chip weight did not influence the contact lengths. Indeed, as the chip does not segment, the chip weight could impact the radius of curvature and consequently the contact lengths. The change in contact lengths can then be explained by the formation of chips.

Table 2. Evolution of chip formation over the duration of the statistical analysis.

Start	**Duration / 4**	**Duration /2**	**End**
			

The study of the effect of cutting conditions on chip formation shows a strong correlation between cutting speed, feed rate and chip geometry. In contrast to the more classical structures where the chips remain, whatever the cutting conditions, more or less scalloped chips, the shape of the chips is much more evolutive. Table 3 shows the effect of cutting conditions on chip formation. At low cutting speeds, the chips are continuous. As the cutting conditions increase, it appears that the chips become scalloped with increasingly constant distances between scallops. However, unlike other alloys, the scalloping becomes more regular as the cutting conditions increase. This relationship is explained by the level of stress that appears at high cutting conditions. As said before, the creation of shear bands is initiated especially when the colonies are oriented perpendicular to the band formation. This initiation is the result of high thermomechanical stress accumulation at the boundary of highly disoriented colonies. Higher stress accumulation then facilitates the creation of primary shear bands. An increase in cutting conditions results in higher stresses and temperatures which then facilitate the appearance of shear bands. Wagner also shows that for certain cutting conditions, shear bands are created regardless of colony orientation [1].
In the study of contact lengths, it would appear that the lengths and especially the variability are a function of chip formation.
For Vc=30 m/min and when fz=0.05 mm, the variability is the lowest. For these conditions, the thermomechanical stresses are so low that the chip is continuous, whatever the structure. In this case, the variability is the lowest. When the feed rate increases, the stresses also increase and the chip formation becomes a function of the orientation of the microstructure. Its morphology becomes variable as well as the contact length. When Vc=50 m/min, there is a significant variability regardless of the feed rate. This disparity is explained by transient phenomena. For the lowest feed rate, the stresses are too low to generate a shear band each time. Conversely, when the feed rate increases, the stresses are greater but above all the probability of the primary bands crossing colonies increases and the chips, like the contact lengths, remain stable.

Table 3. Chip morphology as a function of cutting conditions.

Vc=30 m/min - fz=0,1 mm	**Vc=50 m/min - fz=0,1 mm**	**Vc=70 m/min - fz=0,1 mm**
		
Vc=65 m/min - fz=0,13 mm	**Vc=65 m/min - fz=0,15 mm**	**Vc=65 m/min - fz=0,20 mm**
		

Summary
Through an innovative experimental device, the objective of this study is to observe the evolution of contact lengths during the machining of Ti64β . After having detailed the microstructure and the particularities of the chip formation, the study develops the method of statistical analysis of the collected images. It appears that this evolution is mainly a function of the chip formation process. The study also shows a strong variability of the contact lengths explained by various points like, for example, the weak cutting conditions obtained during certain tests. In order to complete this analysis and to clearly define the relationship between contact length and tool wear, the next step is to chemically analyse the inserts and to propose a diffusion model complementary to those already existing based on a large experimental campaign.

References

[1] V. Wagner, E. Duc, Study of Ti-1023 milling with toroidal tool, Int. J. Adv. Manuf. Technol. 75 (2014) 1473-1491. https://doi.org/10.1007/s00170-014-6217-5
[2] V. Wagner, M. Baili, G. Dessein, The relationship between the cutting speed, tool wear, and chip formation during Ti-5553 dry cutting, Int. J. Adv. Manuf. Technol. 76 (2015) 893-912. https://doi.org/10.1007/s00170-014-6326-1
[3] E.H. Lee, W. Shaffer; The theory of plasticity applied to the problem of machining, J. Appl. Mech. T ASME 18 (1951) 405-413.
[4] N.G. Abuladze. Character and the length of tool-chip contact (in Russian), in: Proceedings of the machinability of heat-resistant and titanium alloys, Kuibyshev, 1962, pp. 68-78.
[5] H.T. Zhang, P.D. Liu, R.S. Hu, A three zone model and solution of shear angle in orthogonal machining, Wear 143 (1991) 29-43. https://doi.org/10.1016/0043-1648(91)90083-7
[6] P.L.B. Oxley, Mechanics of machining: an analytical approach to assessing machinability, Chichester: Ellis Horwood Limited, 1989.
[7] A. Moufki, A. Molinari, D. Dudzinski, Modelling of orthogonal cutting with a temperature dependent friction law, J. Mech. Phys. Solid. 46 (1998) 2103-2138. https://doi.org/10.1016/S0022-5096(98)00032-5
[8] N.N. Zorev, Metal cutting mechanics, Oxford: Pergamon Press, 1966.
[9] F. Barelli, V. Wagner, R. Laheurte, G. Dessein, P. Darnis, O. Cahuc, M. Mousseigne, Orthogonal cutting of TA6V alloys with chamfered tools: Analysis of tool-chip contact lengths,

Proceedings of the Institution of Mechanical Engineers, Part B: J. Eng. Fabric. 231 (2017) 2384-2395.
[10] V. Wagner, F. Barelli, R. Laheurte, G. Dessein, P. Darnis, O. Cahuc, M. Mousseigne, Thermal and Microstructure Study of the Chip Formation During Turning of Ti64 β Lamellar Titanium Structure, J. Manuf. Sci. Eng. 140 (2018) 031010. http://doi.org/10.1115/1.4038597
[11] R. Komanduri, B.F Von Turkovicz, New Observations on the Mechanism of Chip Formation When Machining Titanium Alloys, Wear 69 (1981) 179-188. https://doi.org/10.1016/0043-1648(81)90242-8