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TITANIUM BLADE MILLING WITH MINIMUM PIECE DEFORMATION BASED ON TOOL ORIENTATION

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Abstract
This article analyses the influence of tool orientation on the geometry and surface finish obtained during the machining of thin-walled curved freeform surface parts on multitasking machining centre. These complex surfaces parts have direct application in blade manufacturing for the aeronautical sector, which has very high quality standards and are difficult to achieve. In addition, the material used is Ti6Al4V which adds a challenge due to its difficult machinability. Tool orientation has a significant effect on the accuracy of multi-axis machining reducing the theoretical force in a 6.17 % have achieved a dimensional improvement of a 7.84 %.

Keywords:
Tool orientation, thin wall; ball-end milling, multiaxis machine, Ti6Al4V, dimensional error, surface finish, blade

1 INTRODUCTION

Thin-walled and free-surface parts such as blades or blisks, among others, are considered highly valuable components. These parts supose a significant challenge in the machining industry due to their complex geometry and strict tolerances. It is crucial to control cutting parameters such as, tool path, workpiece and tool orientation and clamping method among others in order to achieve the highest possible precision during machining. Yan et al. have analyzed various articles that investigate the factors that most affect blade machining [Yan 2022].

The titanium alloy Ti6Al4V is one of the most widely used in the industrial environment, both in the aerospace and biomedical fields, due to its excellent characteristics of corrosion resistance, high temperature resistance and low conductivity. However, these properties make the material a great challenge in milling processes as a result of its difficult machinability. Kahya et al. have developed a methodology for the manufacturing of Ti6Al4V blades, ensuring the required high precision and process efficiency [Kahya 2021].

The latest advancements in the industrial sector, including multiaxis machining machines, new materials, and new tool geometries among others, enable the machining free form of complex curved surface thin walled parts with the high dimensional requirements demanded by the aerospace industry.

One of the factors that significantly impact in both dimensional and surface finish error is the tool orientation. Therefore, the common process to reduce this error in the machining industry is modifying this parameter and analysing the obtained results [Habibi 2019].

Lizzul et al. analysed how the tilt angle affects the surface roughness on surfaces inclined at 15°, 45°, and 75°. The results obtained showed better surface quality with an angle of 75 degrees, as it resulted a surface without marks in the feed direction [Lizzul 2021].

Habibi et al. analysed the influence of flute engagement on workpieces in relation to tool orientation in five axis ball end finish milling. A higher flute engagement enhances tool stability during cutting. However, excessive flute engagement can lead to increased tool wear. They have developed a method that drastically reduces surface error almost 90% [Habibi 2020].

Mhamdi et al. studied the surface integrity of concave parts of titanium alloy (Ti6Al4V). They researched that milling with a downward and upward angle of 60º provided the best surface finish [Mhambi 2012].

All this researches focus on the improvement of the dimensional and roughness but no focus in thin wall parts which are crucial in aeronautical industry due to their ability to reduce weight, enable complex designs, provide strength and durability, and meet the industry's high standards for safety and reliability [Hou 2021].

However, the low stiffness of these thin walled parts presents a challenge during the milling process, as the cutting forces applied can cause elastic deformation [Llanos 2023]. This deformation leads to a decrease in machining precision, which can be unacceptable. Stable machining is crucial for achieving accuracy and surface quality of the workpiece. The complex geometric relations involved make process modelling difficult, particularly when dealing with general tool workpiece orientations. One of the major obstacles is determining the tool workpiece engagement.

There are others studies which aim is optimizing tool orientation in thin wall free form parts which geometry seems to blade ones.

Ma et al. method analyses the rigidity of the workpiece and homogenizes the deformation occurring during the manufacturing of thin-walled curved surface parts in five-axis machining. By employing this method, they achieve a reduction of over 80% in deformation error variance without compromising machining efficiency, thereby achieving high-quality machining results [Ma 2018].

Tunc and Zatarain analysed and selected the tool axis to enhance stability in machining thin-walled parts. They chose to focus strictly on the analysis of the tilt angle, disregarding the potential effect of the lead angle. They found that with very small tilt angles, the flexibility was insignificant, while at tilt angles around 90 degrees, the flexibility aligned with the tool. They demonstrated that by using tilt angles of 15 degrees, they increased cutting stability by 25% [Tunc 2019].

In contrast, Gdula focused their research on a control method of the lead angle, which resulted in a reduction of shape deviation by about 25%, as well as a reduction in roughness and the achievement of a uniform distribution on the work surface [Gdula 2019]. Only one study was found in the literature that examine the combined effect of tilt and lead angle on complex free-form thin-walled parts, such as blades.

Habibi et al. developed an algorithm that reduces shape errors by adjusting the tool orientation through modifications of the tilt and lead angles, without changing the tool position or toolpath [Habibi 2019].

It is important to verify that the part was manufactured correctly and meets the strict dimensional and surface finish requirements. The blades, which direct the air in the jet engine, require a surface roughness between 0.2-0.4 µm, which is below the capabilities of machining operations [Yan 2022]. Therefore, finishing processes are necessary when dealing with parts used in jet engines. Tan et al. have analysed the surface finish of blades using different finishing methods such as vibration polishing, shot peening, and polishing. All of these technologies reduce the Ra roughness to values below 0.4 µm, with the best results obtained with vibration polishing at 0.2-0.27 µm [Tan 2020].

The aim of this research is to obtain the optimum orientation of the tool modifying the tilt and lead angle in order to reduce as much as possible the deformations that occur during machining and that are responsible for the geometrical errors in the part. Despite the limitations of machining processes, the surface roughness of the parts will also be analysed, as it is directly related to the cutting conditions used in machining, tool orientation, and vibrations that may have occurred during the manufacturing processes of thin-walled components.

The results of these tests have a direct application in the end-ball finish operation of blade machining as the optimum tool angle is achieved for the manufacture of the blades by means of a multi-axis machine.

2 METHODOLOGY

The tests were carried out on a 5-axis multitasking machine Mazak Integrex I2000, as shown in Fig.1 (a). The material used is TI6Al4V, which due to its low machinability supposes a significant challenge. However, its properties guarantee the necessary standards to withstand extreme working conditions such as temperature, vibrations, and forces. The tool used for the tests is a 6 mm diameter carbide ball end mill with 4 teeth, ensured that any deviations observed in the machined part were not attributed to the tool itself, due to its rigidity. The cutting conditions used throughout the experiments are defined in Tab 1.

After blade manufacturing, both the dimensional and surface finish are analysed. For dimensional verification, a coordinate measuring machine Crysta® APEX S-9106 is used. For surface roughness analysis A microscope ALICONA® Infinite Focus is utilized.

The coordinate measuring machine, in addition to conventional contact measurement, is equipped with a laser scanner. This scanner allows the surface scanning of the piece, creating a mesh representation that enables a more visual comparison through colour mapping. The scanner has a precision of 17 µm, which is sufficient for this type of piece considering the form error is in the range of 200 µm. In addition, it was verified that the results obtained with the laser scanner are of the same order of magnitude as those obtained through contact scanning, which is the methodology commonly used for dimensional verification of the studied pieces.

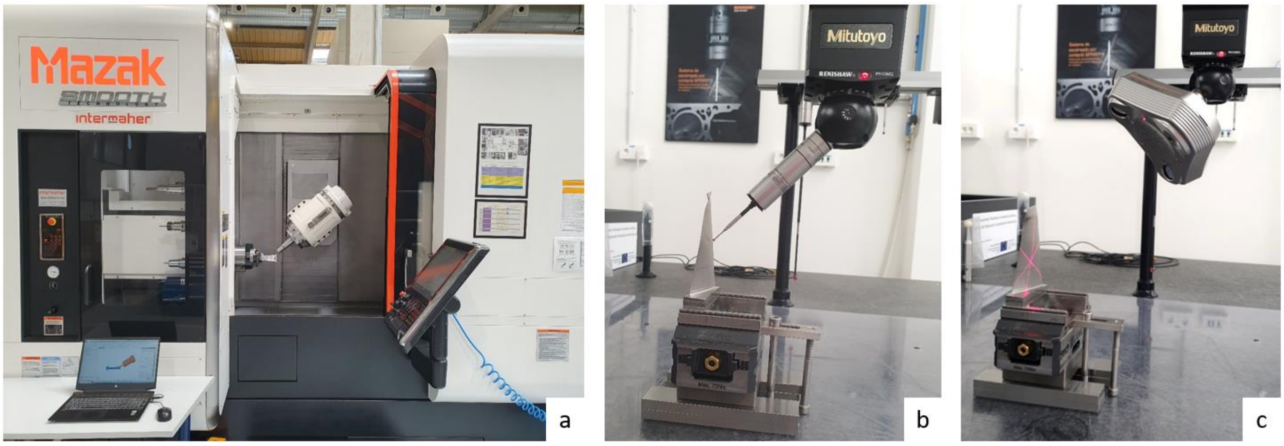

Fig. 1: Set up (a) milling (b) contact measurement (c) optical measurement.

Tab. 1: Test cutting parameters.

	Blade 1	**Blade 2**
Tilt angle	52º	45º
Lead angle	0º	30º
Cutting speed (v_C)	100 m/min	100 m/min
Spindel speed (n)	5305 rpm	5305 rpm
Axial depth of cut (a_p)	1 mm	1 mm
Radial depth of cut (a_e)	0.2 mm	0.2 mm
Feed per tooth (f_z)	0.03 mm/tooth	0.03 mm/tooth
Feed per revolution (f)	0.12 mm/rev	0.12 mm/rev
Tool diameter (Ø)	6 mm	6 mm
Tool teeth (z)	4	4

The microscope is used to obtain the area from which the roughness of the piece will be measured. ALICONA utilizes a high-pass filter to eliminate waviness from the piece. According to ISO 4288 norm, the cut-off length (Lc) of 800 µm is selected, which is suitable for machining processes such as turning and milling, as in this case. According to this standard, the minimum required measurement area for the magnitude of roughness is 4x4 mm. The direction from which the roughness is obtained is the most unfavourable, which is perpendicular to the feed direction.

In 5-axis machining, the combination of tilt and lead angle allows the cutting tool to position and orient itself optimally to reach complex areas of the workpiece. This provides greater flexibility and capability to produce more intricate and precise geometries in a single machining process. Proper utilization of these angles is crucial to achieve optimal efficiency and quality in machining three-dimensional parts.

The tilt angle is the angle formed between the tool and the normal to the cutting surface, as defined in the CAM programming, which is determined based on the feed direction vector. The lead angle is defined as the orientation of the tool axis relative to feed direction, measured from its normal, and both angles are defined in Fig.2.

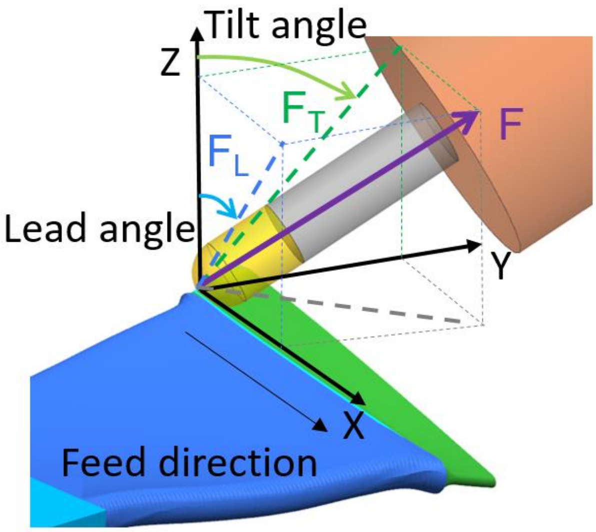

Fig. 2: Tilt and lead angle.

The experiments involve analysing the effect of tool orientation variation on the complex free-form thin-walled surface of the workpiece. Tool orientation is crucial for achieving high-quality machining in terms of surface finish, dimensional accuracy, cutting efficiency, and avoiding unwanted vibrations. Correct tool orientation guarantees precise, efficient, and reliable results in the machining process. Therefore, two tool orientations will be examined, which are specified in Tab. 1.

Blade 1 is machined with a tilt angle of 52 degrees and a lead angle of 0 degrees, which is perpendicular to the feed direction, being the tool force on the plane YZ of the coordinate system. Due to the thin-walled nature of the workpiece, the force that has the most negative impact on the part is the force that promotes its bending, which is the F_z force. Therefore, a theoretical calculation is performed to analyse how the orientation of the tool affects this force:

$$F_{z1} = F\cos(52^{\circ}) = 0.616\,F \quad (1)$$

During the machining of Blade 2, the angles was modified to improve both the surface finish and any dimensional errors that may occur during the final ball finishing operation. To achieve this, the tool was tilted towards the feed direction to stabilize the manufacturing process with the aim of reduce de F_z as said before which is the force that has the greatest influence on the bending of the workpiece. Additionally, the tilt angle was reduced to ensure similar contact areas and maintain a constant chip flow during both experiments.

In this case, calculating the relationship between the force perpendicular to the cutting surface and the force resulting from the tool orientation was more complex. This is because the tool orientation does not lie in any of the planes of the coordinate system. The value is obtained by solving the following equations:

$$\left.\begin{aligned} F_z &= F_T\cos(45^{\circ}) \\ F_z &= F_L\cos(30^{\circ}) \\ F &= \sqrt{{F_T}^2 + (F_L\cos(30^{\circ}))^2} \end{aligned}\right\} F_{z2} = 0.578\,F \quad (2)$$

This new orientation achieves the one purpose of this analysis which is optimize the tool orientation to minimizing in a 6.17% the F_z force and reducing the negative effects of bending on the workpiece.

However, it is even more important verify how the final geometry is affected by the tool orientation while keeping the other cutting parameters constant, such as cutting speed, feed, axial and radial depth, among others. In Fig. 3, the selected positions for the machining of both experiments can be observed. Both the angles and the cutting parameters was maintained throughout the entire machining process.

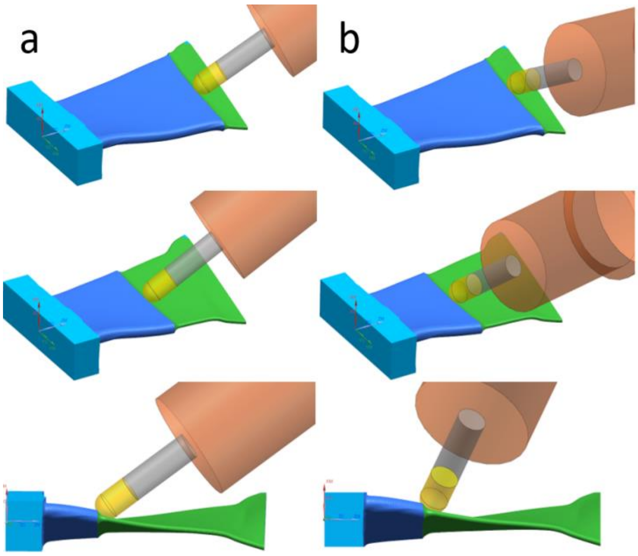

Fig. 3: Tool orientation (a) Blade 1 (b) Blade 2

By selecting an optimal tool orientation, it is possible to enhance the stability of the machining process, improve dimensional accuracy, and mitigate the risk of deformation or failure in the thin-walled part.

3 RESULTS AND DISCUSSION

After machining the blades on the 5-axis multitasking machine, two demonstrators are obtained, as shown in Fig. 4.

During the process, a sound of cutting instability was observed in the initial regions of machining, which gradually stabilized as the overhang of the workpiece decreased. Therefore, a visual inspection of the workpiece was conducted to analyse this phenomenon.

Through visual analysis, the defects that occurred during machining are examined. In both blades, it is observed that at the beginning of machining, where there is a larger overhang, there is a lack of cutting stability and the desired surface finish of the workpiece is not achieved. As the overhang is reduced throughout the experiment, the cutting becomes more stable and better results are obtained.

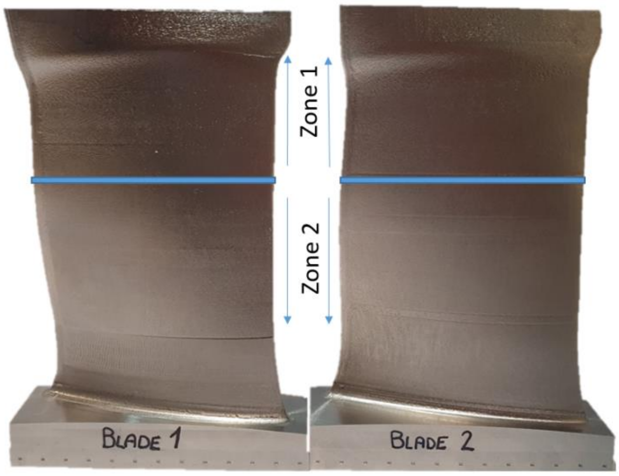

Fig. 4: Milling part

The determination of better results between the two pieces relies on two factors. Firstly, the surface finish of the piece is considered. Secondly, the other factor is associated with the dimensional error generated during machining.

As explained in the methodology, 4x4 mm areas are obtained to analyse the obtained surface roughness along the manufactured piece. Since visually there are two clearly differentiated areas, Zone 1 where instability occurs and Zone 2 where the cutting has already stabilized, both areas will be analysed separately. Combining the results from both areas would result in a large variance, and despite maintaining the same cutting parameters throughout the entire test, the obtained results would not be comparable.

Firstly, surface roughness measurements of Blade 1 were obtained. In Fig. 5, one of the measured values in each of the zones is shown. Measurements were taken in 6 areas distributed along each of the zones, both 3 measurements on the concave and 3 measurements on convex side of the piece. Both surfaces were measured because, being a complex free-form geometry, significant differences could occur depending on the cutting performance on each surface. However, since very similar results were obtained, only the previously described zones, namely instability and stability zones, will be differentiated.

	Blade 1		Blade 2	
	Average	Variances	Average	Variances
Zone 1	2.288	0.015	1.964	0.014
Zone 2	1.653	0.006	1.670	0.033

Tab. 2: Blade 1 and Blade 2 roughness.

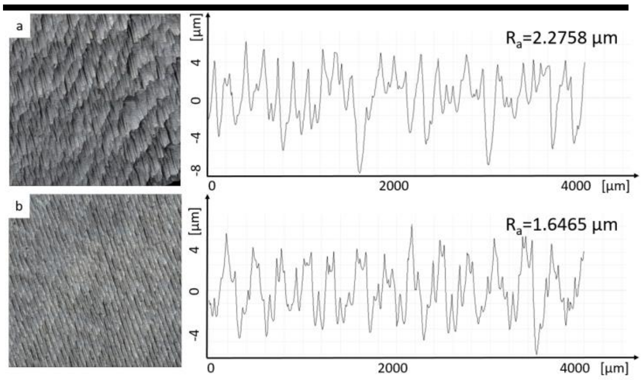

Fig. 5: Roughness Blade 1 (a) zone 1 (b) zone 2.

The same measurements were carried out for Blade 2. In Fig. 6, similar to Blade 1, images of the two representative zones of the machining of the thin-walled free-form surface piece are shown.

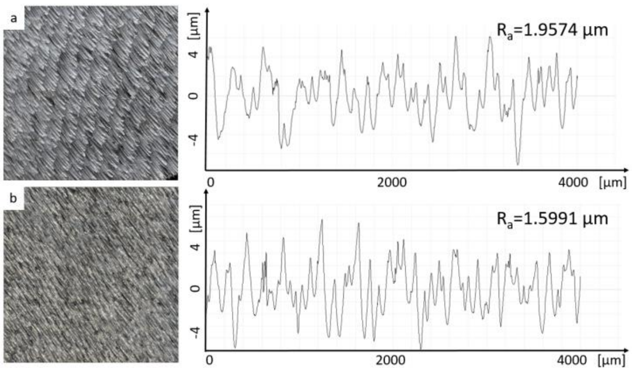

Fig. 6: Roughness Blade 2 (a) zone 1 (b) zone 2.

By observing the figures of the two blades, it can be concluded that the first tool orientation generates greater cutting instability, which results in a more irregular and inconsistent machining across the studied area. On the other hand, with the second tool orientation and a successfully reduce of F_z force, a more homogeneous roughness is achieved throughout the studied areas.

This effect is due to the reduction of the perpendicular force on the surface, resulting in less excitation in the instability area and yielding better roughness results in zone 1. This area is critical in the machining process because it experiences higher bending due to the nature of the studied workpiece, particularly in regions with greater overhangs.

The results were obtained from the figures and visual analysis of the pieces, and they are supported by the results obtained from the 6 measurements. The average roughness and variance for each zone are presented in Tab 2. In addition to the average roughness values, the variance was calculated to quantify the statistical measure of dispersion of a set of measurements around the mean.

As observed in Tab. 2, in zone 1, Blade 2 exhibits better roughness, which is consistent with the observations in the previous figures and the calculations of the forces. Nevertheless, the roughness values in zone 2 are similar with Blade 2 slightly higher at 0.017 µm, suggesting that both blades attained a relatively consistent surface quality in that region. It is worth noting that the slight difference in roughness between the two blades may not be practically significant, and further analysis and evaluation may be required to determine the overall impact on the performance and functionality of the machined parts.

Indeed, the roughness is a crucial factor for these types of parts, as they are responsible for directing the air and therefore need to have low roughness values, typically ranging from 0.2 to 0.4 µm. Since no machining operation alone can achieve such surface finish, additional finishing processes are necessary to achieve the desired roughness [Yan 2022]. This highlights the importance of dimensional accuracy in the final piece.

The dimensional verification of the piece is performed using both contact and optical methods. Although they may not have the same resolution, the results obtained from both technologies are in the same range of value. However, due to the visual nature of the results obtained from the optical scanner, they are the ones shown in Fig. 7.

Through the comparison of surfaces, specifically the mesh of the actual piece and the model of the final piece, the colour mapping is obtained, which allows for a visual representation of the dimensional error of the part at a glance. Dimensional tolerance plays a vital role in guaranteeing that parts function correctly.

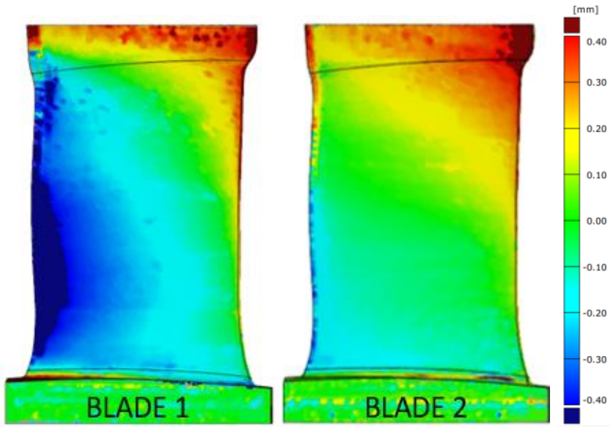

Fig. 7: Dimensional measurement

As can be observed, both blades exhibit the same trend in terms of dimensional error. This indicates that, despite individual differences in the numerical values of the error, there is consistency in the deviation pattern between the real geometry and the target geometry. This information is crucial for evaluating the accuracy and quality of the machined parts.

On one hand, in Blade 1, a lower dimensional error is observed in zone 1, where the cutting was unstable. However, it exhibits a higher dimensional error in the centre of the blade, corresponding to zone 2.

On the other hand, in Blade 2, despite having the same trend and even a higher error in the upper-right zone, there are generally more areas within the tolerance range. This is reflected in a larger green-coloured area, indicating a dimensionally correct zone.

Analysing the results obtained from the contact measurements made on 5 sections along the entire aerodynamic profile, it was determined that the average error for Blade 1 is 0.153 mm, while for Blade 2 it is 0.141 mm. This indicates that the new tool orientation improves the dimensional accuracy of the piece by 7.84%.

In both blades can be observed that the fillets connecting the concave and convex surfaces, also known as trailing edge and leading edge, do not meet the required tolerances. This can be attributed to two main factors.

Firstly, the mesh generated at those points may lack the necessary precision due to the small area involved, making it challenging to obtain the exact geometry of the part. This limitation is inherent to the technology used.

The second factor contributing to the dimensional error in that area is the lack of stability during the cutting process. It can be observed that both the leading edge and trailing edge do not have a rounded shape, but rather a blade-like form with an angle. This discrepancy is unacceptable for this type of component and needs to be improved.

4 CONCLUSIONS

This experiment aims to analyze two tool orientations in order to improve surface finish, dimensional precision, cutting efficiency and prevent vibrations during machining. To evaluate these factors, the study initially focuses on calculating how tool orientation can reduce the force that has the greatest impact on workpiece bending. Subsequently, the results obtained from machining are examined by analyzing the roughness and dimensional tolerance of the workpiece, which are the two most significant factors defining the characteristics of a blade.

After performing a theoretical calculation of the force exerted on the piece, it is determined that the new tool orientation, with a lead angle of 30º and a tilt angle of 45º, reduces the force perpendicular to the cutting surface by 6.17%.

A good surface finish in components that direct air within aircraft engines, such as blades, is critical for achieving optimal aerodynamic efficiency, reducing drag, preventing dirt accumulation, and ensuring durability and wear resistance. This results in efficient and reliable engine performance, lower fuel consumption, and extended component life cicle.

Regarding surface roughness, Blade 2 displayed better roughness values in zone 1. In zone 2, both blades achieved a relatively consistent surface quality.

Dimensional tolerance is crucial for ensuring proper functionality, compatibility, and interchangeability of parts, as well as for supporting efficient manufacturing processes and quality control. By specifying appropriate tolerances, industries can achieve reliable and cost-effective production while meeting design requirements and customer expectations.

From the results obtained, it can be concluded that while Blade 1 shows a lower error in a specific area but a higher error in another, Blade 2 exhibits a more favourable distribution of areas within the tolerance range.

After obtaining these results, despite achieving some improvement, it is clear that further steps are necessary to enhance both surface finish and dimensional accuracy throughout the workpiece. The first step would be to reduce the cutting instability during machining. An option to achieve this is by implementing variable stock machining, which would provide stability to the system and avoid the higher roughness and dimensional errors observed in the study pieces.

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