Process Stability Strategies in Milling of Thin-walled Inconel 718

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ABSTRACT

Trends in Aerospace development have led to thin-walled, reduced-weight engine designs. The demands in manufacturing have forced production speeds and material removal rates (MRR) to increase. As component wall thickness gets thinner, the consequence oftentimes is an increase in chatter vibrations. This paper suggests that a correctly chosen tool-to-workpiece offset geometry may lead to a robust and chatter free process. The results show the differences in force response for three geometries while varying the height overhang of the workpiece. This is part of a concerted effort to develop a robust methodology for the prediction of chatter vibrations during milling operations of thin-walled Aerospace components. This paper gives guidelines on how to accomplish robust machining practices. It also answers the following questions: How critical is the choice of offset between tool and workpiece during milling setup? And what effects do the entry and exit of cut have on system vibrations?

Keywords: Thin-wall, Inconel 718, chatter, machining vibrations

RESUMEN

Las tendencias en el desarrollo aeroespacial han resultado en diseño de motores con paredes delgadas y peso reducido. Las exigencias en la fabricación han forzado la velocidad de producción y las tasas de eliminación de material (MRR) para aumentar. Como las paredes del componente se hacen más delgadas, a menudo la consecuencia es un aumento de las vibraciones charla. Este artículo sugiere que una selección correcta de herramientas a la geometría de la pieza de compensación pueda dar lugar a un proceso robusto y libre de charla. Los resultados muestran las diferencias en la respuesta de la fuerza de tres geometrías diferentes, mientras variando el exceso de altura de la pieza. Esto es parte de un esfuerzo concertado para desarrollar una metodología robusta para la predicción de vibraciones charla durante las operaciones de fresado de componentes aeroespaciales de paredes delgadas. Este documento da pautas sobre cómo llevar a cabo prácticas robustas de mecanizado. También responde a las siguientes preguntas: ¿Qué importancia tiene la opción de la compensación entre la herramienta y la pieza durante la molienda de configuración? ¿Y qué efectos tienen la entrada y salida de la corte sobre las vibraciones del sistema?

Palabras clave: Pared delgada, Inconel 718, charla, vibraciones de mecanizado

1. Introduction

1.1 Background

In an effort to resolve the issues outlined in the abstract, a project was initiated aiming at increasing the process robustness and the understanding of the onset of chatter vibrations during milling. The purpose for this research is to identify risks for chatter vibrations in a dynamic system already during component and machining process development.

When setting up a machining fixture and deciding on the milling geometry, some forethought should be given on what might cause chatter vibrations in the system. Conventional chatter theory [1] may be used for determining the likelihood of chatter during machining setup. The offset position chosen during machining setup will also affect the stability of the dynamic system.

Conventional chatter theory is explained in [1,2,3]. Self-excited chatter vibrations in milling develop due to dynamic interaction between the cutting tool and workpiece. This results in regeneration of waviness on the cutting surface and modulation of the chip thickness [4]. Under certain conditions, the amplitude of vibration grows and the cutting system becomes unstable. The stability of milling process has been investigated using experimental, numerical, and analytical methods [1,5,6,7,8,9,10,11]. An extensive review of publications on chatter in machining processes is found in [12]. As demonstrated in this paper, in certain applications, conventional chatter theories cannot accurately predict instabilities.

1.2 Approach

The focus of this study is to gain a basic understanding of vibration behavior of thin-walled components during cutter entry, in-process milling, and cutter exit. In this case, the effects on Inconel 718 are studied. Three common offset positions were chosen to exemplify the impact the milling geometry has on the resultant cutting force and on the onset of chatter vibrations. The zero offset position has been defined in this paper as head-on face milling as depicted in the center picture of Figure 1. The cases of down milling (left-hand picture) and up milling (right-hand picture) were also investigated. The offset position chosen during machining setup will significantly affect the dynamics of the machining system. This study further shows how the component height overhang affects the overall stability of the system at the different offset positions.

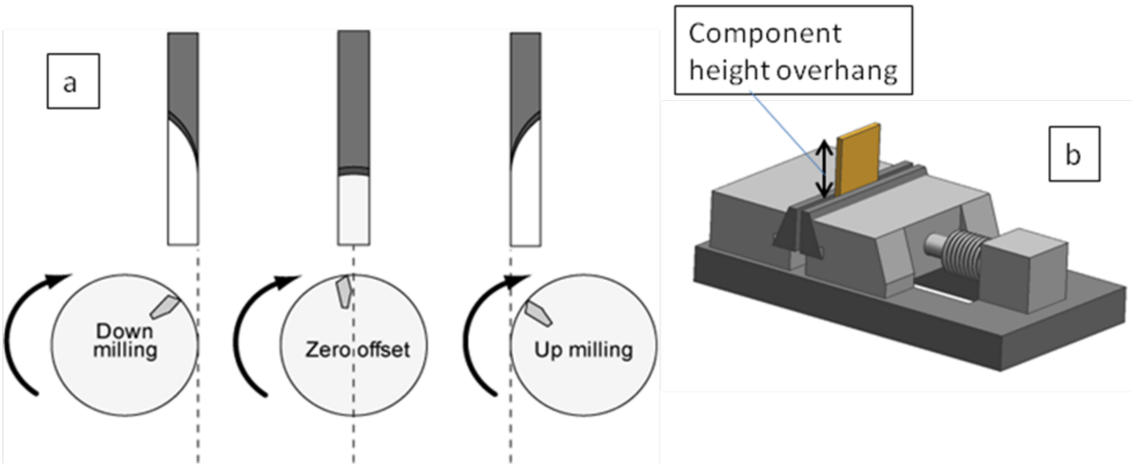

Figure 1.* *a: *Top view of the* **o***ffset positions used in this study. b: Clamping of workpiece.*

Conventional chatter theory [1] was utilized to determine the likelihood of chatter for each of the 24 cases. The results are listed in Table 1. Stability lobe diagrams were obtained of the workpiece/fixture/tool system while mounted in the milling machine. However, the shapes and locations of stability lobes do not remain constant.

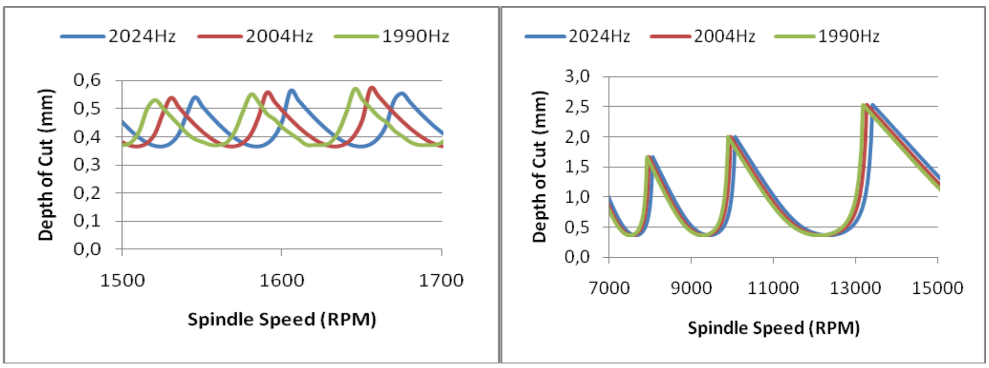

Figure 2. *Stability Lobe Diagram at the beginning (1990Hz), at the middle (2004Hz), and at the end (2024Hz) of the cut for low speed (left) and high speed (right) milling. Data recorded at low spindle speeds (left graph) and high spindle speed (right graph).*

They change during the subsequent milling process as material removal influences the natural frequency of the dynamic system. This is of particular importance during machining of thin-walled components since the material removed constitutes a substantial portion of the starting stock. The effect on the system depends on how fast the spindle is rotating (Figure 2). Nevertheless, stability lobe diagrams give some indication of the critical depth of cut when the system goes from stable to unstable.

In this work, the depth of cut was held constant at a_p=0.5mm while the critical depth of cut a_{lim} decreased as the component height overhang increased (Figure 3). When a_p becomes greater than a_{lim}, the system exhibits chatter vibrations. In other words, as the wall height overhang is increased, the critical limit for the axial depth of cut will be decreased. For a dynamic system with constant depth of cut, chatter vibrations will eventually be introduced.

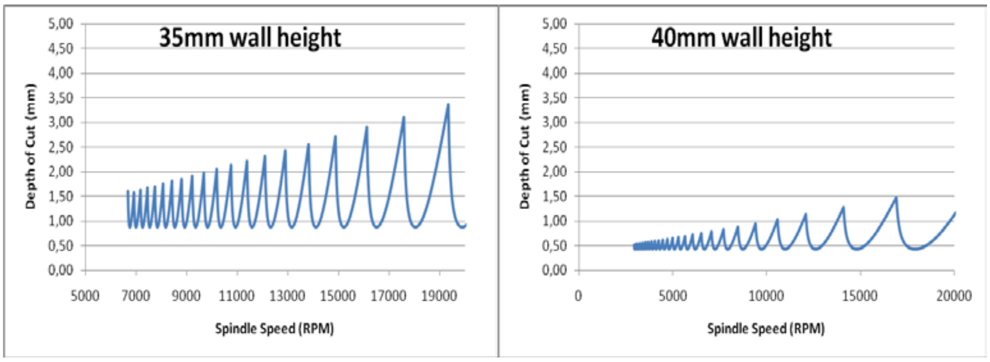

Figure 3. *The effect on a_{lim} as the wall height overhang is increased from 35mm to 40mm. The diagrams are experimentally derived from hammer impact tests. As a_{lim} goes below a_p=0.5mm, chatter vibrations are unavoidable.*

2. Experimental Setup

A three-axis milling machine was utilized for the experiment. The cutting speed was fixed at v_c=50m/min corresponding to a spindle speed of n=637RPM. The depth of cut was set at a_p=0.5mm. The cutting forces were measured with a piezo-dynamic force sensor and recorded into data files from which the resultant cutting forces were extracted. A single coated cemented carbide cutting insert was mounted on a 25mm diameter three-flute milling tool with an axial rake angle of 8.0 degrees and a radial rake angle of -7.6 degrees. The cutting insert had a nose radius of r_ε=0.8mm and the feed was set at f=0.08mm/tooth. Three offset geometries were defined for the experiment as depicted in Figure 1. The workpiece was Inconel 718 plate with a cross section of 5mm x 40mm.

3. Results and Discussion

The resultant forces from the measurements are shown in Figure 4. For a component wall height overhang of 5mm, the depth of cut of a_p=0.5mm does not cause any instability in the system. As the wall height overhang increases, a higher degree of instability is observed, especially for zero offset and up milling. The highest levels of vibrations are seen for the zero offset geometry. Table 1 shows the experimental results together with predictions from conventional chatter theory. It indicates a discrepancy between actual data and theory.

As seen in Figure 4, onset of chatter vibrations occurs at different component wall height overhang for the three offset geometries. For down milling, chatter vibrations seems to start at a wall height overhang of 25mm, for the zero offset case at a wall height overhang of 20mm, and for up milling at a wall height overhang of 30mm. These are critical points where the dynamic system changes from chatter-free vibrations to chatter vibrations. The resultant force amplitudes also show significant differences, especially for the zero offset and up milling geometries. Greater forces are observed for zero offset than for down milling or up milling. Up to a component wall height overhang of 30mm, down milling and up milling seem to require more or less the same amount of resultant force to achieve cutting. For wall height overhang of 35 mm and above, the down milling plots of the resultant force seem to exhibit minor chatter vibrations, whereas the up milling plots seem to exhibit more severe chatter vibrations.

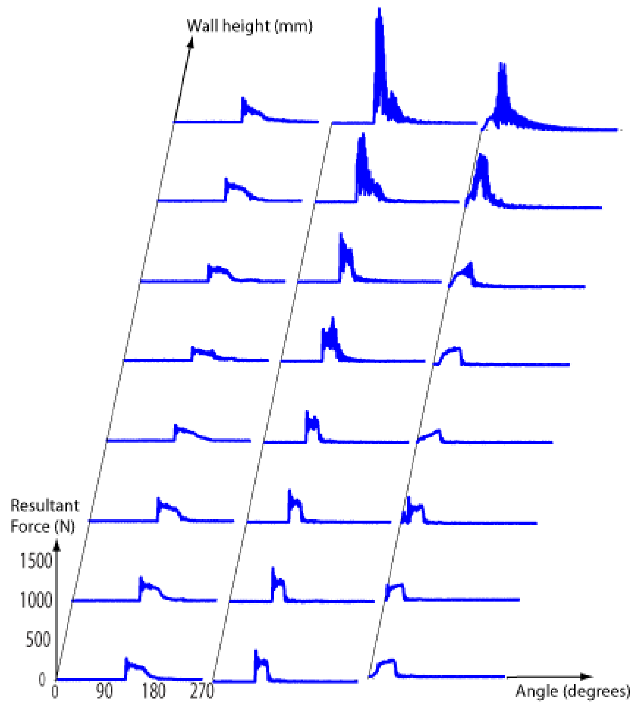

Figure 4. *Down milling (left), zero offset milling (middle), and up milling (right) at 5, 10, 15, 20, 25, 30, 35, and 40mm (from bottom to top) wall height overhang.*

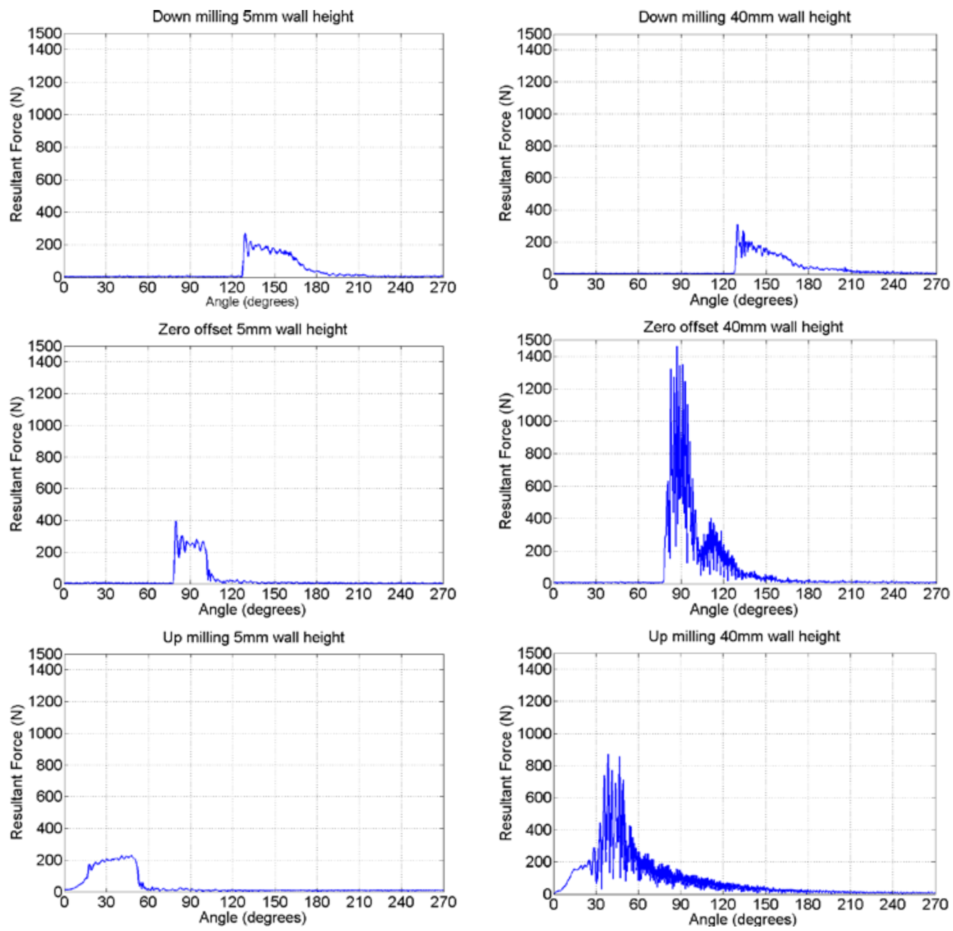

Figure 5. *Example graphs from the plots in Figure 4. Resultant force measurements for down milling (top), zero offset milling (middle), and up milling (bottom) at 5mm (left) and 40mm (right) wall height overhang.*

Table I. *The likelihood for chatter vibrations according to observed force data and conventional chatter vibration theory predictions. The graphs to the right depict the comparison.*

	Workpiece wall height overhang	Chatter Actual data	Chatter From theory
Down milling	5	no	No
	10	no	No
	15	no	No
	20	no	No
	25	no	No
	30	no	Yes
	35	some	Yes
	40	some	Yes
Zero offset	5	no	No
	10	no	No
	15	no	No
	20	no	No
	25	yes	No
	03	yes	No
	35	yes	No
	40	yes	No
Up milling	5	no	No
	10	no	No
	15	no	No
	20	no	No
	25	some	No
	30	yes	No
	35	yes	No
	40	yes	Yes

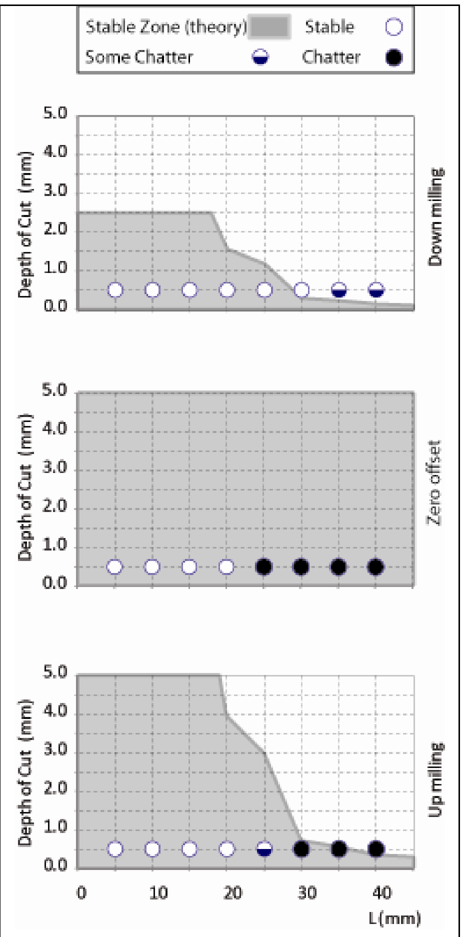

Figure 4 indicates that the offset position has greater influence on chatter vibrations than the amount of wall height overhang of the workpiece. This is especially true for small amounts of workpiece overhang. For large amounts of overhang, both the zero offset and the up milling geometries show significant chatter vibrations. The plot suggests that the down milling position is preferable in order to keep chatter vibrations to a minimum. Because of the dynamic circumstances during the cutting process, it is not obvious that chatter vibrations can be precisely predicted using existing methods. Such circumstances include flexible deformations of the workpiece before cutting takes place and burr formation during cutter exit. The results of this study may be used as an indicator for how to avoid chatter vibrations. The two extreme cases of workpiece protrusion, i.e. 5mm and 40mm, are depicted in Figure 5.

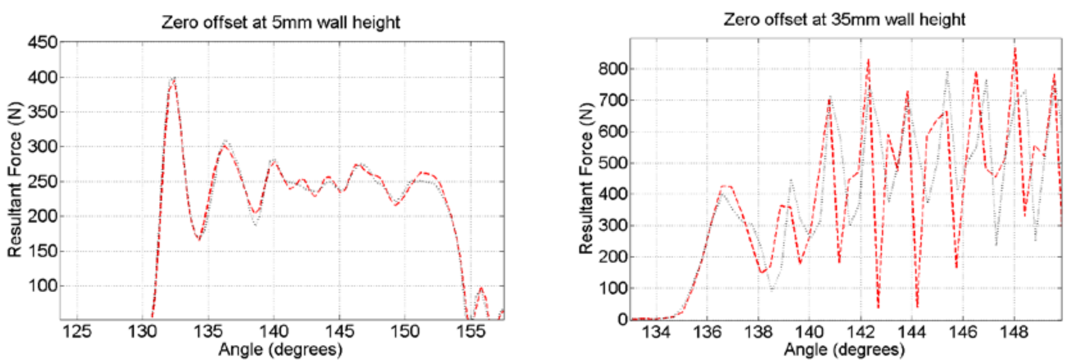

Figure 6. *Two subsequent force measurements: on left in phase depicting forced vibrations, and on right out of phase depicting chatter vibrations.*

For down milling, maximum force is observed during cutter entry as the cutter is traveling in the most flexible direction of the workpiece. The cutter exit, on the other hand, occurs as the cutter is traveling in the stiffest direction of the workpiece. For up milling, we have the opposite scenario. In order to determine whether the vibrations displayed were forced vibrations or chatter vibrations, the force measurements from a random cut was overlaid with the force measurements from the subsequent cut. If the two are in phase, forced vibrations are inherent in the process, whereas if they are out of phase, chatter vibrations prevail. Figure 6 shows examples of these two cases. The results for each of the 24 cases are listed in Table 1.

In addition to what has been discussed in this paper, other factors merit some consideration. For example, there is a non-linearity due to variation in the chip thickness as a function of offset that must be taken into account when analyzing the dynamics of the machining system. This is because of the nonlinear behavior of the cutting coefficient, k_c. Figure 7 shows a k_c curve that was extracted from turning Inconel 718 at a cutting speed of v_c=50m/min. Also, the chip thickness varies together with the component stiffness during the cut as depicted in Figure 1. Future work will further investigate the influence that suchlike factors have on the dynamics of the machining system.

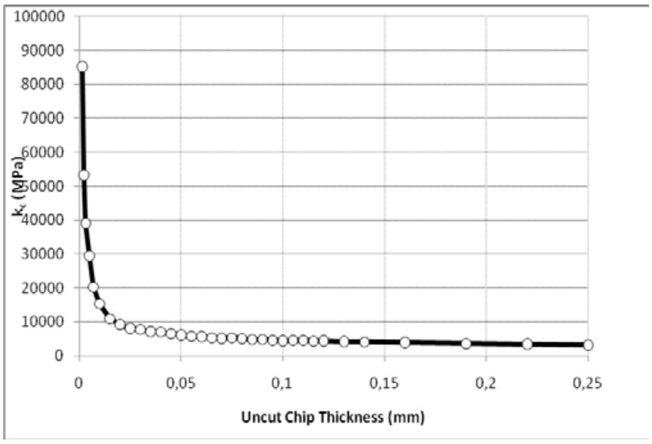

Figure 7. *The k_c curve extracted from turning Inconel 718 at a cutting speed of v_c=50m/min.*

4. Conclusions

The results from the experiment indicate that by changing the offset location of the tool in relation to the workpiece, the amount of chatter vibrations in the system may be significantly reduced. This is particularly noticeable when the offset location is changed from zero offset to down milling. Generally, for small component height overhang, the risk for chatter vibrations is limited. However, as the component height overhang increases, the choice of offset position becomes crucial.
Furthermore, it is more important to have a smooth cutter exit than a smooth cutter entry in order to avoid chatter vibrations. A comparison between experimental results and conventional chatter theory has been presented. Further development of chatter theory is required for an accurate prediction of system stability during machining of thin-walled components.

To summarize:

- Down milling is more robust and less prone to generate chatter vibrations than up milling and the zero offset geometry
- A smooth exit of cut is less prone to generate chatter vibrations than a smooth entry
- Entry and exit forces should be avoided in the most flexible direction of the work piece
- Conventional chatter theory is not sufficient for an accurate prediction of system stability.

5. Acknowledgment

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