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Proceeding Paper

Investigating the Impact of Declination Angle on the Side Milling Process of Additively Manufactured Ti6Al4V Using a 3D Milling Finite Element Model †

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Abstract: This study investigates the impact of declination angles (at 5, 10, and 15°) on the side milling process of additively manufactured Ti6Al4V. The finite element modelling (FEM) simulations are conducted using the Abaqus software and the Johnson–Cook (J-C) model. The main focus is on characterizing the relationship between the declination angles and the cutting forces. The findings demonstrate the significant effects of the declination angle, with noticeable variations observed in the milling forces. By employing the 3D milling finite element model of Abaqus, accurate analyses and predictions of the machining process dynamics are achieved. The insights gained from this research are valuable for optimizing machining parameters and enhancing efficiency, as well as for improving the surface quality of milled additively manufactured Ti6Al4V components.

Keywords: milling; additive manufacturing; FEM; Ti6Al4V

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1. Introduction

Additive manufacturing has gained prominence in various industries, including aerospace and biomedical sectors, due to its unique capabilities. However, machine processes are often required to achieve the desired final dimensions and surface quality [1,2]. This study investigates the effect of the declination angle on the side milling process of additively manufactured Ti6Al4V using a 3D milling finite element model (Abaqus software) with the J-C model [3]. Previous studies have indicated that elevated cutting forces have the potential to accelerate tool wear and compromise the surface quality of a workpiece [4,5]. Consequently, investigating the impact of the spindle's declination angles on the milling process has become crucial in addressing these concerns.

2. Material and Method

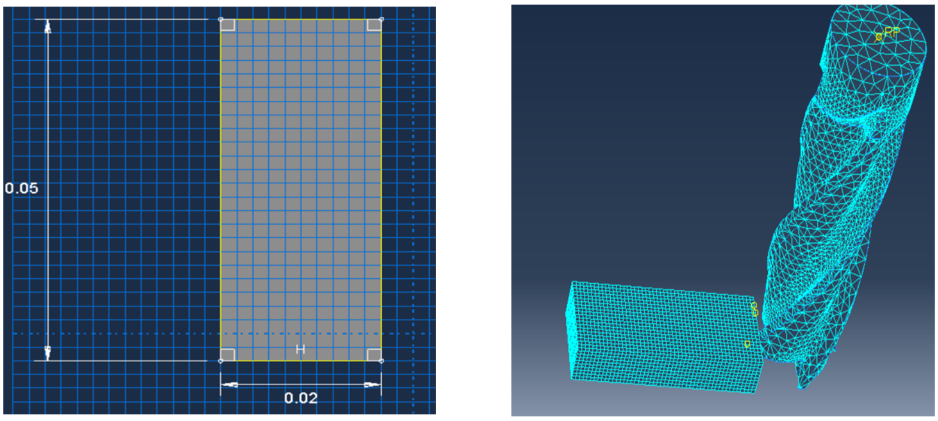
The specific parameters for the Ti6Al4V alloy used in laser additive manufacturing parts were obtained based on the methodology described in reference [6]. Detailed information regarding these parameters can be found in Tables 1 and 2. The sample dimensions, as illustrated in Figure 1, measure $0.05 \times 0.02 \times 0.01$ mm. During the milling process, no coolant or lubricant was applied under the cutting conditions, with a depth of cut of 0.01 mm and a cutting velocity (Vc) of 90 mm/s. The milling tool utilized consists of a pair of four teeth. Moreover, Figure 1 illustrates the 3D mesh model specifically designed for Ti6Al4V.

Table 1. Johnson–Cook constants value.

A (MPa)	B (MPa)	m	n	$T_{transition}$	T_{melt}
1000	780	1.1	0.47	20	1851

Table 2. Johnson–Cook damage model.

d1	d2	d3	d4	d5
−0.09	0.25	−0.5	0.015	3.8



(**a**) (**b**)

Figure 1. Three-dimensional finite element modelling for the milling process of Ti6Al4V: (**a**) used dimension and (**b**) 3D image of workpiece and tool.

3. Simulation Results and Discussion

Figure 2 represents the relationship between milling force and time in research conducted at a constant feed rate of 90 mm/s. The results indicate that, as the spindle declination angle θ increases from 0° to 15°, milling forces display an upward trend. This observation suggests that higher declination angles lead to elevated cutting forces during milling operations. The graphical representation aids engineers and machinists in comprehending and optimizing the milling process to enhance efficiency and prolong tool life. Furthermore, the investigation reveals that von Mises stress increases as the angle rises, jumping by 3.36% at 5°, 9.49% at 10°, and 41.18% at 15°. These findings underscore the significance of considering the impact of the angle on stress levels, as higher angles result in heightened stress levels.

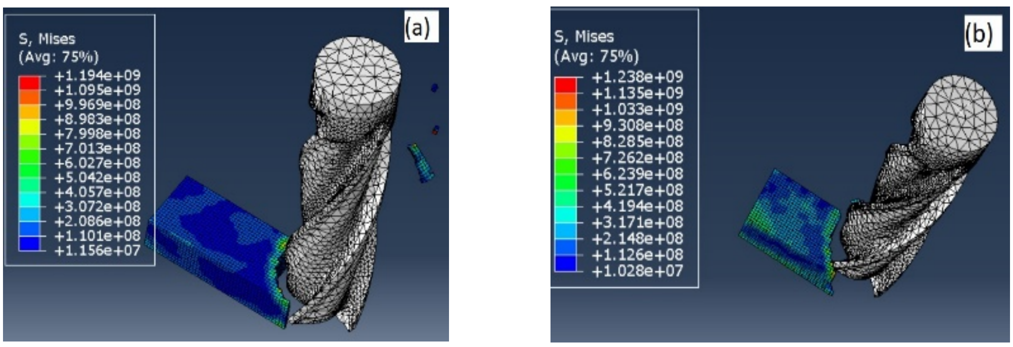


Figure 2. *Cont.*

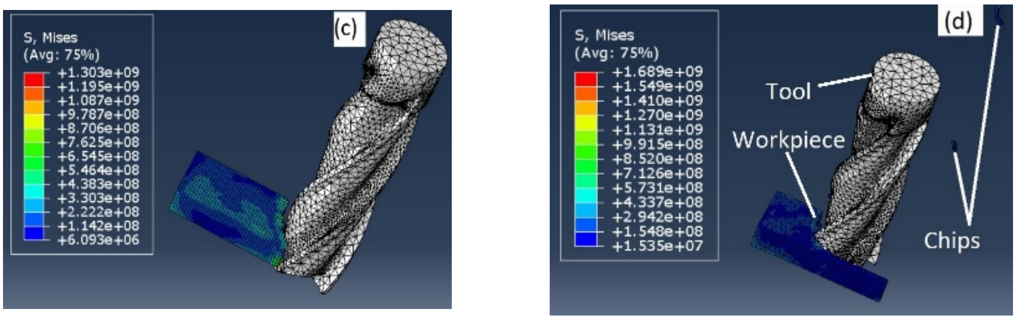


Figure 2. The von Mises stress at various declination angles, including (**a**) 0°, (**b**) 5 °, (**c**) 10 °, and (**d**) 15°.

Impact of Varied Declination Angle θ on Milling Force

Figure 3 illustrates the milling force field obtained as a result of the analysis. Upon examining the figure, it is apparent that the maximum von Mises stress remains relatively consistent across various spindle declination angles θ during the side milling operation. However, a higher milling force was observed, specifically at a spindle declination angle of 15°. Figure 4 provides a visual representation of the stress distribution along a defined path line. The analysis reveals that the maximum stress of 528 MPa occurs at a declination angle of 15° along the path. Comparatively, the stress is lowest at 257 MPa at 0°, indicating higher stress levels as the angle increases. Furthermore, research conducted by Weixin et al. and Xiaohua et al. highlighted that the milling force exhibits greater fluctuations, leading to increased tool wear and diminished surface quality [7,8].

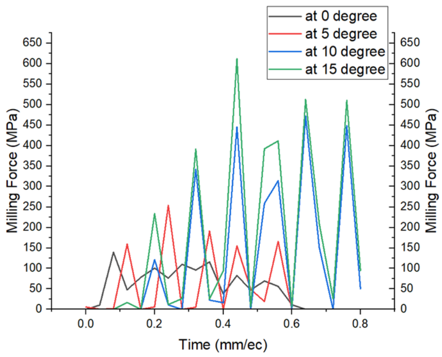


Figure 3. Presents the relationship between milling force and time.

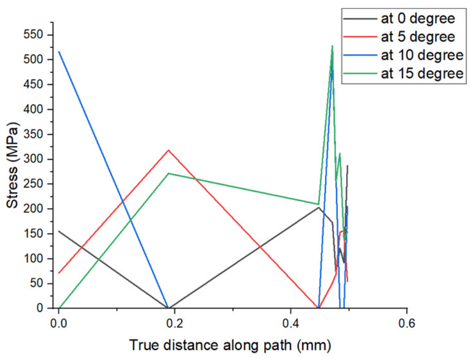


Figure 4. Displays the stress distribution along a defined path line.

4. Conclusions

This study introduces a novel three-dimensional finite element model (FEM) for the continuous milling of Ti6Al4V. The accuracy of the milling force predictions was validated by comparing them with those reported in a prior publication [7]. The application of the established FEM model enabled the investigation of the effects of spindle declination angles (θ) on the side milling process. It was found that, under a consistent feed rate of 90 mm/s, the milling forces exhibited an upward trend as the spindle declination angle θ increased from 0° to 15°. Notably, the axial milling force experienced the most significant increase, with a peak value rise of 14%, while the valley value of the milling force exhibited a minor decline. Overall, the milling forces display greater fluctuations, leading to increased tool wear and reduced surface quality.

Author Contributions: In the collaborative effort to produce this journal article, all authors played a pivotal role in conceiving, drafting, and refining the manuscript. Their expertise in the subject matter and dedication to research laid the foundation for the work. S.P. writes the article and X.V. and W.S. significantly contributed to the project by actively participating in the review process. Their thoughtful feedback and evaluations greatly enhanced the overall quality of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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