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RESEARCH ARTICLE

Investigation on the Mechanism of Laser-Assisted Machining of Surface-Nitrided TC4 Titanium Alloy

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Abstract

The present study systematically investigates the effects of surface nitriding treatment on the laser-assisted machining behavior of TC4 titanium alloy. Numerical simulations were conducted using the ABAQUS finite element platform to elucidate the influence of nitriding on cutting force, cutting temperature, and residual stress evolution. A three-factor, three-level orthogonal experimental design was established, considering nitriding concentration (0.2%–0.8%), laser power (500-1500 W), and laser scanning speed (50-90 m/min), to examine the coupled effects of these parameters. The results reveal that an increase in laser scanning speed leads to a reduction in both cutting force and cutting temperature, whereas higher laser power results in their escalation. Furthermore, elevated nitriding concentration intensifies the sensitivity of cutting force and temperature to laser parameters. Residual compressive stress increases with higher nitriding concentration and laser power, while the influence of laser scanning speed remains comparatively minor. This work provides a theoretical foundation for the optimization of laser-assisted machining parameters for TC4 titanium alloy, contributing to enhanced surface integrity and improved machinability, and offering guidance for its broader application in advanced manufacturing sectors.

Keywords: TC4 titanium alloy, surface nitriding, laser-assisted machining, residual compressive stress, finite element simulation.

1 Introduction

Titanium alloys, particularly Ti–6Al–4V (commonly known as TC4), have been extensively employed in aerospace engineering, biomedical applications, and marine engineering owing to their high specific strength, excellent corrosion resistance, and superior biocompatibility. These outstanding properties make TC4 alloy one of the most significant materials for manufacturing key structural and functional components such as aircraft engine blades, fasteners, surgical implants, and subsea equipment. However, despite its favorable bulk mechanical characteristics, TC4 alloy exhibits relatively low surface hardness, poor tribological behavior, and pronounced chemical reactivity with cutting tools [1, 2], which severely

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restrict its machinability under high temperatures or high-speed cutting conditions. The poor machinability of TC4 often leads to excessive tool wear, high cutting forces, and degraded surface integrity [3–6], thus limiting its broader utilization in advanced manufacturing fields.

To overcome these limitations, researchers have devoted considerable effort to surface modification techniques designed to enhance the wear resistance and surface mechanical properties of titanium alloys. Among the available methods—such as plasma nitriding, laser surface alloying, ion implantation, and coating deposition—surface nitriding has proven to be one of the most effective approaches [7–10]. This process introduces nitrogen atoms into the surface of the titanium substrate, forming a hard and chemically stable titanium nitride (TiN) or titanium oxynitride (TiON) layer [11] that significantly improves the surface hardness, fatigue strength, and oxidation resistance without compromising the inherent toughness of the substrate [12]. Ongtrakulkij et al. [12] demonstrated that plasma nitriding of TC4 at 750–800 °C generates residual compressive stress and markedly increases surface hardness, with both parameters scaling with treatment temperature and duration, while Zhang et al. [11] confirmed that the resulting nitrided layer is primarily composed of TiN and Ti_2N phases with distinct microstructural and corrosion characteristics. Li et al. [13] investigated the combined effect of laser shock peening (LSP) and nitrogen ion implantation on TC6 titanium alloy, revealing that the treated material achieved a surface nanohardness of 7.70 GPa and residual compressive stress of 735.99 MPa at 300 °C, while the wear rate reached its lowest value among all tested conditions. Liu and Pang [14] fabricated nickel-based composite coatings via laser nitriding, where the in-situ synthesized h-BN acted as a high-temperature lubricating phase, effectively improving the tribological properties of the material. Xu et al. [15] developed a fully coupled thermomechanical finite element model for laser-assisted machining of TC4 titanium alloy, revealing that the competition between thermal softening and adiabatic shear instability governs the morphological evolution of serrated chips, and that the laser preheating temperature critically determines surface integrity outcomes. Similarly, Zhang et al. [16] analyzed the effects of three types of nitride coatings on the high-cycle fatigue behavior of TC4 alloy and found that nitriding treatment could enhance wear resistance and erosion resistance, although multilayer coatings slightly reduced the fatigue strength of the substrate. Gu et al. [17] employed a full-domain power-modulated laser system to synthesize ultra-thick titanium nitride coatings on TC4 surfaces, which enhanced nitrogen transfer efficiency and coating uniformity while mitigating stress concentration within the nitride layer. Yang et al. [18] used a hybrid laser–heated nitrogen process to improve the surface hardness of TC4 titanium alloy, attributing the improvement to the synergistic effects of laser annealing and TiN phase formation. Yang et al. [19] prepared Ti–Cu–N coatings with varying Cu contents through combined laser cladding and laser nitriding, reporting a nearly twofold increase in microhardness and significantly improved wear resistance compared with the untreated substrate. In related work, Peng et al. [20] investigated the effect of high-speed ultrasonic vibration cutting on TC4 titanium alloy, demonstrating that this technique significantly refines the surface microstructure, enhances subsurface compressive residual stress, and improves wear resistance compared with conventional cutting, highlighting that machining process design is equally critical to surface modification in achieving superior surface performance. The above studies collectively confirm that nitriding treatments can effectively enhance the surface performance of titanium alloys through improved hardness, lubrication, and oxidation resistance. However, most previous research has primarily focused on the preparation and characterization of nitrided coatings under different process conditions, while limited attention has been paid to the machining behavior of nitrided titanium alloys, particularly under laser-assisted cutting conditions. In practical applications, after nitriding, titanium alloys are often subjected to high-precision or micro-scale machining to achieve desired dimensional accuracy and surface integrity. The combination of nitriding treatment and laser-assisted machining (LAM) may provide a synergistic effect: nitriding enhances surface hardness and stability, while laser preheating reduces material strength and cutting resistance, thereby improving machinability and extending tool life. Despite its potential, the fundamental mechanism governing the interaction between the nitrided surface layer and the laser–cutting thermal field remains insufficiently understood. In recent years, the laser-assisted machining technique has attracted growing attention as an effective method for processing difficult-to-cut materials such as titanium alloys, nickel-based superalloys, and ceramics [21]. By introducing a localized laser heat source prior to cutting, the material is thermally softened within a controlled region, which reduces the cutting force, lowers tool wear, and enhances the surface finish [3, 4]. However, the laser parameters—such as laser power, scanning speed, and spot size—must be carefully optimized, as inappropriate thermal conditions can lead to excessive oxidation, microstructural damage, or residual stress accumulation [22]. When applied to nitrided TC4 titanium alloy, the coupled thermal–mechanical–chemical interactions become even more complex due to the heterogeneous material properties between the hard nitrided layer and the softer substrate. Understanding these coupled effects is therefore critical for establishing a reliable theoretical basis for process optimization.

In this context, the present study aims to investigate the mechanism of laser-assisted machining of nitrided TC4 titanium alloy through finite element simulation using the ABAQUS software platform. A three-factor, three-level orthogonal experimental design is established, incorporating nitriding concentration (0.2%–0.8%), laser power (500–1500 W), and laser scanning speed (50–90 m/min) as the main parameters. The simulation focuses on analyzing the effects of these parameters on cutting force, cutting temperature, and residual stress evolution, and on elucidating the underlying coupling mechanisms between them. The research further explores the role of the nitrided surface layer in modifying the thermal and mechanical response of TC4 alloy during laser-assisted cutting. Through comprehensive numerical analysis, this work seeks to reveal the interaction mechanisms between surface nitriding and laser-assisted machining, providing insights into how nitriding parameters and laser conditions jointly influence machinability and residual stress distribution. The findings will contribute to the establishment of a theoretical framework for optimizing LAM processes of titanium alloys, guiding experimental validation and industrial application. Ultimately, this study aims to enhance the processing efficiency, surface integrity, and functional reliability of TC4 titanium alloy components, thereby promoting their broader implementation in high-end manufacturing sectors such as aerospace propulsion, biomedical devices, and marine engineering.

2 Model and Method

2.1 Material Model

In this study, the work material is TC4 titanium alloy. Finite element modeling is carried out using the ABAQUS simulation software. The substrate has dimensions of $1 \times 0.5 \times 0.5$ mm, and the thickness of the chip layer is 0.2 mm. A refined mesh is applied to the chip layer to improve the accuracy of the simulation in the region of severe deformation. The geometrical model of the cutting simulation is illustrated in Figure 1. In the simulation, the cutting tool is assumed to be a rigid body, with its translational freedom constrained to the horizontal direction only. The tool's motion corresponds to the cutting velocity, which is set to $V_x = 60$ m/min [23]. The frictional behavior between the cutting tool and the chip layer follows Coulomb's friction law, with the coefficient of friction set to 0.2, consistent with values reported for titanium alloy machining simulations [24].

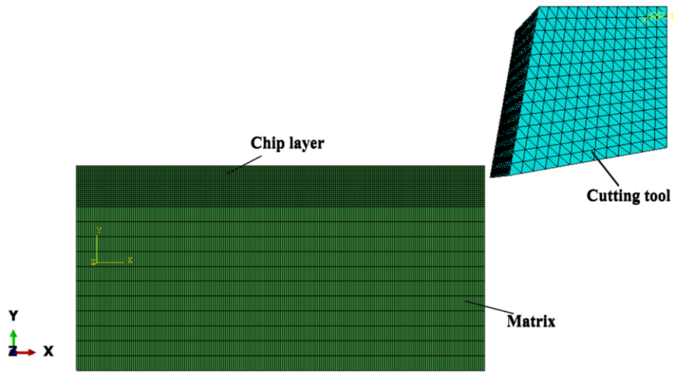

Figure 1. Geometrical model of chip formation in the cutting simulation.

The constitutive behavior of TC4 titanium alloy is described using the Johnson–Cook (J–C) constitutive model [25, 26]. The J–C model accounts for the combined effects of strain hardening, strain rate, and thermal softening on the material's flow stress. Ribeiro-Carvalho et al. [25] confirmed through comparative finite element analysis that the J–C model provides satisfactory accuracy in predicting machining forces for Ti6Al4V, validating its suitability for the present simulation framework. These effects are expressed in a multiplicative form, representing the quantitative relationship among the thermo-mechanical deformation parameters. The expression of the model is given as Equation (1):

$$\sigma = (A + B\varepsilon^n)\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right] \quad (1)$$

WC (tungsten carbide) is selected as the tool material, while the workpiece material is Ti–6Al–4V (TC4) titanium alloy. The parameters of the Johnson–Cook (J–C) constitutive model for TC4 titanium alloy [26] are listed in Table 1.

Table 1. Parameters of the Johnson–Cook constitutive model for TC4 titanium alloy.

A/MPa	B/MPa	n	C	m	D_1	D_2	D_3	D_4	D_5
1098	1092	0.93	0.014	1.1	-0.09	0.25	-0.5	0.014	3.87

The laser heat source [27, 28] is defined in the form of a heat flux by means of the VDFLUX user subroutine written in Fortran. The surface heat flux follows a Gaussian distribution, as expressed in Equation (2):

$$I = \frac{3\eta Q}{\pi R^2} \exp\left[-3\left(\frac{r^2}{R^2}\right)\right]. \tag{2}$$

where η is the absorption coefficient of the workpiece for the laser, Q denotes the laser power, R represents the radius of the laser spot, and r is the distance from the center of the laser beam.

The relative distance between the laser beam and the cutting zone must be sufficiently short to minimize heat loss due to cooling of the irradiated region. However, if this distance is too small, the reflected laser energy may impinge directly on the cutting tool, resulting in thermal damage and reduced tool life. To balance these effects, the laser–tool offset is set to 0.3 mm in the simulation.

2.2 Experimental Design

In this study, a systematic investigation is conducted on the machining performance of TC4 titanium alloy by regulating three primary factors: nitriding concentration, laser power, and laser scanning speed. A three-factor, three-level orthogonal experimental design is employed to explore the coupling effects among these parameters. For nitriding concentration, three representative levels are selected: 0.2% corresponding to a low-level or mild nitriding treatment, 0.5% representing a typical medium nitriding condition, and 0.8% indicating a deep nitriding state. The laser power is set at 500 W (low power), 1000 W (medium power), and 1500 W (high power). Meanwhile, the laser scanning speed is defined at 50 m/min (low speed), 70 m/min (medium speed), and 90 m/min (high speed). Accordingly, an orthogonal test matrix comprising 27 experimental combinations is established based on the three factors and three levels, as summarized in Table 2.

Table 2. Experimental variables and orthogonal design parameters.

Nitriding concentration (%)	Laser power (W)	Laser speed (m/min)
0.2	500	50
0.5	1000	70
0.8	1500	90

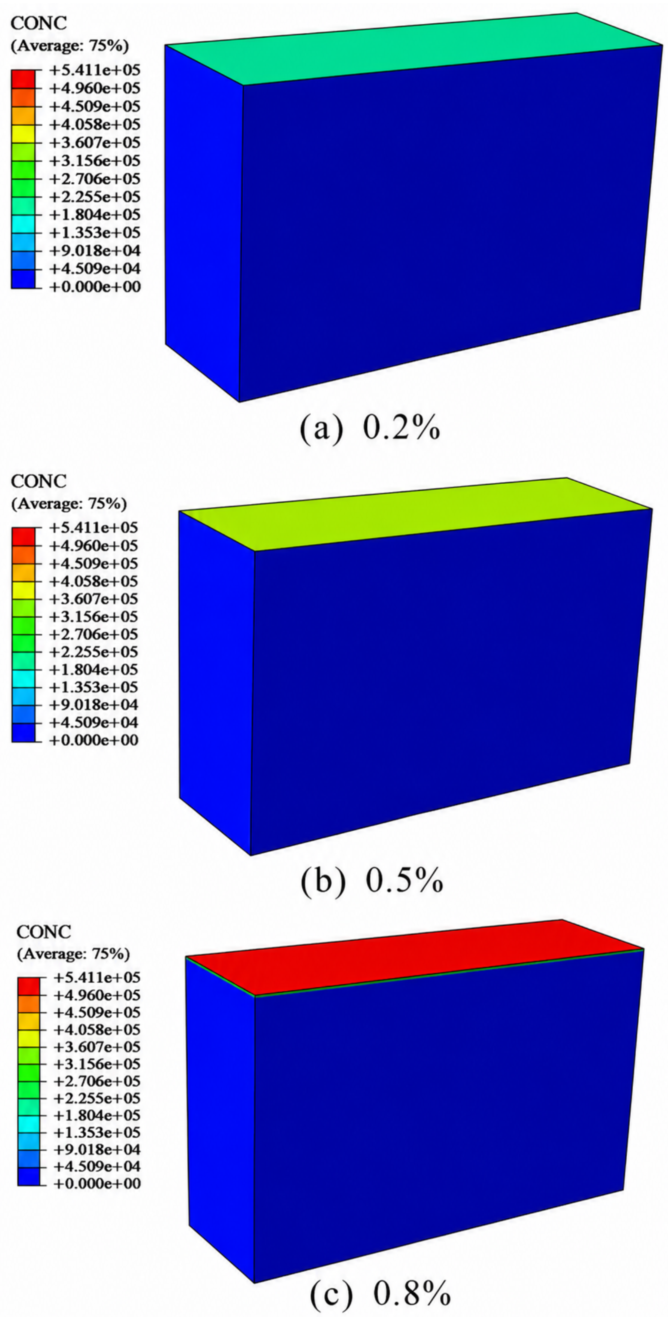

Figure 2. Simulation contour of nitriding diffusion in TC4 titanium alloy.

In this study, the diffusion module of ABAQUS is first employed to simulate the nitriding process of the

TC4 titanium alloy. The resulting nitriding simulation contour map is illustrated in Figure 2. Subsequently, the laser-assisted cutting process is performed on the nitrided model through a user-defined subroutine, enabling the incorporation of the laser heat source and its dynamic interaction with the workpiece material. In the simulation, a dual-track laser irradiation strategy is adopted to ensure uniform thermal distribution and enhanced cutting efficiency. The schematic representation of the dual-track laser model is shown in Figure 3.

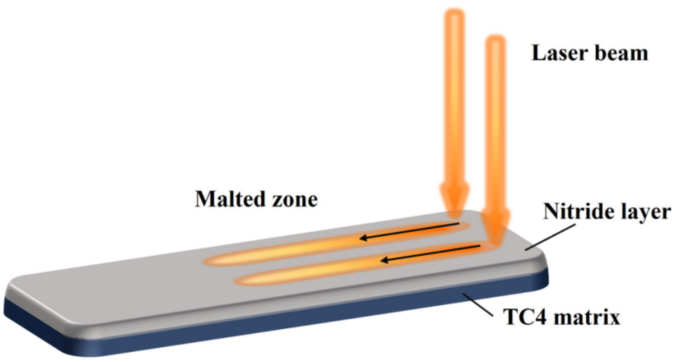

Figure 3. Schematic diagram of the dual-track laser irradiation model.

2.3 Model Validation

To verify the accuracy of the ABAQUS cutting force simulation model, the simulation results are compared with the experimental data reported in the literature. Table 3 presents a comparison between the simulated and experimental values. The deviations of all test schemes are found to be within 5%, indicating a high level of agreement between the finite element simulation results and the experimental data reported in the literature [23]. This close correspondence demonstrates the reliability and predictive capability of the established simulation model. Consequently, the model provides a robust foundation for subsequent optimization of cutting parameters and analysis of mechanical characteristics based on the same computational framework.

Table 3. Comparison between simulation and experimental data for model validation.

Scheme design (m/min)	Cutting force simulation data (N)	Cutting force literature data (N)	Error%
60	150.23	147.64	1.75
94	143.87	140.82	2.16
150	140.65	139.25	1.01

3 Results and Discussion

3.1 Analysis of Cutting Force

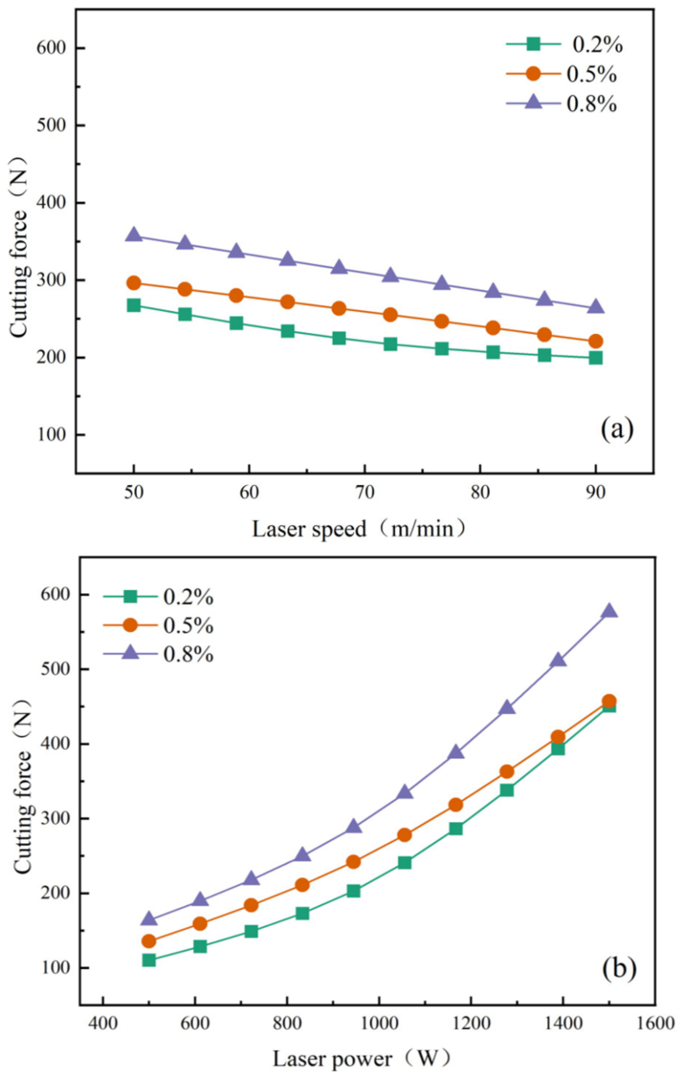

Figure 4. Variation of cutting force for nitrided TC4 titanium alloy under different laser parameters: (a) laser scanning speed; (b) laser power.

Figure 4 illustrates the variation of cutting force for TC4 titanium alloy subjected to different laser parameters during laser-assisted machining.

Figure 4(a) presents the cutting force behavior when the laser power is fixed at 1000 W, while the laser scanning speed increases from 50 m/min to 90 m/min. Under these conditions, a gradual reduction in cutting force is observed across all nitriding concentrations. This trend can be attributed to the shortened interaction time between the laser beam and the workpiece surface at higher scanning speeds. As the laser traversal speed increases, the effective heat input per unit area decreases, resulting in lower energy absorption by the material and a reduction in thermal softening intensity. Consequently, the material's flow stress remains relatively high, and the softened layer becomes thinner. Meanwhile, the material removal rate during cutting is improved due to the reduced dwell time of the laser, collectively resulting in a noticeable decrease in the resultant cutting force.

It is noteworthy that the magnitude of this reduction varies with nitriding concentration. Alloys with higher nitriding levels (e.g., 0.8%) exhibit a more pronounced decrease in cutting force compared to those with lower concentrations. This can be explained by the increased thermal conductivity and surface hardness introduced by nitriding, which alter the laser absorption and heat distribution characteristics of the surface layer. A higher nitriding concentration enhances the laser–material coupling sensitivity, resulting in a more distinct correlation between laser speed and cutting force. In other words, the interaction between the laser-induced thermal softening zone and the nitrided diffusion layer intensifies as nitriding depth increases, thereby amplifying the rate-dependent variation of cutting force.

Figure 4(b) shows the cutting force variation at a constant laser scanning speed of 70 m/min, while the laser power is increased from 500 W to 1500 W. The results demonstrate an overall upward trend in cutting force with increasing laser power, which can be ascribed to the combined effects of enhanced heat input, surface melting, and evaporative mass loss. As the laser power rises, the material absorbs a greater amount of thermal energy, leading to a substantial increase in local temperature and an intensified thermal softening effect. Although such softening tends to facilitate material removal, excessive heat input simultaneously promotes surface melting and partial vaporization. These thermal phenomena modify the frictional and adhesive interactions at the tool–chip interface, generating unstable chip formation and increased cutting resistance. Consequently, the net cutting force exhibits a noticeable rise despite the apparent thermal softening of the matrix.

Furthermore, the amplitude of force increase is more significant at higher nitriding concentrations, indicating that the nitrided surface layer strongly affects the material's response to laser energy. With greater nitrogen content, the TiN and Ti_2N phases formed on the surface exhibit higher reflectivity and thermal stability. These phases partially inhibit heat penetration into the subsurface region, thereby reducing the uniformity of the softened zone. As a result, the effective cutting area becomes more concentrated and the stress gradient more pronounced, leading to an overall increase in cutting force. This behavior suggests that nitriding concentration not only influences the absorption and distribution of laser energy but also affects the mechanical load transfer during chip formation.

From a mechanistic perspective, the observed trends highlight a complex coupling relationship among laser parameters, nitriding treatment, and material deformation behavior. At low laser speeds or moderate power levels, the dominant factor governing the cutting force is thermal softening, which reduces resistance to deformation. However, at excessive power or high nitriding concentrations, thermally induced material instability and localized melting become more significant, counteracting the beneficial effect of softening and resulting in an overall increase in cutting force. These findings are consistent with previous studies reporting that the balance between laser heating and material softening critically determines the cutting performance of titanium alloys under laser-assisted conditions.

In summary, the cutting force exhibits a decreasing trend with increasing laser scanning speed and an increasing trend with rising laser power. Both trends are modulated by the nitriding concentration, which governs the material's absorptivity, heat transfer characteristics, and deformation resistance. These results not only validate the predictive capability of the numerical model but also provide valuable insights for optimizing laser-assisted cutting parameters of nitrided TC4 titanium alloys, aiming to achieve lower cutting resistance, improved tool life, and enhanced surface integrity.

Figure 5 presents the coupled effects of laser power and scanning speed on the cutting force during the laser-assisted machining of nitrided TC4 titanium alloy. The results reveal a complex, nonlinear interaction between the two parameters. In the low laser power and low scanning speed region, the cutting force remains relatively small, suggesting that moderate heating and controlled energy input contribute to a stable machining state. However, as laser power increases and scanning speed varies, the cutting force exhibits distinct and non-monotonic trends, reflecting the sensitive interplay between the thermal and mechanical behaviors of the workpiece.

At low laser power levels, the heat flux applied to the material surface is limited, leading to a moderate

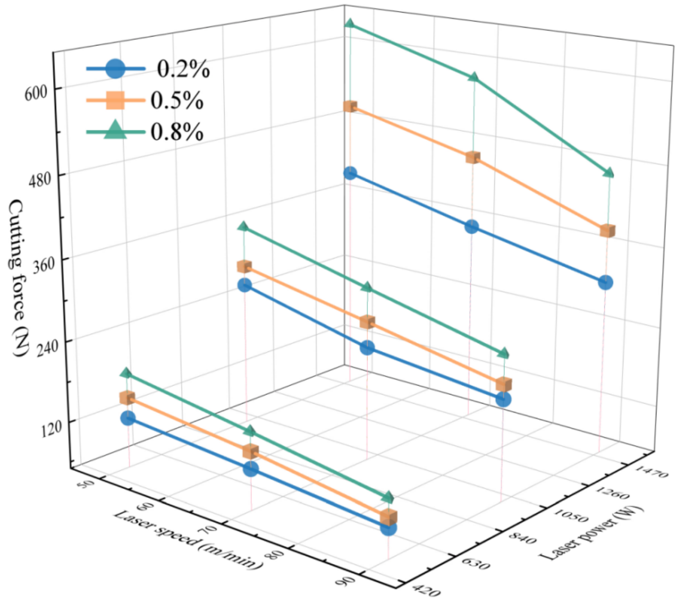

Figure 5. Coupled variation of cutting force in nitrided TC4 titanium alloy under different combinations of laser power and scanning speed.

degree of thermal softening in the cutting zone. In this regime, the cutting force is primarily governed by the intrinsic mechanical strength of the nitrided layer, and variations in scanning speed exert a moderate influence. As the scanning speed increases, the interaction time between the laser beam and the workpiece surface decreases, thereby reducing the total absorbed energy per unit area. Consequently, the temperature rise in the shear deformation zone is insufficient to induce pronounced thermal softening, and the material retains higher flow stress. Under these conditions, the cutting force remains relatively low and stable, owing to a balance between heat input and material removal rate.

Conversely, at higher laser power levels, the overall energy input intensifies, substantially increasing the local temperature of the cutting region. This promotes enhanced thermal softening and even partial melting of the surface material. When coupled with variations in scanning speed, this condition gives rise to more pronounced fluctuations in the cutting force. Specifically, at higher power, even a small change in scanning speed can lead to significant alterations in the spatial and temporal distribution of the heat field, resulting in stronger gradients of temperature and residual stress. These gradients affect chip formation stability and the frictional behavior at the tool–chip interface, thereby amplifying the overall variation in cutting force.

When comparing the effects of scanning speed and power independently, the results indicate that for a fixed scanning speed, increasing laser power leads to a greater amplitude of force variation, while for a fixed power level, reducing scanning speed causes a more significant change in cutting force. This asymmetry highlights the dominant role of heat accumulation in controlling material softening and stress evolution. Lower scanning speeds allow for longer laser–material interaction times, which enhance heat conduction into the subsurface layer and extend the thermal softening zone. As a result, the deformation zone expands and the effective material strength decreases, making the cutting process more sensitive to changes in power. In contrast, at higher speeds, heat accumulation is weaker, and the material responds more elastically, leading to a lower degree of variation in cutting force.

Furthermore, the influence of nitriding concentration introduces an additional layer of complexity into this coupled system. All three nitriding levels exhibit distinct responses to the combination of laser power and speed. At higher nitriding concentrations, the surface layer exhibits increased hardness and altered optical properties, particularly higher reflectivity and lower absorptivity for the incident laser beam. These characteristics reduce the amount of absorbed thermal energy and shift the peak temperature location closer to the surface. Consequently, the softened region becomes thinner, and the cutting force shows a sharper response to changes in laser parameters. In contrast, at lower nitriding concentrations, where the diffusion layer is shallower and the surface absorption rate is higher, the material displays a more gradual variation in cutting force, indicating a smoother transition between thermal and mechanical regimes.

The observed coupling behavior between laser power and scanning speed suggests that neither parameter can be optimized in isolation. Instead, their combined influence determines the overall thermal field, deformation behavior, and energy efficiency of the machining process. A suitable balance between heat input and heat dissipation is essential to achieve reduced cutting force while avoiding excessive melting or oxidation of the surface. This interplay also underscores the critical role of the nitrided surface layer, which modulates both the energy absorption and heat transfer pathways during laser-assisted cutting.

In summary, Figure 5 demonstrates that the cutting force of nitrided TC4 titanium alloy is jointly governed by the interaction between laser power and scanning speed, with nitriding concentration acting as a significant moderating factor. Low-power and moderate-speed conditions provide a more stable thermal–mechanical environment with minimized cutting resistance, whereas excessive power or insufficient speed results in unstable chip formation and elevated cutting forces. These findings highlight the importance of considering multi-parameter coupling effects in optimizing laser-assisted machining of surface-treated titanium alloys, paving the way for improved process control, enhanced tool life, and superior surface integrity in advanced manufacturing applications.

3.2 Cutting Temperature Analysis

Figure 6 illustrates the temperature distribution and variation of the cutting zone during laser-assisted machining of nitrided TC4 titanium alloy under different laser scanning speeds, with the laser power fixed at 1000 W. As shown in the contour maps and data plots, when the laser speed increases from 50 m/min to 90 m/min, the cutting temperature exhibits a distinct decreasing trend for all nitriding concentrations (0.2%, 0.5%, and 0.8%).

The simulation contour maps in Figures 6(a)–(c) clearly demonstrate that as the scanning speed increases, the interaction time between the laser beam and the workpiece surface decreases significantly. This reduction in irradiation duration limits the total energy absorption by the material, thereby reducing the extent of thermal accumulation in the cutting zone. Consequently, less heat is generated during the cutting process, leading to a lower overall cutting temperature.

The observed reduction in cutting temperature can be primarily attributed to the dynamic balance between heat input and heat dissipation during high-speed laser–material interaction. At lower laser speeds, the energy density absorbed per unit area is relatively high because the laser beam remains on the surface longer, allowing greater thermal conduction into the material. This localized heating raises the surface temperature and promotes thermal softening, which, although beneficial to reducing cutting forces, can also cause excessive thermal gradients and potential microstructural degradation. In contrast, at higher laser scanning speeds, the laser heat source moves rapidly, leading to reduced localized heating and more uniform temperature distribution across the cutting zone. The diminished heat accumulation not only lowers the maximum cutting temperature but also mitigates the risk of surface oxidation, material melting, and subsurface microcrack formation.

Moreover, the extent of temperature reduction varies with nitriding concentration, indicating that the nitrided surface layer significantly influences the thermal response of TC4 titanium alloy under laser-assisted cutting conditions. As shown in Figure 6(d), at higher nitriding concentrations (e.g., 0.8%), the cutting temperature decreases more sharply with increasing laser speed compared to alloys with lower nitriding levels. This behavior is associated with the modification of thermal and optical properties induced by nitriding. The formation of TiN and Ti_2N phases in the surface layer enhances the alloy's reflectivity and thermal conductivity, which alter the laser energy absorption efficiency. A higher nitriding concentration reduces the effective absorptivity of the laser beam, meaning that less energy is converted into heat within the surface layer, leading to a more pronounced temperature drop as the scanning speed increases.

Another contributing factor is the enhanced heat conduction capability of the nitrided layer. The TiN-rich surface exhibits higher thermal diffusivity, which facilitates faster heat dissipation away from the laser-irradiated region. Consequently, even when the same amount of laser energy is delivered, the steady-state temperature rise in highly nitrided samples remains lower. This effect becomes increasingly evident at elevated laser speeds, where the transient heat input is already limited. The combined impact of reduced laser absorption and accelerated heat transfer explains the steeper temperature reduction observed in highly nitrided TC4 alloys.

From a process optimization standpoint, these results emphasize the critical importance of controlling the laser scanning speed to maintain an optimal temperature window during machining. Excessively low speeds result in excessive heat buildup, which may deteriorate the mechanical integrity of the surface through oxidation, grain coarsening, or residual stress accumulation. Conversely, excessively high scanning speeds may cause insufficient thermal softening, leading to higher material strength and reduced machinability. The ideal laser speed should therefore ensure adequate preheating for material softening while avoiding thermal damage or phase instability in the nitrided layer.

In summary, Figure 6 reveals that with constant laser power, the cutting temperature of nitrided TC4 titanium alloy decreases consistently with

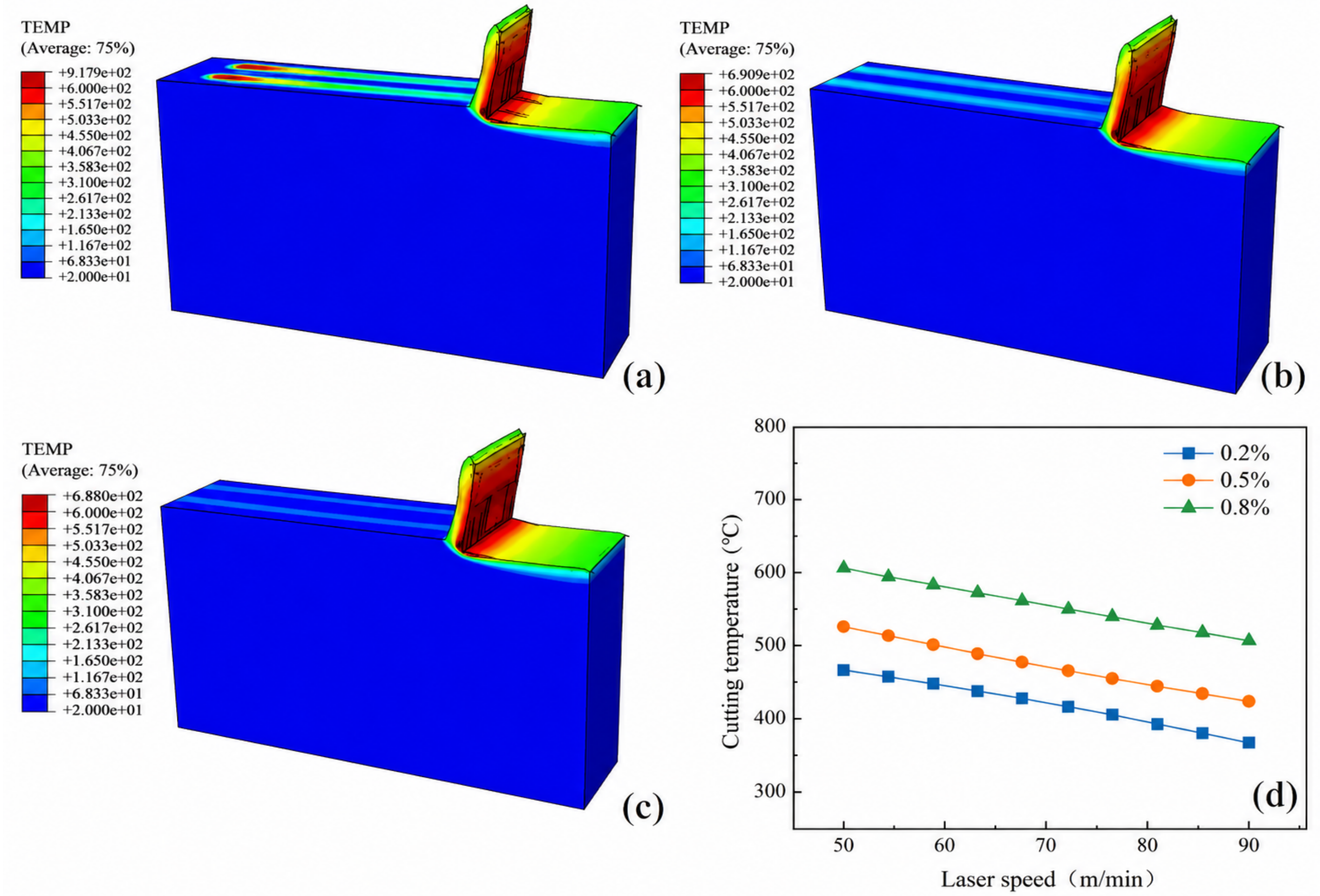

Figure 6. Temperature distribution and variation of nitrided TC4 titanium alloy under different laser scanning speeds: (a) V = 50 m/min; (b) V = 70 m/min; (c) V = 90 m/min; (d) temperature variation data plot.

increasing laser scanning speed. The degree of temperature reduction is positively correlated with nitriding concentration, as higher nitrogen content modifies the material's heat absorption and conduction characteristics. These findings highlight the coupled influence of laser parameters and surface modification on the thermo-mechanical behavior of titanium alloys, providing a theoretical basis for optimizing laser-assisted machining conditions to achieve balanced temperature control, enhanced process stability, and superior surface integrity.

Figure 7 presents the variation in cutting temperature for nitrided TC4 titanium alloy under different laser power levels, with the laser scanning speed fixed at 70 m/min. The results reveal a clear positive correlation between laser power and cutting temperature for all nitriding concentrations (0.2%, 0.5%, and 0.8%).

As shown in the contour maps Figures 7(a)–(c) and the corresponding data plot Figure 7(d), when the laser power increases from 500 W to 1500 W, the cutting temperature rises consistently across all cases. This demonstrates that the thermal energy input per unit time is the dominant factor controlling the temperature field in the laser-assisted cutting process.

The fundamental reason for this trend lies in the energy balance of the laser–material interaction. As the laser power increases, the incident energy density on the material surface becomes higher, leading to greater heat absorption and more intense localized heating in the cutting zone. The enhanced temperature promotes thermal softening of the workpiece material, reducing its flow stress and potentially improving machinability. However, it also increases the likelihood of surface melting, oxidation, and vaporization if the thermal load exceeds a critical threshold. This phenomenon results in a complex interplay between the beneficial and detrimental effects of laser heating on the overall cutting process.

Furthermore, the contour distributions in Figures 7(a)–(c) reveal that the temperature gradient near the cutting zone becomes steeper with increasing laser power. At 500 W, the heat-affected zone (HAZ) is

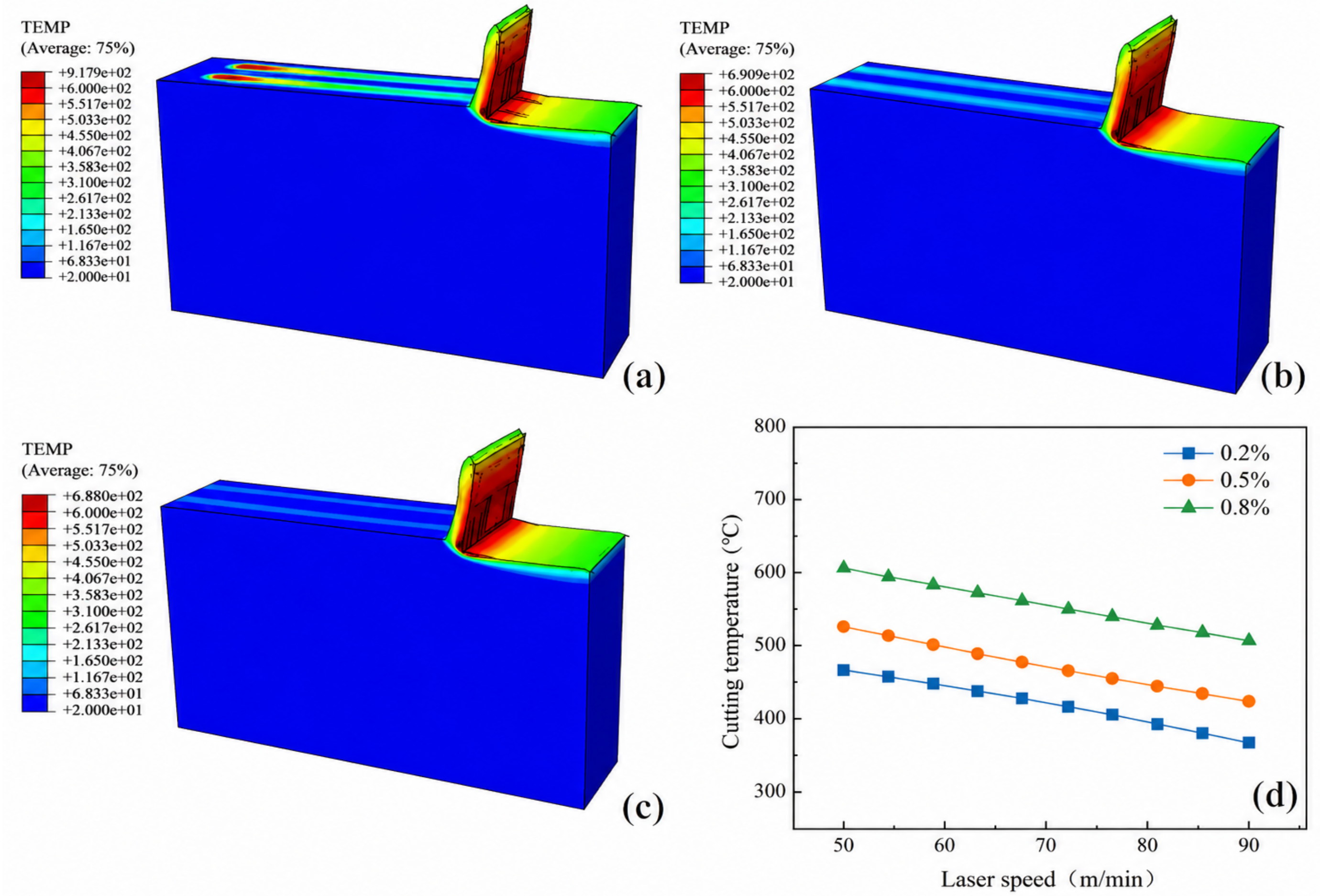

Figure 7. Cutting temperature distributions of nitrided TC4 titanium alloy under different laser powers: (a) P = 500 W; (b) P = 1000 W; (c) P = 1500 W; (d) temperature variation data plot.

relatively confined, and the temperature distribution remains uniform. As the power increases to 1000 W, the HAZ expands, and the peak temperature region extends toward the cutting interface. At 1500 W, a significant thermal accumulation is observed, accompanied by higher temperature gradients both along the cutting direction and in depth. This rapid temperature rise intensifies thermal stresses in the surface layer, which may contribute to microstructural transformations such as α–β phase redistribution or even local melting of the nitrided layer.

The influence of nitriding concentration on this thermal response is also pronounced. All three nitriding levels exhibit the same upward temperature trend with increasing power, yet the magnitude of temperature increase differs notably. As shown in Figure 7(d), higher nitriding concentrations (e.g., 0.8%) lead to a more significant temperature rise under the same laser power increment. This behavior can be attributed to the modified optical and thermal properties of the nitrided surface. The formation of titanium nitride (TiN) and titanium oxynitride (TiON) phases enhances both laser absorptivity and thermal conductivity, allowing the surface layer to absorb and conduct heat more effectively. Consequently, at high power levels, more energy is retained within the upper layers of the material, leading to a steeper and more localized temperature rise.

In addition, the increased thermal conductivity of the nitrided layer facilitates rapid heat transfer along the surface but also promotes the accumulation of heat in the near-surface region due to limited dissipation into the bulk. The combined effect results in a more pronounced temperature gradient and a higher steady-state temperature compared with the non-nitrided or lightly nitrided material. This indicates that nitriding concentration not only affects the energy absorption characteristics but also alters the heat transfer dynamics during laser-assisted cutting, thus changing the overall temperature distribution pattern.

From a process optimization perspective, these findings underscore the necessity of achieving a balanced combination of laser power and nitriding level. Excessively low power may result in inadequate thermal softening, increasing cutting resistance and tool wear, while overly high power may lead to material burning, microcrack formation, or surface oxidation. Therefore, maintaining a moderate power range (around 1000 W in this study) is critical for establishing a stable temperature field that supports effective cutting while avoiding adverse thermal effects.

In summary, Figure 7 demonstrates that the cutting temperature of nitrided TC4 titanium alloy increases monotonically with rising laser power, and this relationship is strongly modulated by the nitriding concentration. The higher the nitrogen content, the greater the temperature sensitivity to power variations. This coupling effect highlights the dual role of the nitrided layer in both enhancing laser energy absorption and modifying heat dissipation behavior. The results provide valuable guidance for the precise control of laser parameters in the machining of surface-treated titanium alloys, enabling the optimization of temperature fields to achieve improved cutting stability, reduced thermal damage, and superior surface quality.

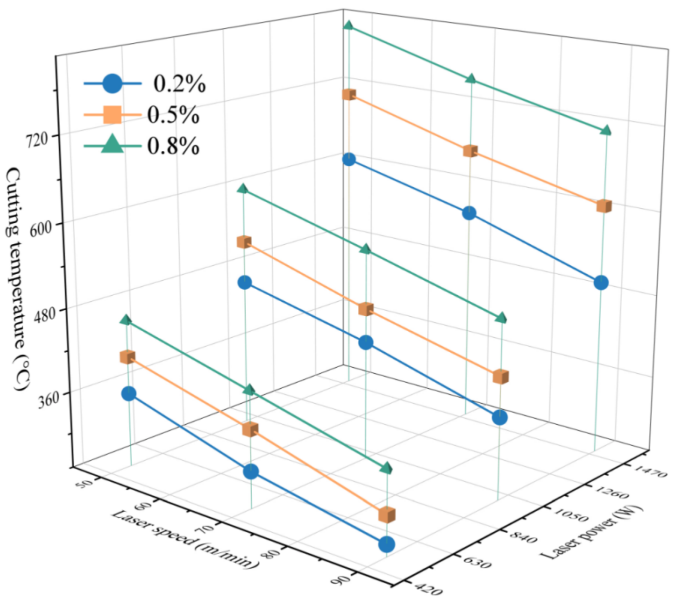

Figure 8. Coupled variation of cutting temperature for nitrided TC4 titanium alloy under different combinations of laser power and scanning speed.

Figure 8 illustrates the coupled influence of laser power and laser scanning speed on the cutting temperature during the laser-assisted machining of nitrided TC4 titanium alloy. The results show that the thermal behavior of the cutting zone is governed by a complex interaction between the two parameters. In the low laser power and low scanning speed region, the cutting temperature remains relatively low, reflecting a balanced energy input and efficient heat dissipation. However, as laser power increases and scanning speed varies, the cutting temperature exhibits nonlinear trends, indicating strong thermo-mechanical coupling within the machining zone.

At low power levels, the heat flux delivered to the material surface is limited, resulting in moderate energy absorption and a restricted heat-affected zone (HAZ). In this regime, variations in scanning speed cause only minor temperature fluctuations because the total heat input per unit time remains small. As laser power increases, however, the heat input becomes significantly higher, and the temperature sensitivity to scanning speed is greatly amplified. For the same change in scanning speed, the temperature variation is larger under high-power conditions, as higher energy density enhances local heating and prolongs the duration of elevated temperatures within the cutting region. This leads to greater thermal gradients and a more pronounced influence on material softening, oxidation, and potential phase transformation in the nitrided layer.

Conversely, when the laser power is fixed, the effect of scanning speed becomes dominant. At low scanning speeds, the laser beam interacts with the workpiece surface for a longer time, allowing more energy to be absorbed and stored in the near-surface layer. This extended exposure causes significant temperature rises, which may enhance thermal softening but also risk excessive heat accumulation and localized melting. In contrast, at high scanning speeds, the shorter interaction time limits heat transfer into the material, reducing the overall temperature and confining the HAZ. These observations suggest that scanning speed primarily governs the temporal distribution of heat, while laser power determines the magnitude of energy input—their coupling defines the overall thermal behavior of the cutting process.

The nitriding concentration further modulates this coupling effect. Different concentrations (0.2%, 0.5%, and 0.8%) display distinct temperature responses to the combined variation of power and speed. At higher nitriding levels, the presence of TiN and Ti_2N phases alters both laser absorptivity and thermal conductivity, thereby changing how the surface layer interacts with the incoming laser energy. High nitriding concentrations typically result in greater temperature sensitivity, where the cutting temperature increases more sharply with rising laser power and decreases more noticeably with increasing scanning speed. This is because the dense nitride layer promotes localized heating while simultaneously restricting heat dissipation into the substrate, amplifying the temperature fluctuation range.

Overall, the results in Figure 8 reveal that the cutting temperature in laser-assisted machining of nitrided TC4 is determined by a synergistic interaction between laser power and scanning speed, with nitriding concentration acting as a critical moderator. Low power and high speed favor lower, more stable temperatures conducive to process control, whereas excessive power or slow scanning induces higher temperatures and thermal instability. These findings provide important insights for the optimization of laser-assisted machining parameters, highlighting the need for multi-parameter coordination to maintain an appropriate thermal balance that ensures efficient cutting, minimal surface damage, and enhanced dimensional accuracy.

3.3 Residual Stress Analysis

Figure 9 illustrates the extraction path of residual stress and the variation of residual stress in nitrided TC4 titanium alloy under different laser parameters. The stress distributions along the machined surface provide insight into the thermo-mechanical response of the material during laser-assisted cutting.

As shown in Figure 9(b), under a laser power of 1000 W and a scanning speed of 70 m/min, the residual compressive stress increases in magnitude with higher nitriding concentrations, rising steadily as the nitrogen content increases from 0.2% to 0.8%. This behavior is attributed to the formation of a hard and brittle TiN-rich layer during nitriding, which possesses a thermal expansion coefficient different from that of the titanium alloy substrate. During the cooling phase following laser heating, the nitrided layer undergoes delayed contraction relative to the substrate, inducing compressive stress at the interface. Moreover, the nitriding process alters the microstructural morphology of the surface by introducing high-hardness phases and grain refinement. These modifications restrict plastic deformation and degrade the deformation compatibility between the nitrided layer and the substrate. As a result, localized strain mismatches develop, leading to the accumulation of residual compressive stress in the near-surface region.

From a mechanical perspective, the enhanced compressive stress in the nitrided surface layer is beneficial for improving fatigue strength and wear resistance, since it counteracts tensile stresses generated during service. However, excessive compressive stress may also increase the risk of microcrack initiation in the hard TiN layer due to its brittleness. Hence, the nitriding concentration must be optimized to balance improved mechanical integrity with surface stability.

Figure 9(c) presents the distribution of residual stress along the cutting surface for a fixed nitriding concentration of 0.5% under different laser scanning speeds. As the scanning speed increases from 50 m/min to 90 m/min, the variation in compressive stress is relatively small, indicating that laser speed plays a secondary role compared to nitriding concentration and laser power. At lower scanning speeds, the laser–material interaction time is longer, which enhances the thermal influence and causes more substantial plastic deformation, leading to slightly higher compressive stress values. However, as the scanning speed continues to increase, the shorter exposure time reduces the temperature gradient and thermal penetration depth, partially offsetting the effect of strain accumulation. Beyond a certain speed threshold, dynamic deformation mechanisms such as strain-rate hardening and thermal contraction mismatch again contribute to a mild increase in residual stress. Overall, the influence of scanning speed on residual stress exhibits a nonlinear trend, yet its magnitude remains smaller compared with the effects of nitriding concentration and laser power.

Figure 9(d) shows the relationship between laser power and residual stress at a nitriding concentration of 0.5% and a laser speed of 70 m/min. The results indicate a linear increase in compressive stress from approximately 180 MPa to 380 MPa as the laser power increases from 500 W to 1500 W. This phenomenon arises because higher laser power delivers more thermal energy to the cutting zone, resulting in enhanced thermal softening and increased elastic recovery during chip formation. The amplified plastic–elastic transition intensifies the backward spring-back effect after material removal, thereby accumulating compressive stress at the surface. Additionally, higher power levels generate stronger thermal gradients and nonuniform cooling rates, which promote residual stress concentration near the machined interface. The elevated heat input also facilitates microstructural transformations and

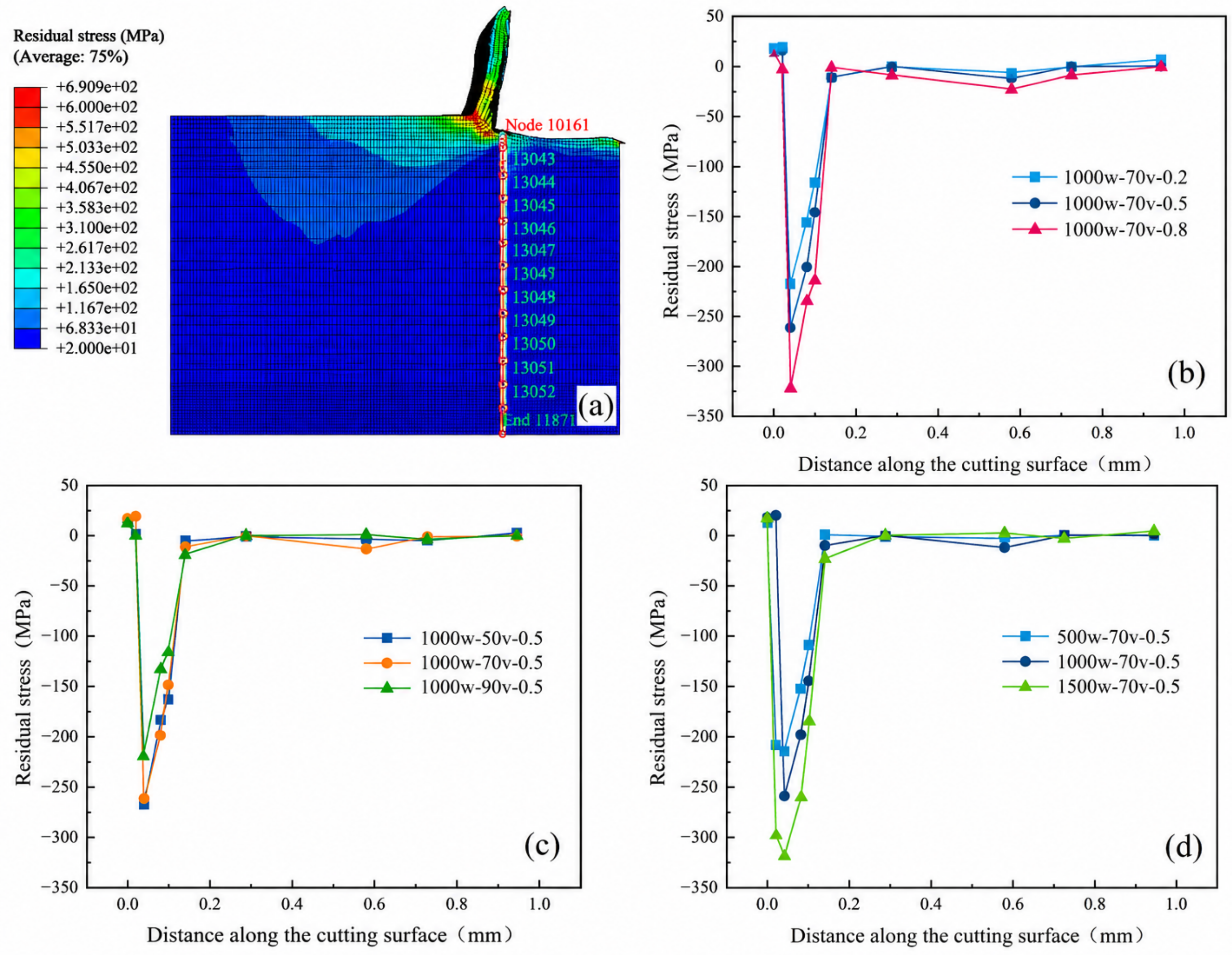

Figure 9. Residual stress extraction path and variation of residual stress in nitrided TC4 titanium alloy under different parameters: (a) extraction path; (b) nitriding concentration; (c) laser scanning speed; (d) laser power.

residual strain locking within the nitrided layer, further contributing to the observed stress increase.

The combined analysis of Figures 9(b)–(d) demonstrates that the residual stress evolution in nitrided TC4 titanium alloy during laser-assisted machining results from a complex coupling among nitriding concentration, laser power, and scanning speed. Nitriding primarily dictates the mechanical rigidity and deformation compatibility of the surface layer, while laser power controls the thermal loading intensity. Scanning speed, on the other hand, regulates the time-dependent distribution of heat. These factors interact nonlinearly: excessive nitriding hardens the surface but reduces compliance; higher power amplifies both heating and cooling gradients; and inappropriate speed either promotes heat accumulation or insufficient softening. Consequently, the residual stress state reflects a delicate balance between thermal expansion mismatch, plastic strain recovery, and phase transformation stress.

From a process optimization viewpoint, a moderate nitriding concentration (≈0.5%) combined with intermediate laser power (≈1000 W) and medium scanning speed (≈70 m/min) yields a favorable residual compressive stress state that enhances surface integrity without inducing microstructural instability. These findings provide critical guidance for controlling residual stress through multi-parameter coupling optimization in laser-assisted machining of surface-modified titanium alloys, contributing to improved mechanical reliability, dimensional stability, and service performance of TC4 components.

4 Discussion

4.1 Mechanistic Interpretation of Laser–Nitriding Interaction

The laser-assisted machining (LAM) process of surface-nitrided TC4 titanium alloy is fundamentally governed by the interaction between the laser-induced thermal field, the nitrided surface microstructure, and the mechanical response of the substrate. The nitriding treatment forms a TiN/Ti_2N-rich diffusion layer characterized by high hardness, brittleness, and a significantly lower thermal expansion coefficient compared with the underlying $\alpha - \beta$ titanium matrix. This structural gradient leads to a strong mismatch in both mechanical and thermal properties. During laser irradiation, the nitrided layer absorbs part of the incident energy, generating localized heating and steep thermal gradients near the surface. The high reflectivity of TiN slightly reduces overall energy absorption, but its lower thermal diffusivity causes heat to accumulate at the interface between the nitrided layer and the substrate. Upon subsequent cooling, differential contraction between the hard TiN layer and the ductile base metal induces residual compressive stresses, which intensify with increasing nitriding concentration. This observation is consistent with the results of Li et al. [13] and Gu et al. [17], who found that nitrogen diffusion and TiN formation enhance surface compressive stress due to the mismatch in thermal strain during the cooling phase. Additionally, the hard and brittle nitrided surface restricts the plastic flow of the substrate during machining, leading to localized strain accumulation beneath the diffusion zone. This reduced deformation compatibility causes stress concentration and further amplifies the magnitude of residual compressive stress. From a microstructural standpoint, the nitriding process not only modifies surface hardness but also introduces a fine-grained, strain-hardened substructure that affects subsequent heat conduction and deformation behavior during laser-assisted cutting. Consequently, the combined effects of high hardness, thermal expansion mismatch, and constrained deformation create a unique thermomechanical coupling field that dominates the stress evolution of the nitrided TC4 surface during and after laser-assisted machining.

4.2 Thermo–Mechanical Coupling Mechanism during Laser-Assisted Cutting

The experimental and simulation results demonstrate that the variations in cutting force, temperature, and residual stress are the result of a coupled relationship between laser power, scanning speed, and nitriding concentration, which collectively determine the energy input, heating duration, and deformation behavior. Laser power controls the magnitude of heat flux, while scanning speed influences the effective irradiation time and the rate of energy distribution along the cutting path. At moderate power levels (approximately 1000 W) and intermediate scanning speeds (around 70 m/min), a stable thermal field forms in which the heat input and dissipation are balanced. This condition produces uniform softening of the substrate material, lowering cutting resistance without inducing surface melting. However, at high power levels or low scanning speeds, excessive heat input generates steeper temperature gradients and partial melting of the TiN surface, resulting in unstable chip formation, higher cutting forces, and greater residual stress accumulation. These effects indicate that the LAM process operates within a narrow thermal stability window, where the benefits of softening compete with detrimental thermal stresses and microstructural instability.

The nitriding concentration further amplifies this coupling effect by altering the optical and thermal properties of the surface. Higher nitrogen content increases reflectivity but also improves lateral thermal conductivity, redistributing heat along the surface rather than through the substrate. As a result, the heat-affected zone (HAZ) becomes shallower, and temperature sensitivity to laser parameters increases. The cutting temperature rises more sharply with higher power and decreases more significantly with faster scanning speeds in highly nitrided samples. This enhanced thermal response is accompanied by stronger mechanical effects—specifically, elevated compressive residual stresses and reduced plastic deformation depth. The mechanical implications of these thermal phenomena align with the observations of Zhang et al. [16] and Yang et al. [18], who reported that multilayer TiN coatings and laser-induced nitrided surfaces exhibit greater residual stress due to constrained contraction and localized heating.

From a mechanistic perspective, the thermo–mechanical behavior of nitrided TC4 alloy during LAM can be summarized as a competition among thermal softening, thermal stress accumulation, and microstructural phase transformation. Optimal machining performance requires balancing these three effects: sufficient softening to reduce cutting force, moderate thermal stress to improve fatigue resistance, and controlled heating to avoid microcracking or phase degradation. The results of this study show that a combination of medium nitriding concentration (0.5%), moderate laser power (1000 W), and medium scanning speed (70 m/min) achieves this equilibrium, yielding efficient cutting performance with desirable surface integrity.

4.3 Comparative Analysis and Process Optimization Insights

Compared with conventional laser-assisted machining of untreated titanium alloys, the inclusion of a nitrided layer introduces an additional layer of complexity due to the formation of a heterogeneous thermal–mechanical interface. In traditional LAM processes, increased laser power typically leads to reduced cutting forces because of enhanced softening; however, in nitrided TC4, the surface layer modifies both the energy absorption and the heat transfer path, resulting in nonlinear and coupled responses between process parameters. A comparable non-monotonic behavior has been reported by Dargusch et al. [30], who observed that although laser assistance lowers the cutting forces during milling of titanium alloys, the dominant contribution of the laser to the total heat at the tool–workpiece interface can accelerate tool wear and offset the benefits of thermal softening, thereby underscoring the need to carefully control the thermal input.

In the present study, this phenomenon is further compounded by the presence of the TiN layer, which, while improving surface hardness and wear resistance, also enhances the tendency for compressive stress buildup when subjected to repeated heating and cooling cycles. Compared with other surface modification techniques such as coating deposition or laser alloying [7–9], nitriding provides better metallurgical bonding and controlled diffusion depth, ensuring improved surface strength without compromising substrate ductility. However, this advantage requires precise control of laser parameters during cutting to avoid overstressing the interface.

The discussion of results also suggests that multi-parameter coupling optimization is essential to achieve stable and high-quality machining. Since laser power, scanning speed, and nitriding concentration are interdependent, tuning one parameter without compensating the others may lead to undesirable effects such as thermal cracking, residual stress accumulation, or poor surface finish. This conclusion is consistent with the energy-efficiency perspective of thermally assisted machining articulated by Pfefferkorn et al. [29], who demonstrated that the benefit of preheating hinges on how effectively the deposited thermal energy is utilized in softening the removed material, implying that the laser energy input must be balanced against the heat conduction and dissipation characteristics of the workpiece to remain effective.

Based on the current results, maintaining laser power around 1000 W and a scanning speed near 70 m/min achieves an effective energy balance, producing controlled thermal softening while minimizing excessive residual stress. A nitriding concentration of approximately 0.5% offers an optimal compromise between surface hardness and deformation compatibility, resulting in superior mechanical and thermal stability. For future applications, incorporating real-time temperature monitoring and feedback control systems could further refine the process by dynamically adjusting laser power and speed to maintain thermal equilibrium.

The insights gained from this study not only deepen the mechanistic understanding of laser–nitriding–machining interactions but also provide valuable guidelines for process optimization in advanced manufacturing of titanium alloys used in aerospace, biomedical, and marine engineering applications.

5 Conclusion

(1) The finite element simulations and analyses demonstrate that surface nitriding significantly modifies the thermomechanical response of TC4 titanium alloy during laser-assisted machining. The formation of a TiN/Ti_2N diffusion layer enhances surface hardness and compressive residual stress, while introducing thermal expansion mismatch with the substrate. This dual effect improves surface integrity but also increases the sensitivity of the material to laser parameters.

(2) The coupling between laser power, scanning speed, and nitriding concentration governs the evolution of cutting force, cutting temperature, and residual stress. Increasing laser power enhances thermal softening but simultaneously promotes residual stress accumulation, whereas higher scanning speeds reduce temperature and cutting force by shortening heat interaction time. A medium nitriding concentration ($\approx$0.5%), moderate power ($\approx$1000 W), and balanced speed ($\approx$70 m/min) yield optimal cutting performance with stable thermal behavior.

(3) The study elucidates the underlying mechanism of laser–nitriding interaction in titanium alloys, revealing that the process involves a competition among thermal softening, residual stress formation, and microstructural evolution. These insights provide theoretical guidance for optimizing laser-assisted machining of nitrided titanium alloys, enabling enhanced surface quality, reduced tool wear, and improved efficiency in advanced manufacturing applications such as aerospace, biomedical, and precision engineering.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] Lü, Q., Chai, Y., Yang, L., Liu, X., Li, G., & Xiang, D. (2023). Experimental study on cutting force and surface integrity of TC4 titanium alloy with longitudinal ultrasonic-assisted milling. *Coatings, 13*(10), 1725. [CrossRef]

[2] Zha, X., Qin, H., Yuan, Z., Xi, L., Zhang, T., & Jiang, F. (2024). Effect of cutting feed rate on machining performance and surface integrity in cutting process of Ti-6Al-4V alloy. *The International Journal of Advanced Manufacturing Technology, 131*(5), 2791–2809. [CrossRef]

[3] Kalantari, O., Jafarian, F., & Fallah, M. M. (2021). Comparative investigation of surface integrity in laser assisted and conventional machining of Ti-6Al-4 V alloy. *Journal of Manufacturing Processes, 62*, 90–98. [CrossRef]

[4] Kalantari, O., Fallah, M. M., Jafarian, F., & Hamzeloo, S. R. (2021). Surface integrity in laser-assisted machining of Ti6Al4V. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 235*(20), 5009–5016. [CrossRef]

[5] Li, Q., Wu, Z., Ji, B., Zhang, S., & Tu, R. (2025). Cutting performance of tin/tisin coated tool during turning of Ti6Al4V titanium alloy. *Journal of Materials Engineering and Performance, 34*(11), 9374–9387. [CrossRef]

[6] He, T., Tang, Y., Wu, H., Liu, Y., & Chen, J. (2024, June). Research and analysis of TC4 titanium alloy cutting based on crystal plasticity theory. In *Journal of Physics: Conference Series* (Vol. 2785, No. 1, p. 012131). IOP Publishing. [CrossRef]

[7] Takesue, S., Kikuchi, S., Misaka, Y., Morita, T., & Komotori, J. (2020). Rapid nitriding mechanism of titanium alloy by gas blow induction heating. *Surface and Coatings Technology, 399*, 126160. [CrossRef]

[8] Fujita, K., Ijiri, M., Inoue, Y., & Kikuchi, S. (2021). Rapid nitriding of titanium alloy with fine grains at room temperature. *Advanced Materials, 33*(20), 2008298. [CrossRef]

[9] Tarnowski, M., Borowski, T., Skrzypek, S., Kulikowski, K., & Wierzchoń, T. (2021). Shaping the structure and properties of titanium and Ti6Al7Nb titanium alloy in low-temperature plasma nitriding processes. *Journal of Alloys and Compounds, 864*, 158896. [CrossRef]

[10] Zong, X., Wang, H., Tang, H., Cheng, X., Tian, X., & Ran, X. (2023). Microstructure evolution and mass transfer behavior during multi-pass laser surface nitriding process on titanium alloy. *Surface and Coatings Technology, 466*, 129565. [CrossRef]

[11] Zhang, L., Shao, M., Zhang, Z., Yi, X., Yan, J., Zhou, Z., ... & Li, Y. (2023). Corrosion behavior of nitrided layer of Ti6Al4V titanium alloy by hollow cathodic plasma source nitriding. *Materials, 16*(8), 2961. [CrossRef]

[12] Ongtrakulkij, G., Kajornchaiyakul, J., Kondoh, K., & Khantachawana, A. (2022). Investigation of microstructure, residual stress, and hardness of Ti-6Al-4V after plasma nitriding process with different times and temperatures. *Coatings, 12*(12), 1932. [CrossRef]

[13] Li, Y., Liang, X., Cao, Z., Zhang, H., Lang, M., Xie, C., ... & He, W. (2025). Enhancement of wear resistance in TC6 titanium alloy through a combined treatment of laser shock peening and nitrogen ion implantation at 300° C. *Journal of Materials Research and Technology, 36*, 203–216. [CrossRef]

[14] Liu, F. H., & Pang, M. (2024). Effect of laser scanning velocity on the microstructure and wear resistance of laser nitride h-BN self-lubricating. *Materials Today Communications, 39*, 108601. [CrossRef]

[15] Xu, B., Zhang, J., Liu, X., Liu, H., & Zhao, W. (2023). Fully coupled thermomechanical simulation of laser-assisted machining Ti6Al4V reveals the mechanism of morphological evolution during

serrated chip formation. *Journal of Materials Processing Technology, 315*, 117925. [CrossRef]

[16] Zhang, Z., Chai, Y., Yang, M., & He, G. (2024). Enhancing mechanism of TC4 high-cycle fatigue performance by the introduction of hard nitride mono-and multilayer coatings. *International Journal of Fatigue, 182*, 108219. [CrossRef]

[17] Gu, Y., Duan, X., Xu, Y., Shi, Y., Zhu, M., Feng, X., ... & Korzhyk, V. (2024). Preparation of ultra-thick, crack-free, titanium nitride coatings using a full-domain power-modulated laser. *Journal of Manufacturing Processes, 113*, 346–359. [CrossRef]

[18] Yang, Y. L., Zhao, G. J., Zhang, D., & Liu, C. S. (2006). Improving the surface property of TC4 alloy by laser nitriding and its mechanism. *Acta metallurgica sinica (English letters), 19*(2), 151–156. [CrossRef]

[19] Yang, Y., Cao, S., Zhang, S., Xu, C., & Qin, G. (2017). Microstructure and wear resistance of Ti–Cu–N composite coating prepared via laser cladding/laser nitriding technology on Ti–6Al–4V alloy. *Applied Physics A, 123*(7), 474. [CrossRef]

[20] Peng, Z., Zhang, X., Liu, L., Xu, G., Wang, G., & Zhao, M. (2023). Effect of high-speed ultrasonic vibration cutting on the microstructure, surface integrity, and wear behavior of titanium alloy. *Journal of materials research and technology, 24*, 3870–3888. [CrossRef]

[21] Kong, X., Hu, G., Hou, N., Liu, N., & Wang, M. (2023). Numerical and experimental investigations on the laser assisted machining of the TC6 titanium alloy. *Journal of Manufacturing Processes, 96*, 68–79. [CrossRef]

[22] Khajehzadeh, M., & Razfar, M. R. (2020). Process parameters influence on laser-assisted machining-induced residual stresses. *Materials and Manufacturing Processes, 35*(15), 1680–1689. [CrossRef]

[23] Rashid, R. R., Sun, S., Wang, G., & Dargusch, M. S. (2012). An investigation of cutting forces and cutting temperatures during laser-assisted machining of the Ti–6Cr–5Mo–5V–4Al beta titanium alloy. *International Journal of Machine Tools and Manufacture, 63*, 58–69. [CrossRef]

[24] Gupta, M. K., Niesłony, P., Korkmaz, M. E., Kuntoğlu, M., Królczyk, G. M., Günay, M., & Sarikaya, M. (2023). Comparison of tool wear, surface morphology, specific cutting energy and cutting temperature in machining of titanium alloys under hybrid and green cooling strategies. *International Journal of Precision Engineering and Manufacturing-Green Technology, 10*(6), 1393–1406. [CrossRef]

[25] Ribeiro-Carvalho, S., Horovistiz, A., & Davim, J. P. (2021). Material model assessment in Ti6Al4V machining simulations with FEM. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 235*(21), 5500–5510. [CrossRef]

[26] Qian, X., & Duan, X. (2019). Constitutive model and cutting simulation of titanium alloy Ti6Al4V after heat treatment. *Materials, 12*(24), 4145. [CrossRef]

[27] Divse, V., Bhandarkar, A., Nayak, J., Thomas, V., & Marla, D. (2024). A FEM-based coupled thermo-mechanical model of laser-assisted machining of Ti6Al4V—a focus on chip morphology. *The International Journal of Advanced Manufacturing Technology, 134*(5), 2587–2605. [CrossRef]

[28] Yang, J., Sun, S., Brandt, M., & Yan, W. (2010). Experimental investigation and 3D finite element prediction of the heat affected zone during laser assisted machining of Ti6Al4V alloy. *Journal of Materials Processing Technology, 210*(15), 2215–2222. [CrossRef]

[29] Pfefferkorn, F. E., Lei, S., Jeon, Y., & Haddad, G. (2009). A metric for defining the energy efficiency of thermally assisted machining. *International Journal of Machine Tools and Manufacture, 49*(5), 357–365. [CrossRef]

[30] Dargusch, M. S., Sivarupan, T., Bermingham, M., Rashid, R. A. R., Palanisamy, S., & Sun, S. (2021). Challenges in laser-assisted milling of titanium alloys. *International Journal of Extreme Manufacturing, 3*(1), 015001. [CrossRef]