Journal of Materials Durability and Engineering
http://dx.doi.org/10.62762/JMDE.2026.741108

RESEARCH ARTICLE

Influence of Heat Treatment Processes on the Machinability and Surface Integrity of Ti-6Al-4V Alloy During Precision Machining

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Abstract

Ti-6Al-4V titanium alloy (TC4) has been extensively applied in advanced manufacturing fields owing to its outstanding combination of mechanical properties and corrosion resistance. However, its poor machinability remains a critical challenge that limits further application. In this study, the effects of three categories of heat treatment processes, including annealing, solution treatment, and aging treatment, comprising eight specific heat treatment schemes, on the precision cutting performance of TC4 alloy were systematically investigated using DEFORM-3D numerical simulations. The results demonstrate that stress-relief annealing and full annealing effectively reduce cutting forces by up to 15.17% through grain refinement and residual stress relaxation, while also lowering cutting temperatures and improving residual stress distribution, with the stress gradient decreasing to 50–80 MPa/μm. In contrast, solution treatment increases hardness, resulting in intensified fluctuations in cutting forces. Aging treatment promotes the precipitation of strengthening phases, achieving the most significant reduction in cutting force with a maximum decrease of 43.09%, though it introduces localized thermal accumulation during cutting. This study reveals the regulation mechanism of heat treatment on machining performance through the sequential interaction of microstructure evolution–mechanical property modification–cutting response transformation. Among the investigated processes, annealing exhibits the most comprehensive improvement in overall machinability. The findings provide theoretical guidance for the synergistic optimization of heat treatment strategies and cutting parameters for TC4 titanium alloy machining.

Keywords: heat treatment, Ti-6Al-4V titanium alloy, precision machining, mechanical properties, microstructural evolution.

Submitted: 28 May 2026
Revised: 18 June 2026
Accepted: 29 July 2026
Published: 02 September 2026

Vol. 1, **No.** 1, 2026.
10.62762/JMDE.2026.741108

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1 Introduction

Titanium alloy Ti-6Al-4V, also known as TC4 alloy, is one of the most extensively utilized

Citation
Zhao, Z., Gao, J., Wang, H., & Yang, H. (2026). Influence of Heat Treatment Processes on the Machinability and Surface Integrity of Ti-6Al-4V Alloy During Precision Machining. *Journal of Materials Durability and Engineering*, 1(1), 35–51.

$\alpha + \beta$ titanium alloys in advanced engineering applications, particularly in aerospace, biomedical implants, chemical processing equipment, and high-performance mechanical systems [1–3]. The widespread adoption of Ti-6Al-4V is primarily attributed to its exceptional combination of high specific strength, excellent corrosion resistance, superior fatigue performance, and outstanding biocompatibility. These advantages make it an indispensable structural material for components requiring lightweight design and long-term service reliability. However, despite these remarkable properties, the poor machinability of Ti-6Al-4V remains a critical limitation during precision manufacturing processes. The inherent characteristics of titanium alloys, including low thermal conductivity, relatively low elastic modulus, high chemical reactivity, and strong affinity with cutting tool materials, lead to severe heat accumulation in the cutting zone, intensified tool wear, unstable cutting forces, and undesirable surface integrity degradation. In particular, the concentrated distribution of cutting heat and mechanical loading during machining can induce significant residual stresses and microstructural alterations on the machined surface, thereby affecting the dimensional accuracy, fatigue life, and service reliability of fabricated components. Therefore, improving the machinability of Ti-6Al-4V while maintaining its superior mechanical properties has become an important research topic in both academia and industrial manufacturing.

The machinability of metallic materials is strongly influenced by their intrinsic microstructural characteristics and mechanical responses. For titanium alloys, parameters such as phase composition, grain morphology, dislocation density, hardness, and residual stress state play crucial roles in determining the interaction between the workpiece material and cutting process [4, 5]. Heat treatment technology provides an effective approach to modify these microstructural features and optimize material performance by controlling phase transformation behavior, grain refinement, precipitation evolution, and internal stress redistribution [6, 7]. Conventional heat treatment processes for Ti-6Al-4V mainly include annealing, solution treatment, and aging treatment. These thermal processes can significantly alter the balance between strength and ductility through the regulation of α and β phase morphology, thereby influencing cutting deformation behavior, thermal generation, and surface integrity during machining [8–11]. Consequently, understanding the relationship between heat treatment-induced microstructural evolution and machining behavior is essential for achieving efficient and high-quality manufacturing of titanium alloy components. Extensive investigations have been conducted to clarify the influence of heat treatment on the microstructure and mechanical properties of titanium alloys. Sun et al. [12] systematically investigated the effects of heat treatment on the microstructure and elevated-temperature tensile properties of a near-α as-cast titanium alloy. Their results demonstrated that variations in heat treatment conditions produced limited changes in ultimate tensile strength (UTS), yield strength (YS), and elongation (EL), while microstructural characterization revealed only slight morphological modifications. Chen et al. [13] studied the anisotropic machinability of selective laser melted (SLM) Ti-6Al-4V before and after heat treatment by evaluating milling forces, surface quality, top burr formation, and machining-induced hardening behavior. Their research indicated that appropriate heat treatment could effectively reduce anisotropic machining characteristics originating from additive manufacturing processes. In addition to conventional manufacturing routes, heat treatment has also demonstrated significant influence on the microstructure evolution of additively manufactured titanium alloys. Wang et al. [14] investigated the effects of post-weld heat treatment on the microstructure and properties of Ti-6Al-4V alloy, reporting that different thermal cycles promoted significant variations in α phase morphology and $\alpha+\beta$ phase distribution. The observed formation of basket-weave structures and columnar grain transformation highlight the sensitivity of TC4 microstructure to heat treatment parameters, which is similarly applicable to conventional thermomechanical processing routes. Elshaer et al. [15] investigated the influence of annealing, solution treatment, and aging on the microstructure evolution, tensile properties, and tribological behavior of Ti-6Al-4V alloy. Their results demonstrated that solution treatment followed by aging promoted the precipitation of secondary α phase within the retained β phase, leading to significant improvements in strength, while annealing routes contributed to improved ductility and microstructural homogeneity. Similarly, Jamhari et al. [16] investigated the influence of heat treatment parameters on the microstructure and mechanical properties of Ti alloys fabricated by laser powder bed fusion (LPBF). Their findings suggested that heating temperature played a dominant role in controlling microstructural development, while post-treatment processes contributed to reducing porosity and relieving residual stresses. The relationship between thermal treatment, machining conditions, and surface performance has also attracted increasing attention. Niu et al. [17] explored the influence of cutting speed on the surface integrity and fatigue behavior of Ti-6Al-4V (ASTM Grade 5) and Ti-6Al-4V ELI (ASTM Grade 23) alloys subjected to β annealing and milling annealing treatments. Their results demonstrated that cutting speed exhibited relatively limited effects on surface roughness and fatigue properties, whereas microstructural characteristics played a dominant role in determining surface performance. Li et al. [18] investigated the mechanical responses of hot-rolled TA15 aviation titanium alloy under different heat treatment conditions, demonstrating that stress-relief annealing produced finer α phase structures and improved strength-toughness balance compared with conventional annealing routes. These findings highlight the general role of annealing temperature and cooling path in regulating α phase morphology across near-α and $\alpha+\beta$ titanium alloys, which provides a useful reference for understanding similar microstructural responses in TC4 alloy during heat treatment. Furthermore, solution treatment and aging strategies have been widely employed to achieve desirable combinations of strength and ductility in titanium alloys. Pfeffer et al. [11] demonstrated that short-duration solution treatment combined with subsequent annealing could enhance the mechanical properties of Ti-6Al-4V by promoting martensitic transformation and β grain strengthening while maintaining acceptable ductility. Their study further revealed that increasing solution temperature resulted in higher strength accompanied by reduced ductility. Du et al. [19] investigated the evolution of microstructure and mechanical properties of Ti-6Al-4V alloy under combined heat treatment and multi-axial forging processes. Their findings revealed that the synergistic effect of thermal processing and deformation promoted α phase refinement and improved the balance between strength and ductility. Hoareau et al. [20] employed in-situ high-energy X-ray diffraction to analyze phase transformation kinetics of Ti-575 titanium alloy during solution annealing, cooling, and subsequent aging processes, providing valuable insights into thermally induced phase evolution mechanisms. Guo et al. [21] reported that duplex aging treatment of metastable β titanium alloys significantly increased yield strength through enhanced precipitation strengthening and increased dislocation density. For TC4 titanium alloy specifically, Zhou et al. [22] systematically reviewed the microstructure evolution and mechanical properties of TC4 alloy fabricated by selective laser melting under various heat treatment conditions, providing insight into the thermal regulation of phase composition and its effects on material performance in this alloy system. Shekhar et al. [23] investigated the effects of solution treatment and aging on the microstructure and tensile properties of a high-strength β titanium alloy (Ti–5Al–5V–5Mo–3Cr), demonstrating that the transformation and interaction between α and β phases under different thermal conditions strongly influenced yield strength, ultimate tensile strength, and plastic deformation capability. These findings provide a mechanistic reference for understanding phase-dependent mechanical responses during heat treatment of $\alpha+\beta$ titanium alloys such as TC4. Although previous studies have extensively explored the influence of heat treatment on microstructure modification and mechanical enhancement of titanium alloys, most investigations have focused on mechanical properties, phase transformation mechanisms, corrosion behavior, or additive manufacturing processes. The influence of different heat treatment states on the precision machining behavior of Ti-6Al-4V alloy, particularly regarding the coupling relationship between microstructural characteristics and machining responses, remains insufficiently understood. During precision cutting, the interaction between thermo-mechanical loading and heat treatment-induced material evolution determines cutting force characteristics, temperature distribution, and residual stress formation. Therefore, establishing a comprehensive understanding of the regulation of machining performance by heat treatment is essential for optimizing manufacturing processes of titanium alloy components.

Numerical simulation techniques, especially finite element-based machining simulations, provide an effective approach for investigating complex thermo-mechanical interactions during cutting processes. Compared with experimental approaches alone, simulation methods enable detailed analysis of cutting force evolution, temperature distribution, stress formation, and material deformation mechanisms under controlled conditions. In this study, DEFORM-3D finite element simulations are employed to investigate the influence of multiple heat treatment conditions, including annealing, solution treatment, and aging treatment, on the precision machining behavior of Ti-6Al-4V alloy. The effects of heat treatment on microstructural characteristics, cutting force response, cutting temperature evolution, and residual stress distribution are systematically analyzed. The objective of this research is to provide a deeper understanding of the relationship between heat treatment-induced material modification and machining performance, thereby offering theoretical guidance for optimizing heat treatment strategies and precision cutting processes of Ti-6Al-4V titanium alloy.

2 Materials and Methods

2.1 Material Model

A three-dimensional finite element model was established using the DEFORM-3D software package [24, 25] to simulate the coupled effects of heat treatment-induced material modification and subsequent cutting processes. The constitutive behavior of Ti-6Al-4V titanium alloy was described using the Johnson–Cook (J–C) constitutive model, and the corresponding material parameters are listed in Table 1 [26]. The J–C model was selected due to its capability of accurately describing the flow stress evolution of metallic materials under high strain rate, elevated temperature, and plastic deformation conditions during machining processes. The friction coefficient between the tool and workpiece was set to 0.6 to represent the contact interaction during cutting [9, 24]. To improve the calculation accuracy in the highly deformed cutting region, local mesh refinement was applied, with the minimum element size reduced to 0.06 mm.

Table 1. Johnson–Cook constitutive parameters of Ti-6Al-4V titanium alloy.

Parameter	Coefficient	Unit
A	1060	MPa
B	1090	MPa
n	0.884	–
C	0.0117	–
m	1.1	–

2.2 Design of Heat Treatment Processes

To systematically investigate the influence of thermal treatment on the machining behavior of Ti-6Al-4V alloy, eight heat treatment conditions were designed, as summarized in Table 2. The selected treatment schemes covered three typical thermal processing routes, including annealing, solution treatment, and aging treatment. By adjusting the heating temperature, holding duration, and cooling method, different microstructural states were generated to evaluate their effects on subsequent cutting responses. These heat-treated conditions provide a comprehensive basis for analyzing the relationship between thermally induced microstructural evolution and machining performance.

2.3 Finite Element Simulation Model

In the numerical simulation, Ti-6Al-4V titanium alloy was selected as the workpiece material, with dimensions of $10 \times 3 \times 5$ mm. The cutting tool was modeled as a tungsten carbide (WC)-based tool material due to its widespread application in titanium alloy machining. The cutting parameters were maintained at a cutting speed of 60 m/min, a feed rate of 0.1 mm/rev, and a cutting depth of 0.3 mm. The overall configuration of the cutting simulation model is illustrated in Figure 1.

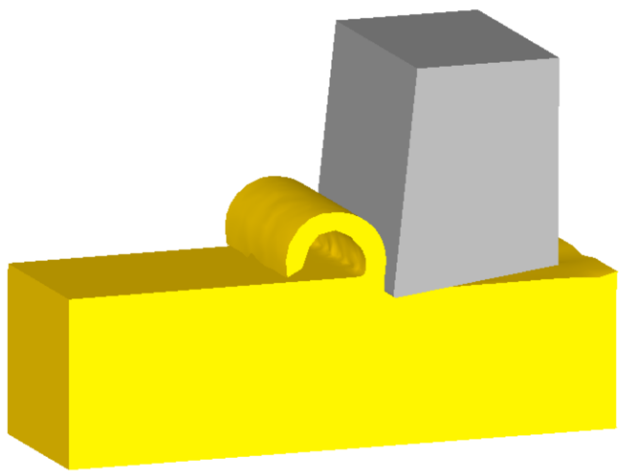

Figure 1. Schematic illustration of the cutting simulation model.

The initial average grain size of the simulated material was defined as 8 μm. During the machining simulation, microstructural evolution was analyzed at two representative regions, including the machined surface (P1) and the subsurface layer (P2), as shown in Figure 2. These locations were selected to characterize the influence of cutting-induced thermo-mechanical loading on surface and near-surface microstructural changes, which are closely associated with machining quality and surface integrity.

Table 2. Heat treatment parameters and processing procedures.

Process type	Scheme Number	Heat treatment process
Stress relief annealing	I	Heat at 550°C for 2 hours with constant temperature, then cool down in the air for 1 hour;
	II	Heat at 650°C for 2 hours with constant temperature, then cool down in the air for 1 hour;
Complete annealing	III	Heat at 750°C for 2 hours with constant temperature, then cool down in the air for 1 hour;
	IV	Heat at 850°C for 2 hours with constant temperature, then cool down in the air for 1 hour;
Duplex annealing	V	Heat at 850°C for 1 hour → cool down in the air for 1 hour → heat at 600°C for 2 hours → cool down in the air for 1 hour;
Solution treatment	VI	Heat at 920°C for 1.5 hours → oil quench at 100°C for 20 minutes → cool down in the air for 1 hour;
	VII	Heat at 900°C for 1 hour → heat at 980°C for 30 minutes → oil quench at 100°C for 20 minutes → cool down in the air for 1 hour;
Aging	VIII	Heat at 980°C for 2 hours → oil quench at 100°C for 20 minutes → heat at 480°C for 2 hours → cool down in the air for 1 hour;

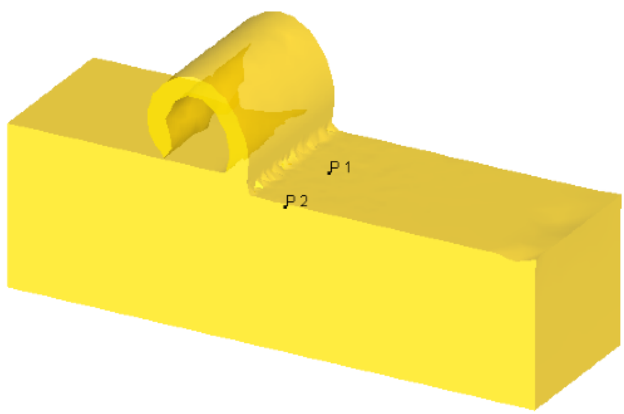

Figure 2. Locations selected for microstructure evolution analysis: machined surface (P1) and subsurface region (P2).

3 Results and Discussion

3.1 Microstructural Evolution in the Cutting Zone of Ti-6Al-4V Alloy after Different Heat Treatments

The evolution of grain morphology in the machined surface and subsurface regions under different heat treatment conditions was investigated based on the simulated microstructural results. The average grain sizes extracted from the cutting surface (P1) and subsurface region (P2) are presented in Figure 3, while the corresponding grain size distribution contours are illustrated in Figure 4. Since machining-induced plastic deformation involves intense thermo-mechanical coupling effects, the evolution of grain characteristics in the cutting affected zone is strongly influenced by the initial microstructural state generated by heat treatment.

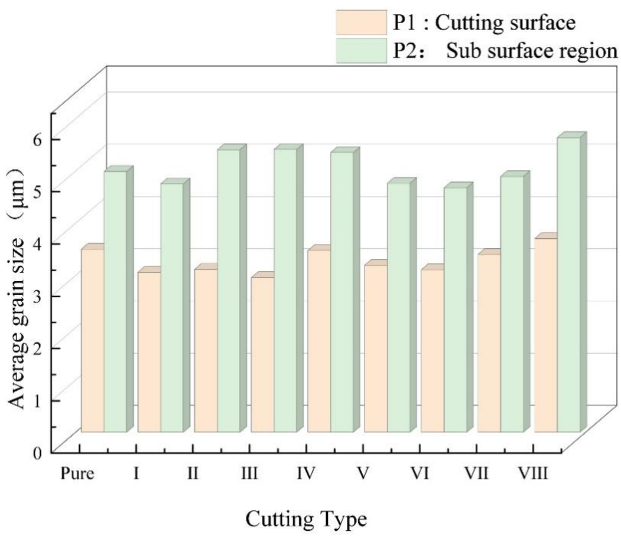

Figure 3. Average grain size of Ti-6Al-4V alloy after different heat treatment processes.

As shown in Figures 3 and 4, the stress-relief annealing

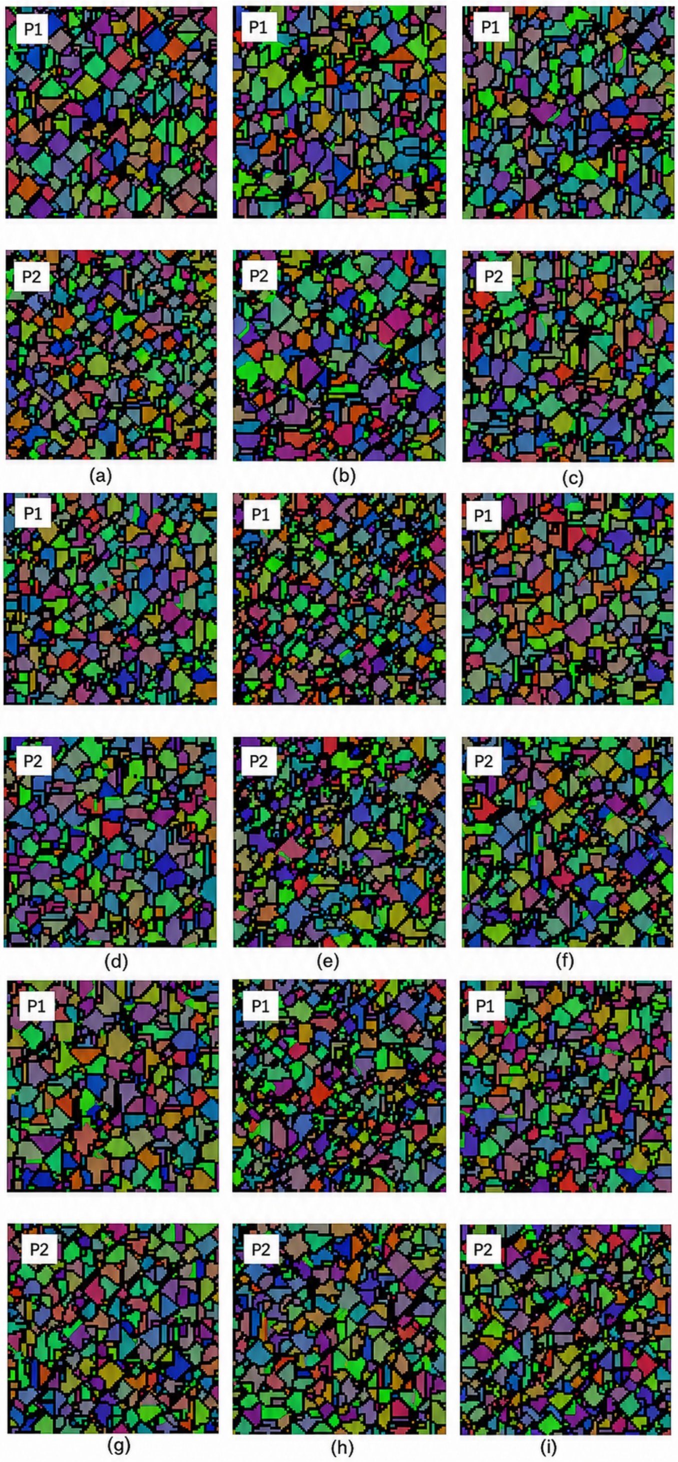

Figure 4. Grain size distribution contours after different heat treatment processes. (a) Untreated cutting condition; (b–i) heat treatment schemes I–VIII.

and full annealing treatments (schemes I–IV) resulted in relatively finer grain structures in both the machined surface and subsurface regions compared with the untreated condition. This phenomenon can be mainly attributed to the recrystallization behavior promoted by annealing treatment. During annealing, the stored deformation energy and internal residual stresses accumulated in the alloy are partially released, providing favorable conditions for nucleation and growth of recrystallized grains. The formation of newly recrystallized fine grains reduces microstructural heterogeneity and improves the uniformity of deformation behavior during subsequent cutting processes. Consequently, the cutting-induced plastic deformation is distributed more evenly within the surface affected layer, preventing excessive grain coarsening and localized deformation accumulation.

For stress-relief annealing treatments (schemes I and II), the reduction in grain size was relatively limited compared with full annealing treatments. This is mainly because the primary objective of stress-relief annealing is to eliminate internal residual stress rather than induce significant phase transformation or recrystallization. The thermal exposure during this process promotes recovery of the distorted lattice structure, reduces dislocation density, and improves stress equilibrium, while the overall grain morphology remains relatively stable. Therefore, stress-relief annealing mainly contributes to improving machining stability through stress relaxation rather than substantial grain refinement.

In comparison, full annealing treatments (schemes III and IV) exhibited more pronounced grain refinement effects. The higher thermal input and sufficient holding time promote recrystallization and phase redistribution between α and β phases, resulting in a more homogeneous microstructure. The refined grain structure obtained after full annealing provides a more consistent deformation response during cutting, which is beneficial for reducing local deformation concentration and improving the integrity of the machined surface. The smaller grain size observed in both P1 and P2 regions indicates that full annealing can effectively modify the initial microstructural state and influence the subsequent machining-induced grain evolution.

The double annealing treatment (scheme V) produced an intermediate grain size between conventional annealing and solution treatment conditions. This behavior is associated with the multi-stage thermal regulation mechanism of double annealing. During the high-temperature stage, coarse microstructural features and non-uniform phase distributions are partially dissolved or redistributed. Subsequently, the intermediate-temperature treatment controls grain growth and promotes a more balanced microstructural

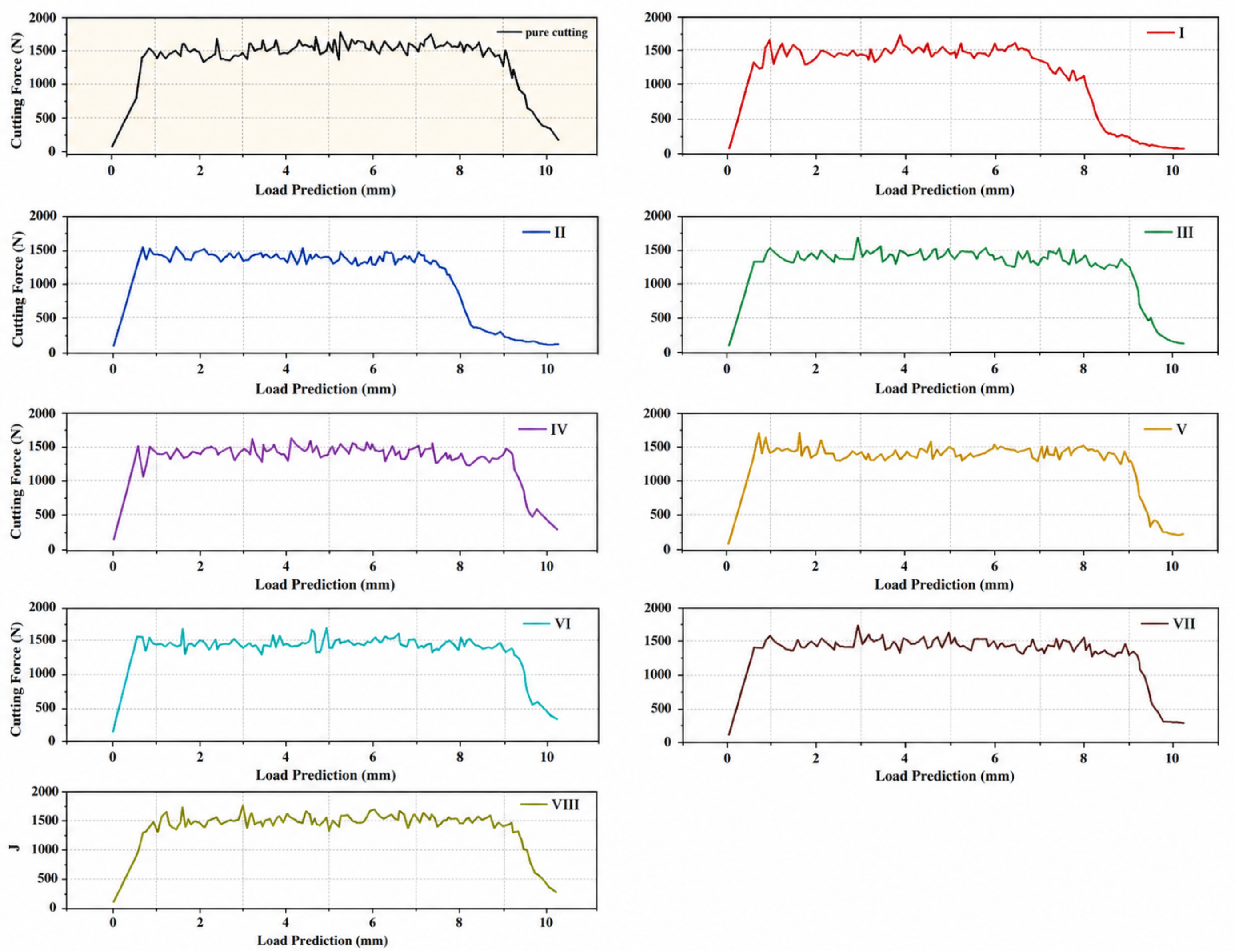

Figure 5. Variation of cutting force with cutting distance under untreated and different heat-treated conditions.

configuration. As a result, double annealing achieves a compromise between grain refinement and structural stability, producing relatively uniform grains without excessive grain growth.

For solution-treated samples (schemes VI and VII), the grain size distribution exhibited different characteristics compared with annealing conditions. Solution treatment promotes the dissolution of alloying elements into the β phase region, resulting in a more homogeneous elemental distribution. During subsequent cooling, phase transformation occurs, and the rapid cooling process suppresses excessive grain growth. The resulting transformed microstructure contributes to grain refinement and enhances structural stability. However, compared with annealing treatments, the grain refinement effect is accompanied by increased strengthening characteristics due to supersaturated solid solution formation, which may alter the deformation behavior during machining.

After aging treatment (scheme VIII), the average grain size showed relatively limited variation compared with other heat treatment conditions. This is because aging treatment primarily modifies mechanical properties through precipitation strengthening rather than significant grain morphology transformation. During aging, fine strengthening phases precipitate within the matrix, increasing resistance to plastic deformation and improving hardness. However, the precipitation process generally has a weaker influence on grain size compared with recrystallization and phase transformation processes occurring during annealing or solution treatment.

The grain size distribution within the cutting affected zone further demonstrates that different heat treatment routes regulate machining-induced microstructural evolution through distinct mechanisms. Annealing treatments mainly influence the material by relieving residual stresses and promoting recrystallization, leading to improved microstructural uniformity. Double annealing achieves additional structural optimization through sequential thermal regulation. Solution treatment modifies the alloy structure through elemental redistribution and phase transformation, whereas aging treatment mainly enhances mechanical properties through precipitation strengthening with limited grain modification.

Overall, the initial microstructural state produced by heat treatment plays a critical role in determining the subsequent grain evolution behavior during machining. The differences in grain refinement, phase stability, and strengthening mechanisms among various heat treatment conditions provide a fundamental basis for understanding the variation in cutting force, stress distribution, and surface integrity of Ti-6Al-4V alloy during precision machining.

3.2 Mechanical Performance of Ti-6Al-4V Alloy after Different Heat Treatments

The cutting force evolution during machining was extracted from the simulation results under different heat treatment conditions, and the corresponding variation curves as a function of cutting distance are presented in Figure 5. The eight heat treatment schemes are denoted by Roman numerals (I–VIII). The cutting force reflects the resistance of the workpiece material to plastic deformation and chip formation, and its variation is closely associated with the material hardness, microstructural uniformity, and residual stress state after heat treatment.

Compared with the untreated Ti-6Al-4V alloy, stress-relief annealing treatments (schemes I and II) resulted in a noticeable reduction in cutting force throughout the machining process. The average cutting force decreased by 13.44% and 15.17%, respectively. The improved cutting response after stress-relief annealing can be attributed primarily to the reduction of internal residual stresses generated during previous processing and the relaxation of the non-equilibrium stress state within the material. In particular, scheme II, performed at a higher annealing temperature of 650 °C, exhibited a slightly greater reduction in cutting force than scheme I. This behavior suggests that increasing the annealing temperature promotes more effective stress relaxation, thereby reducing the resistance encountered during plastic deformation. The lower cutting force indicates that the material undergoes more stable shear deformation during chip formation, which is beneficial for improving machining efficiency and reducing mechanical loading on the cutting tool.

Full annealing treatments (schemes III and IV) also contributed to the reduction of cutting force compared with untreated machining. The decrease in cutting resistance is mainly associated with the modification of the α/β phase morphology and improvement in microstructural homogeneity induced by annealing. A more uniform microstructure reduces local variations in deformation resistance, resulting in smoother material removal during cutting. Similarly, the double annealing treatment (scheme V) exhibited an intermediate reduction in cutting force. The multi-stage thermal cycle provides additional opportunities for phase redistribution and microstructural adjustment, allowing a more balanced combination of strength and deformation capability. However, compared with conventional annealing treatments, the reduction effect was relatively limited, indicating that excessive thermal processing does not necessarily provide additional advantages for reducing cutting resistance.

Solution treatments (schemes VI and VII) showed a reduction in cutting force of approximately 10.91% compared with the untreated condition. However, unlike annealing treatments, the cutting force curves under solution-treated conditions exhibited stronger fluctuations during machining. This phenomenon can be attributed to the microstructural strengthening effect caused by solution treatment. During solution treatment, the redistribution of alloying elements and possible formation of supersaturated phases increase material strength and hardness, resulting in higher local deformation resistance during cutting. Meanwhile, the heterogeneous deformation behavior caused by strengthened regions leads to unstable chip formation and periodic variations in cutting resistance, which explains the increased fluctuation amplitude of cutting force.

Among all investigated conditions, aging treatment (scheme VIII) achieved the most significant reduction in cutting force, with a maximum decrease of 43.09% compared with untreated machining. This substantial improvement is related to the precipitation strengthening mechanism induced during aging. The formation of finely distributed strengthening phases can modify the deformation behavior of the alloy by improving microstructural stability and reducing localized plastic instability. As a result, the cutting process requires less energy for material removal,

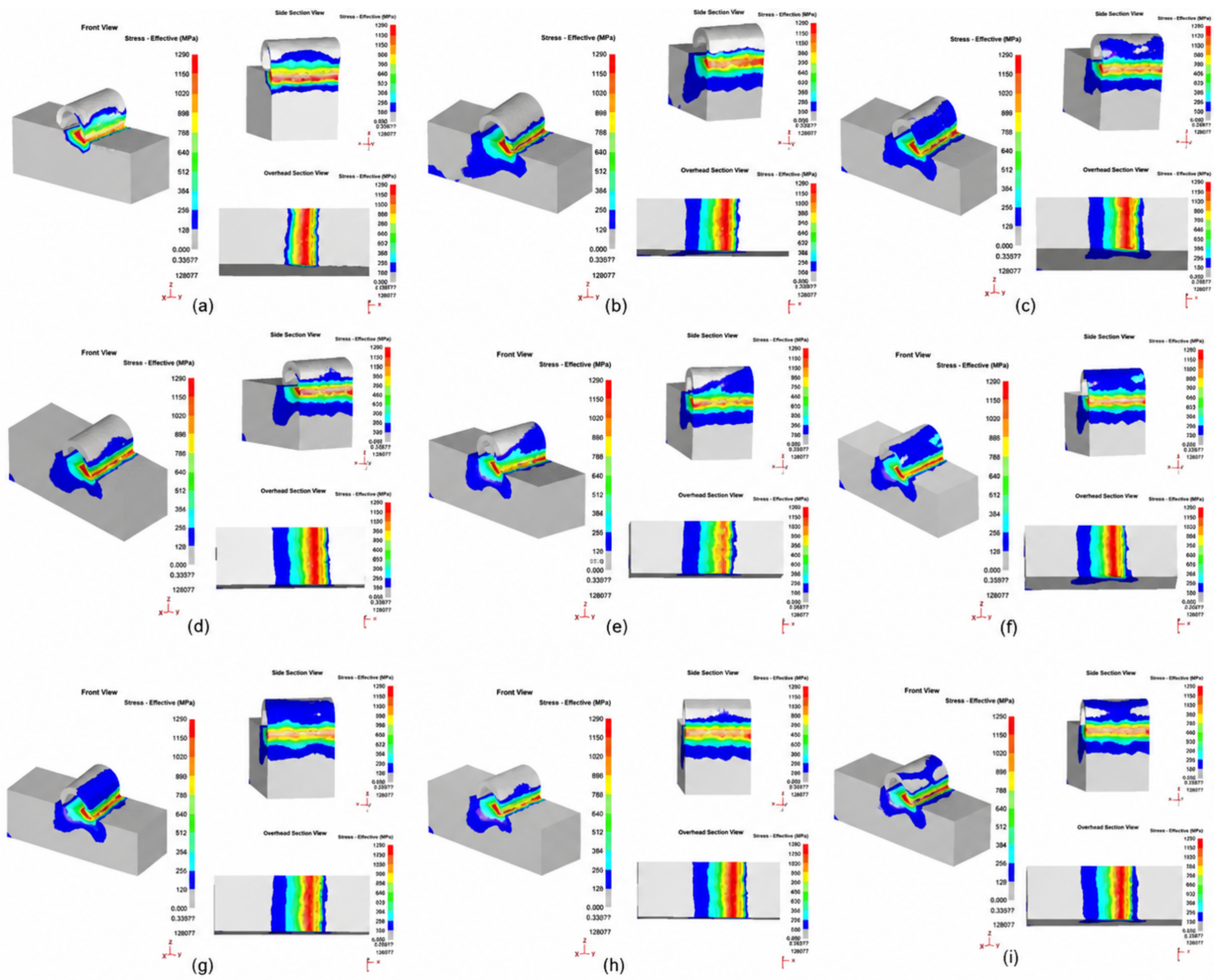

Figure 6. Equivalent stress distributions during machining of untreated and heat-treated Ti-6Al-4V alloy. (a) Untreated condition; (b–i) heat treatment schemes I–VIII.

leading to a significant reduction in cutting force. Nevertheless, the cutting force fluctuation under aging treatment remained higher than that observed after full annealing, indicating that the strengthening phases may introduce local differences in deformation behavior during cutting.

In addition to the average cutting force level, the fluctuation characteristics of cutting force provide important information regarding machining stability. As shown in Figure 5, the cutting force curves obtained after stress-relief annealing and full annealing treatments (schemes I–IV) exhibited relatively smooth variations with limited oscillation amplitude. This indicates that annealing treatments improve machining stability by reducing internal stress gradients and enhancing microstructural uniformity. In contrast, the solution-treated samples (schemes VI and VII) demonstrated more pronounced force fluctuations, suggesting unstable deformation behavior caused by increased hardness and heterogeneous strengthening effects. The cutting force variation of double annealing and aging treatments (schemes V and VIII) was located between annealing and solution treatment conditions. The optimized microstructure obtained through double annealing reduced deformation instability compared with solution treatment, while precipitation strengthening during aging provided relatively stable cutting behavior. However, their machining stability remained inferior to that achieved by conventional annealing treatments.

Overall, the results demonstrate that heat treatment significantly influences the cutting response of Ti-6Al-4V alloy by regulating material hardness, phase morphology, and internal stress distribution. Annealing-based treatments primarily improve machinability by relieving residual stresses and homogenizing the microstructure, resulting in reduced cutting force and improved machining stability. Solution treatment increases material strengthening effects, which may enhance mechanical performance but simultaneously introduces greater cutting resistance fluctuations. Aging and double annealing treatments provide moderate improvements by modifying strengthening mechanisms and microstructural characteristics.

The equivalent stress distributions of Ti-6Al-4V alloy after machining under untreated and different heat-treated conditions are presented in Figure 6. The stress field was extracted when the cutting distance reached 5 mm. As observed from the stress contour maps, the maximum equivalent stress was mainly concentrated in three characteristic regions: the tool–workpiece contact zone, the primary shear deformation zone associated with chip formation, and the subsurface region beneath the machined surface. The equivalent stress values under all conditions were within the range of 0–1680 MPa, indicating that severe plastic deformation occurred mainly in localized regions during the cutting process.

For stress-relief annealing and full annealing treatments (schemes I–IV, Figures 6 (b–e)), the high-stress concentration regions became narrower, and the area occupied by high equivalent stress was significantly reduced compared with untreated machining. This behavior can be attributed to the relaxation of residual stresses and improvement of microstructural uniformity after annealing. By reducing the initial internal stress state, the material exhibits a more coordinated deformation response during cutting, thereby preventing excessive stress accumulation in localized areas. The smoother stress distribution indicates that annealed materials can accommodate cutting-induced deformation more effectively.

After double annealing treatment (scheme V, Figure 6 (f)), the high-stress region exhibited further dispersion, accompanied by a smoother stress gradient. This indicates that the multi-step thermal treatment promotes a more uniform redistribution of internal stress and improves the stress transfer capability during cutting deformation. The reduction of localized stress concentration is beneficial for preventing surface damage and maintaining machining-induced surface integrity.

For solution-treated conditions (schemes VI and VII, Figures 6 (g) and (h)), the peak stress magnitude in the concentrated region decreased slightly compared with untreated machining; however, the distribution range of high stress showed limited variation. This suggests that although solution treatment modifies the internal structure and improves material strength, it does not completely eliminate stress localization during cutting. The strengthened microstructure may still resist plastic deformation, resulting in concentrated stress accumulation near the cutting zone.

In the aging-treated sample (scheme VIII, Figure 6 (i)), the stress distribution became more uniform compared with the untreated condition, and the stress concentration intensity decreased. The precipitation of strengthening phases during aging modifies the deformation mechanism and improves the stability of material response under cutting loads. Consequently, the stress field becomes more evenly distributed during machining.

Overall, the heat treatment processes regulate the cutting stress state of Ti-6Al-4V alloy by modifying microstructural characteristics and residual stress conditions. Among the investigated treatments, annealing processes demonstrate a pronounced capability for reducing stress concentration due to their effective stress relaxation and microstructural homogenization effects. These findings indicate that appropriate thermal treatment selection plays a crucial role in controlling machining-induced mechanical responses and improving the surface integrity of Ti-6Al-4V components.

3.3 Temperature Field Distribution Characteristics during Machining of Ti-6Al-4V Alloy after Different Heat Treatments

The temperature evolution during machining is a critical factor affecting cutting performance and surface integrity, particularly for Ti-6Al-4V alloy due to its low thermal conductivity and strong tendency for heat accumulation in the cutting zone. To evaluate the influence of different heat treatment conditions on the thermal behavior during machining, the maximum cutting temperature and temperature distribution at step 50 were extracted from the simulation results under untreated and eight heat-treated conditions, as shown in Figure 7. The corresponding temperature gradient contours are presented in Figure 8.

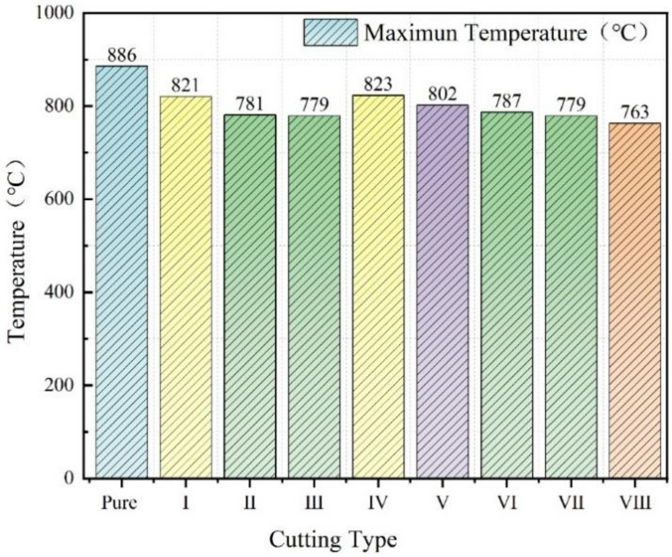

Figure 7. Maximum cutting temperature during machining of untreated and heat-treated Ti-6Al-4V alloy.

As illustrated in Figure 7, the untreated Ti-6Al-4V alloy exhibited the highest cutting temperature, reaching approximately 886 °C during the cutting process. In contrast, all heat-treated conditions demonstrated lower maximum cutting temperatures, indicating that thermal treatment effectively modified the heat generation and transfer characteristics during machining. The reduction in cutting temperature can be attributed to the combined effects of microstructural refinement, residual stress relaxation, and improved deformation behavior induced by heat treatment. During machining, cutting heat is mainly generated from plastic deformation within the primary shear zone and frictional interaction between the tool and workpiece interface. For untreated Ti-6Al-4V alloy, the heterogeneous microstructure and residual stress state increase the resistance to plastic deformation, resulting in higher mechanical energy consumption and conversion of cutting energy into thermal energy. Furthermore, the poor thermal conductivity of titanium alloys restricts rapid heat dissipation, causing significant heat accumulation in the cutting region. After heat treatment, the optimized microstructural characteristics reduce the local deformation resistance and improve the uniformity of material flow during chip formation. Therefore, less mechanical energy is converted into heat, leading to a decrease in the cutting temperature.

Among the investigated heat treatment conditions, annealing-based processes exhibited relatively significant temperature reduction effects. In particular, schemes II and III showed lower maximum cutting temperatures compared with other conditions. This behavior is mainly associated with the effective elimination of residual stresses and reduction in deformation resistance after annealing treatment. The stress-relieved and homogenized microstructure enables smoother plastic deformation during cutting, reducing energy dissipation caused by unstable deformation. Meanwhile, the improved machinability decreases the frictional interaction between the tool and workpiece, thereby reducing additional heat generation at the tool–chip interface.

The temperature field characteristics also reveal the influence of heat treatment on thermal distribution behavior. As shown in Figure 8, the temperature contours of heat-treated samples generally exhibit smoother color transitions compared with untreated machining, indicating a reduction in temperature gradients and a more uniform thermal distribution within the cutting region. The untreated condition (Figure 8 (a)) presents a concentrated high-temperature zone accompanied by steep temperature gradients. This phenomenon results from the non-uniform initial microstructure and insufficient heat transfer capability, causing localized heat accumulation during cutting. Such concentrated thermal loading may accelerate tool wear and increase the possibility of machining-induced surface damage.

For stress-relief annealing conditions (Figures 8 (b) and (c)), the temperature distribution becomes more homogeneous, and the high-temperature concentration area is reduced. The refined and stabilized microstructure after annealing improves the consistency of heat generation during plastic deformation, allowing cutting heat to spread more uniformly. In addition, the reduction of residual stress decreases the occurrence of localized deformation concentration, which contributes to a smoother thermal field. The double annealing treatment (Figure 8 (d)) further modifies the thermal distribution through multi-stage microstructural regulation. The combination of high-temperature and intermediate-temperature treatments promotes phase adjustment and structural homogenization, resulting in improved thermal transport behavior. Consequently, the accumulation of localized cutting heat is reduced, and the generated heat can be transferred away from the cutting zone more effectively.

For the remaining annealing-related and solution-treated conditions (schemes I–VII, Figures 8 (b–h)), the cutting heat distribution was generally more dispersed compared with the untreated

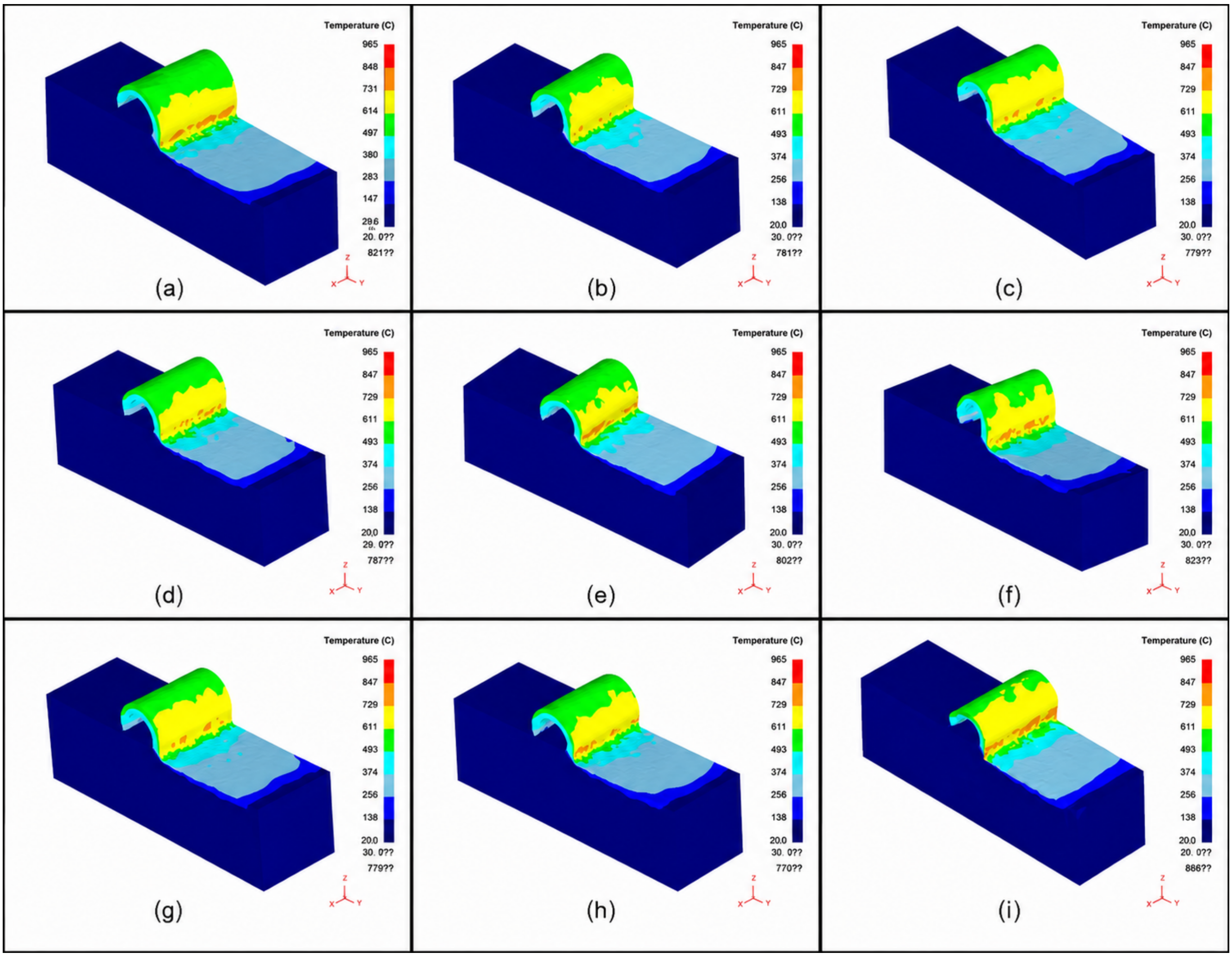

Figure 8. Temperature gradient distributions during machining under untreated and different heat treatment conditions. (a) Untreated condition; (b–i) heat treatment schemes I–VIII.

condition. The improved thermal response is related to the modification of grain structure and phase distribution after heat treatment. A more uniform microstructure provides more consistent pathways for heat transfer and reduces extreme temperature variations caused by localized deformation differences. Therefore, the cutting zone experiences reduced thermal concentration and improved temperature stability.

However, the aging-treated sample (scheme VIII, Figure 8 (i)) exhibited a different thermal distribution characteristic. A relatively continuous high-temperature band appeared near the cutting region, indicating localized heat accumulation. This phenomenon can be explained by the precipitation strengthening mechanism during aging treatment. The formation of strengthening precipitates increases the hardness and deformation resistance of the alloy, which may increase the mechanical energy required for material removal. Meanwhile, the heterogeneous distribution of precipitates and strengthened regions can influence local thermal conductivity, resulting in less efficient heat diffusion and the formation of localized high-temperature zones. Although aging treatment improves the mechanical strength of Ti-6Al-4V alloy, its influence on thermal behavior during machining requires careful consideration.

Overall, the temperature field analysis demonstrates that heat treatment significantly regulates the thermal response of Ti-6Al-4V alloy during precision machining. Annealing treatments effectively reduce cutting temperature by relieving residual stresses, refining microstructure, and improving deformation uniformity. Double annealing further enhances thermal stability through multi-stage structural optimization, while solution treatment modifies thermal behavior through phase transformation and strengthening effects. Aging treatment improves material strengthening but may cause localized thermal accumulation due to increased deformation resistance and non-uniform heat transfer. These findings indicate that selecting an appropriate heat treatment strategy is essential for controlling machining-induced thermal loads and improving the surface integrity of Ti-6Al-4V components.

3.4 Characteristics of Residual Stress Gradient Distribution in Ti-6Al-4V Alloy after Different Heat Treatments

Residual stress generated during machining plays a critical role in determining the surface integrity and long-term service performance of Ti-6Al-4V components. Excessive tensile residual stress near the machined surface can promote crack initiation, reduce fatigue resistance, and deteriorate the reliability of precision-manufactured parts. Therefore, understanding the influence of heat treatment on machining-induced residual stress distribution is essential for optimizing the manufacturing process of titanium alloys. The residual stress contour maps and corresponding stress distribution curves under untreated and different heat treatment conditions are presented in Figure 9. The residual stresses at three representative locations along the depth direction of the workpiece (P1, P2, and P3), located at a position of 5 mm × 1.5 mm after machining, were extracted to characterize the stress gradient evolution from the machined surface to the internal region. The selected points represent different depths beneath the machined surface and provide an effective evaluation of the influence of heat treatment on near-surface stress redistribution.

As shown in Figure 9, a clear gradient distribution of residual stress was observed in all machining conditions. The residual stress magnitude at the surface point (P1) was generally higher than those at the subsurface points (P2 and P3), indicating that the machining process mainly affects the near-surface region. This phenomenon is associated with the severe thermo-mechanical coupling effects generated during cutting. The intense plastic deformation, frictional heat generation, and rapid cooling process near the tool–workpiece interface introduce significant stress accumulation in the surface layer. In contrast, the internal regions experience weaker deformation and thermal influence, resulting in relatively lower residual stress levels.

For the untreated cutting condition (Figure 9 (a)), the residual stress exhibited a rapid attenuation trend with increasing depth. A pronounced stress concentration appeared near the machined surface, and the stress gradient reached approximately 150–200 MPa/μm within the first 100 μm depth region. The steep stress gradient indicates a strong mismatch between the highly deformed surface layer and the relatively stable internal material. Such non-uniform stress distribution can lead to unstable mechanical behavior and increase the risk of surface damage during subsequent service conditions.

After applying different heat treatment processes (Figures 9 (b–i)), the residual stress gradients were significantly reduced compared with the untreated condition. This improvement can be attributed to the combined effects of residual stress relaxation, microstructural homogenization, and modification of deformation resistance caused by thermal treatment. Heat treatment reduces the initial internal stress state before machining, allowing the material to accommodate cutting-induced deformation more uniformly. Consequently, the difference between surface and subsurface stress levels becomes smaller, resulting in a smoother residual stress transition.

Among the investigated heat treatment conditions, annealing-based processes demonstrated significant effectiveness in reducing machining-induced residual stresses. Stress-relief annealing treatments (schemes I and II, Figures 9 (b) and (c)) substantially decreased the tensile residual stress at the machined surface, with reductions of approximately 60–80% compared with untreated machining. This behavior is mainly related to the recovery effect during annealing, where lattice distortion and dislocation accumulation caused by previous processing are partially eliminated. The reduction in initial residual stress decreases the driving force for additional stress accumulation during cutting, resulting in a more uniform stress distribution.

Full annealing treatments (schemes III and IV, Figures 9 (d) and (e)) further improved residual stress characteristics by promoting recrystallization and microstructural homogenization. The refined and more uniform grain structure reduces localized deformation differences during cutting, thereby decreasing stress concentration near the machined surface. Compared with stress-relief annealing, full annealing provides additional benefits through microstructural adjustment, leading to improved stress relaxation capability.

The double annealing treatment (scheme V, Figure 9 (f)) exhibited the most pronounced reduction in

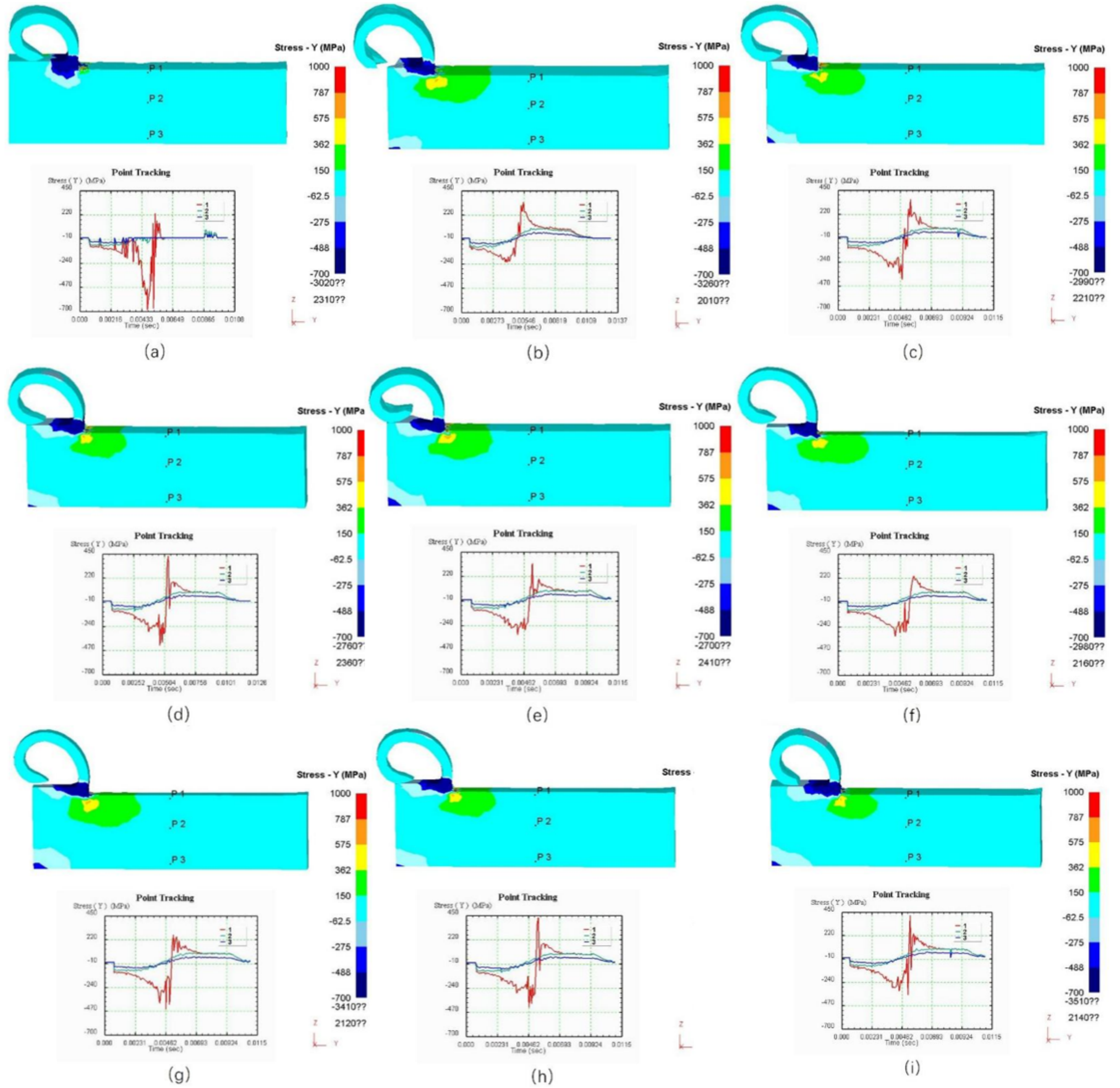

Figure 9. Residual stress contour maps and residual stress distribution curves under untreated and different heat treatment machining conditions. (a) Untreated cutting condition; (b–i) heat treatment schemes I–VIII.

residual stress gradient among all investigated conditions. The stress gradient decreased to approximately 50–80 MPa/μm, indicating a much smoother transition between surface and internal stress states. This improvement can be explained by the synergistic effect of the multi-stage thermal treatment. During the first high-temperature stage, accumulated internal stresses and unstable microstructural features are effectively reduced. Subsequently, the intermediate-temperature treatment further optimizes grain morphology and phase distribution, resulting in enhanced stress accommodation ability during machining. Therefore, double annealing provides a more balanced approach for reducing both residual stress magnitude and gradient distribution.

For solution-treated samples (schemes VI and VII, Figures 9 (g) and (h)), the reduction in surface residual stress was relatively limited, approximately 30% compared with untreated machining. However, the internal stress distribution became more uniform, suggesting that solution treatment mainly influences stress redistribution rather than directly eliminating surface tensile stress. The formation of a modified phase structure and more homogeneous elemental distribution after solution treatment improves the consistency of deformation behavior, reducing internal stress fluctuations.

The aging-treated condition (scheme VIII, Figure 9 (i)) exhibited an intermediate residual stress state between annealed and untreated conditions. Although aging treatment improved the mechanical stability of the alloy through precipitation strengthening, the strengthened microstructure increased resistance to plastic deformation during machining. As a result, localized stress concentration remained near the machined surface. The precipitation phases may also contribute to heterogeneous deformation behavior, preventing complete elimination of machining-induced residual stress.

Overall, the residual stress analysis demonstrates that heat treatment plays a crucial role in controlling machining-induced stress accumulation and gradient distribution in Ti-6Al-4V alloy. Increasing heat treatment intensity and applying more complex thermal processes generally promote stress relaxation and improve stress uniformity. Annealing treatments effectively reduce surface tensile residual stress through recovery and recrystallization mechanisms, while double annealing achieves the most significant improvement due to sequential microstructural optimization. Solution treatment mainly enhances stress redistribution, whereas aging treatment provides a compromise between strengthening and stress control. These results highlight the importance of selecting appropriate heat treatment strategies for minimizing residual stress gradients and improving the surface integrity of precision-machined Ti-6Al-4V components.

4 Conclusions

(1) Heat treatment significantly modifies the microstructural characteristics of Ti-6Al-4V alloy, thereby affecting its machining response. Annealing treatments promote recrystallization, grain refinement, and residual stress relaxation, resulting in improved microstructural homogeneity. Solution and aging treatments mainly regulate mechanical behavior through phase transformation and precipitation strengthening, respectively.

(2) The machining performance of Ti-6Al-4V alloy is strongly dependent on the selected heat treatment strategy. Annealing treatments effectively reduce cutting force, temperature accumulation, and stress concentration, while aging treatment achieves the largest reduction in cutting force due to precipitation strengthening. However, solution treatment increases deformation resistance and leads to greater cutting force fluctuations.

(3) Heat treatment provides an effective approach for controlling machining-induced surface integrity degradation. The optimized thermal treatments reduce temperature gradients and residual stress accumulation by improving material deformation uniformity and stress redistribution. Among the investigated conditions, double annealing exhibits superior capability in minimizing residual stress gradients and enhancing machining stability.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported in part by the National Natural Science Foundation of China under Grant 51705270 and Grant 51575289; in part by the Natural Science Foundation of Guangdong Province under Grant 2023A1515030171; in part by the Science and Technology Project of Zhanjiang City, Guangdong Province under Grant 2022A01004; in part by the Natural Science Foundation of Shandong Province under Grant ZR2016EEP03; in part by the Applied Basic Research Program of Qingdao City under Grant 19-6-2-69-cg; in part by Shandong Qingchuang Science and Technology Project under Grant 2019KJB022.

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.

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