

Article

Effect of Different Cooling Strategies on Surface Topography, Microstructure and Residual Stress of Turned γ -TiAl Alloy

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Abstract

This study investigates the surface integrity of γ -TiAl alloy during turning under different cooling strategies and reveals the regulation mechanisms of cooling conditions on surface morphology, plastic deformation, microstructure, and residual stress. Turning experiments were conducted under conventional cooling and high-pressure cooling conditions at different cutting speeds, combined with wavelet-based three-dimensional surface morphology analysis, scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), and residual stress measurements. The results show that high-pressure cooling reduces the fluctuation of both high- and low-frequency surface morphology components, particularly suppressing low-frequency profile variations, thereby improving machining stability and surface consistency. Plastic deformation layers are formed under both cooling conditions and increase with cutting speed; however, high-pressure cooling reduces deformation depth and alleviates lamellar bending and deflection. EBSD analysis reveals that machining-induced microstructural characteristics is mainly characterized by grain rotation, crystallographic orientation adjustment, and deformation-induced texture formation, without obvious dynamic recrystallization features. Compared with conventional cooling, high-pressure cooling maintains higher crystal integrity and suppresses excessive microstructural reconstruction. Residual stress results demonstrate that compressive residual stresses are generated under both cooling strategies, while high-pressure cooling produces higher compressive residual stress and a more stable stress distribution. These findings indicate that cooling strategies regulate surface integrity by modifying tool–workpiece interfacial interactions and mechanical load transfer behavior. High-pressure cooling improves interfacial lubrication, reduces friction-induced disturbance, and promotes more coordinated plastic deformation, resulting in reduced surface morphology fluctuation, suppressed microstructural damage, and enhanced compressive residual stress. This work provides theoretical guidance for precision machining of γ -TiAl alloy and other high-value difficult-to-machine materials.

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conditions of the [Creative Commons](#)[Attribution \(CC BY\)](#) license.**Keywords:** γ -TiAl alloy; turning; high pressure cooling; surface morphology; microstructure; plastic deformation; residual stress

1. Introduction

γ -TiAl alloys are characterized by their low density, high specific strength, excellent oxidation resistance, and stable mechanical properties at elevated temperatures, making them promising candidates for critical hot-section components in aero-engines, such as low-pressure turbine blades and turbocharger turbines [1–3]. However, owing to their high strength, low ductility, and low fracture toughness, γ -TiAl alloys are inherently brittle at room temperature, leading to several machining difficulties, including excessive cutting temperatures, severe tool wear, and poor machined-surface integrity [4,5]. Surface integrity directly affects the fatigue life, resistance to crack propagation, and service performance of machined components. Therefore, developing high-performance machining strategies for γ -TiAl alloys and improving the quality of machined surfaces are of great significance for achieving high-quality manufacturing and enhancing the service performance of γ -TiAl components [6–8].

Surface integrity generally encompasses surface morphology, subsurface plastic deformation, microstructural evolution, and residual stress, and is therefore considered an important indicator for evaluating machining quality. With respect to surface morphology, previous studies have demonstrated that cutting parameters have a direct influence on the geometric characteristics of machined surfaces. Wang et al. [9] systematically investigated the evolution of the machined surface of γ -TiAl alloys through milling experiments and reported that cutting parameters significantly affected the surface condition. Zhou et al. [10] further demonstrated that cutting speed was the most influential cutting parameter affecting the surface condition during milling. Shi et al. [11] reported from grinding experiments that reducing the grinding speed and increasing the feed rate could improve the surface condition and reduce the formation of undesirable surface defects. Cutting parameters also have a direct influence on subsurface plastic deformation. Zhang et al. [12] observed fibrous plastic deformation along the cutting direction through cutting experiments. Yao et al. [13] investigated the turning of γ -TiAl alloys and found that the depth of the plastic deformation layer increased directly with increasing cutting speed and depth of cut. Cutting parameters also play an important role in microstructural evolution. Chen et al. [14] demonstrated through experiments on polycrystalline iron that ultrahigh-speed machining significantly affected microstructural evolution. Klocke et al. [15] further compared the effects of conventional flood cooling and high-pressure cooling on the surface integrity of machined γ -TiAl alloys. Their results indicated that high-pressure cooling significantly reduced microstructural alterations compared with conventional flood cooling. Regarding residual stress, previous studies have generally recognized cutting parameters and thermo-mechanical coupling as key factors governing the distribution characteristics of residual stresses in machined surfaces. Ulutan et al. [16] systematically reviewed the formation mechanisms of residual stresses during titanium alloy machining and pointed out that cutting speed and feed rate jointly determine the nature of surface residual stresses (tensile or compressive) by altering the degree of plastic deformation and the temperature field. Wang et al. [17] experimentally investigated residual stresses generated during the ultrasonic vibration side milling of Ti-6Al-4V alloy under dry high-speed conditions and found that, compared with conventional milling, ultrasonic vibration side milling increases the residual compressive stress by up to 79%, whereas higher cutting parameters (increased cutting speed and feed rate) lead to lower residual compressive stresses. Yi et al. [18] experimentally investigated residual stresses induced by milling of aerospace aluminum alloys and revealed the effects of milling parameters on residual stress evolution. These studies indicate that the surface integrity of machined γ -TiAl alloys exhibits pronounced multiscale characteristics and that its formation is governed by the coupled effects of thermal and mechanical loads.

In response to the difficult-to-machine characteristics of γ -TiAl alloys, various cooling and lubrication strategies have been investigated by researchers worldwide. Dahlman et al. [19] investigated the application of ultra-high-pressure cooling to the turning of near-net-shape components made of decarburized steel. Compared with dry cutting, ultra-high-pressure cooling reduced the surface roughness by approximately 80%, suppressed surface defects, and improved the overall surface quality. Benedicto et al. [20] compared the effects of several green cooling and lubrication strategies during the turning of γ -TiAl alloys and found that improving heat transfer conditions in the cutting zone was beneficial for reducing the degree of surface damage. Wu et al. [21] reported from cutting experiments on GH4169 that high-pressure cooling reduced subsurface plastic deformation and grain refinement, while the residual tensile stress on the machined surface decreased significantly with increasing cooling pressure. Shi et al. [22] combined numerical simulations and experimental investigations to demonstrate that advanced cooling and lubrication technologies could improve the temperature-field distribution in the cutting zone and mitigate thermal damage. Fan et al. [23] compared supercritical CO₂ minimum quantity lubrication with dry cutting and found that minimum quantity lubrication effectively improved surface morphology and suppressed subsurface damage. Meanwhile, advanced manufacturing technologies, including energy-field-assisted machining, cryogenic machining, and laser-assisted machining, have also been demonstrated to improve the machinability of γ -TiAl alloys and enhance surface integrity.

Although these studies have established the potential of advanced cooling and lubrication strategies for improving machining performance, several aspects remain insufficiently clarified. First, previous studies have generally focused on specific surface or subsurface responses, and the relationships among surface topography, machining-induced plastic deformation, microstructural evolution, and residual stress under different cooling strategies have not been systematically established for γ -TiAl turning. Second, although the effects of high-pressure cooling on the overall surface condition and microstructural response of γ -TiAl have been investigated [15], the influence of cooling strategy on surface morphology at different spatial scales remains insufficiently understood. Third, the relationship between cooling strategy, subsurface plastic deformation, crystallographic response, and residual stress evolution under different cutting speeds has not been comprehensively compared for γ -TiAl alloys. Therefore, further systematic experimental investigation is required to establish how different cooling strategies affect the multiscale surface and subsurface responses of γ -TiAl during turning.

In this study, turning experiments were conducted to systematically compare the effects of conventional cooling and high-pressure cooling on the machined γ -TiAl alloy at different cutting speeds. The surface topography, subsurface plastic deformation, microstructural characteristics, and residual stress were characterized and compared, with particular attention to the multiscale characteristics of surface morphology and their responses to different cooling strategies. Based on the experimental results and relevant literature, the possible mechanisms responsible for the observed differences are discussed. The findings provide further insight into the effects of cooling strategies on the surface and subsurface responses of γ -TiAl during turning and provide a basis for improving its machining quality.

2. Experimental Design

2.1. Experimental Procedure

The workpiece material used in this study was a second-generation γ -TiAl alloy with a nominal composition of Ti-48Al-2Cr-2Nb, as listed in Table 1. The workpiece was a cylindrical bar with dimensions of Φ 42 mm $\times$ 196 mm. γ -TiAl alloys exhibit good mechanical properties at elevated temperatures. The mechanical property data of the investigated

alloy were provided by the Northwest Institute for Nonferrous Metal Research, and the relevant parameters are listed in Table 2.

Table 1. Composition of γ -TiAl Alloy (Mass Fraction, %).

Al	Cr	Nb	C	H	N	O	Ti
32.6	2.55	4.69	<0.004	0.007	0.004	0.054	The rest

Table 2. Mechanical properties of γ -TiAl Alloy.

Main Performance Indicators	γ -TiAl Alloy
Density (g/cm ³)	3.8
Ductility (%)	2
Thermal conductivity (W/(m·K))	8.6
Young's modulus (GPa)	170
Yield strength (MPa)	525
Tensile strength (MPa)	625
Creep limit (MPa)	1000

The turning experiments were designed to investigate the effects of cutting speed and cooling strategy, including conventional cooling and high-pressure cooling, on the surface integrity of machined γ -TiAl alloy. According to previous studies on high-pressure cooling by Klocke et al. [15], Benedicto et al. [20], and Wu et al. [21], a cutting-fluid pressure of ≥ 7 MPa is generally considered to represent high-pressure cooling. Therefore, a cooling pressure of 7 MPa was employed in the present study to ensure that the cutting fluid could effectively penetrate the tool–chip contact zone. The parameters of the cooling and lubrication system are listed in Table 3. A TRIM E206 soluble cutting-fluid concentrate manufactured by Master Chemical Corporation (Perrysburg, OH, USA) was diluted with water to a concentration of 5–7%. The detailed cutting parameters are listed in Table 4. It should be noted that, in this study, conventional cooling and high-pressure cooling differ not only in coolant supply pressure but also in other supply parameters such as coolant flow rate, nozzle number, and nozzle diameter. Therefore, this study compares the comprehensive effects of the two complete cooling systems on the machined surface integrity of γ -TiAl alloy, rather than examining the independent role of cooling pressure as a single factor. The effects of high-pressure cooling mentioned hereafter refer to the combined effects arising from the overall coolant supply conditions of the high-pressure cooling system as shown in Table 3. The individual contributions of the different supply parameters remain to be distinguished through further single-factor controlled experiments.

Table 3. Cooling and lubrication system parameters.

Parameter	Conventional Cooling	High-Pressure Cooling
Cutting fluid type	TRIM E206	TRIM E206
Concentration	5%~7%	5%~7%
Coolant temperature	20 °C	20 °C
Cooling pressure	0.25 MPa	7 MPa
Flow rate	13 L/min	68 L/min
Number of nozzles	2	3
Nozzle diameter	2.5 mm	1.3 mm
Spray angle	Approx. 45 °	Approx. 45 °
Nozzle distance from cutting zone	1.1 cm	1.1 cm

Table 4. Experimental parameters.

Cooling Strategies	Cutting Speed v_c (m/min)	Feed f (mm/r)	Depth of Cut a_p (mm)
Conventional cooling	30, 50, 70	0.08	0.25
High-pressure cooling	30, 50, 70	0.08	0.25

The turning experiments were conducted on a GLS-2000 LY CNC lathe manufactured by Goodway Machine Co., Ltd. (Wujiang, China), as shown in Figure 1a. The high-pressure cooling system integrated into the machine tool is shown in Figure 1b. A high-pressure coolant external turning toolholder (PCLNR 2525X-12X-JHP-MC, ISCAR) equipped with a CNMG120408-NMS coated carbide insert (Walter AG, Tübingen, Germany) was used, as shown in Figure 1c,d. The insert has an 80° rhombic negative geometry, an inscribed circle diameter of 12.7 mm, a thickness of 4.76 mm, a nose radius of 0.8 mm, and a nominal clearance angle of 0°. The NMS geometry features a sharp cutting-edge design, with a rake-face geometry of approximately 18° in the main cutting-edge region. The toolholder was mounted in a right-hand configuration with an approach angle of 95°, an axial rake angle of −6°, and a radial rake angle of −6°, and had a shank cross-section of 25 mm × 25 mm. The same tool orientation and geometric setup were maintained for all machining tests to minimize the influence of tool mounting variations.

Specifically, the axial cutting length for each cutting condition was approximately 20 mm, and each experimental condition was completed using a single cutting pass. Since the present study involved an external turning operation, the radial engagement corresponds to the radial depth of cut, which was maintained at $a_p = 0.25$ mm for all tests. The feed rate was fixed at 0.08 mm/rev. Before the formal experiments, the workpiece surface was pre-turned to remove the original surface layer and previous machining marks, thereby providing a consistent initial surface condition for all tests.

To minimize the influence of accumulated tool wear on the comparison between cooling strategies, a fresh cutting edge was used for each cutting condition. The cutting edge and flank face were inspected after each test using an optical microscope. The maximum flank wear width (VBmax) was used as the tool-wear indicator. If obvious edge chipping or a VBmax value exceeding approximately 0.10 mm was observed, the cutting edge was replaced and the corresponding test was repeated. Therefore, no cutting edge with accumulated wear from a previous cutting condition was reused in the subsequent condition.

In this study, a nose radius of 0.8 mm and a depth of cut of 0.25 mm were used. This combination of parameters was selected based on the tool manufacturer's recommended range and is intended to simulate finishing conditions for γ -TiAl alloy. It should be noted that under a small depth of cut, the nose radius region plays an important role in material removal and the formation of the machined surface. Consequently, the surface morphology features obtained in this work are closely associated with the tool geometry employed, and the related findings are primarily applicable to the ranges of tool geometry and cutting parameters examined in this study.

To ensure experimental reproducibility, each machining condition was independently repeated three times under the same nominal cutting parameters and cooling conditions. Multiple measurement locations were selected from each machined specimen where appropriate to account for local spatial variations.

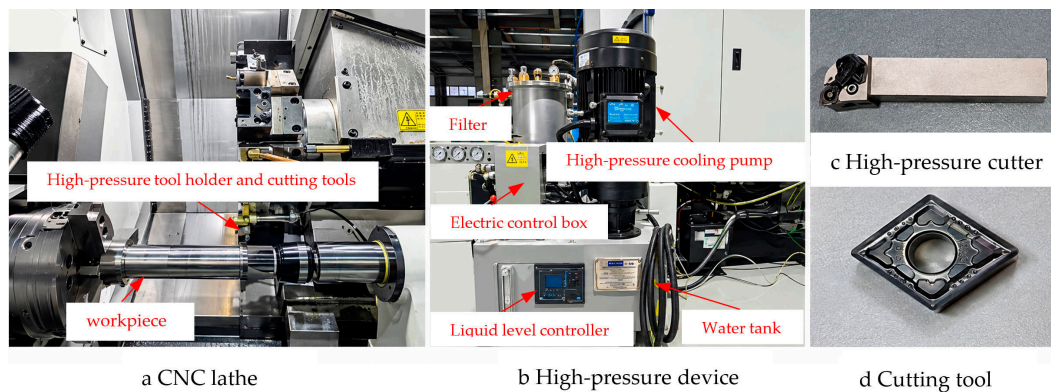


Figure 1. Turning experimental platform.

2.2. Characterization Methods

After each turning test, the machined specimens were characterized in terms of surface topography, subsurface deformation and microstructural characteristics, and residual stress. For cross-sectional characterization, the specimens were sectioned perpendicular to the machined surface using wire electrical discharge machining (WEDM, Seibu M50B, Seibu Electric & Machinery Co., Ltd., Koga, Fukuoka, Japan). The WEDM was operated with a peak current of 2.2 A and a wire feed speed of 0.08 m/s, using deionized water as the working fluid. To minimize the potential influence of WEDM-induced thermal effects, a surface layer of at least 6 μm was subsequently removed by sequential grinding and polishing before SEM and EBSD observations. For surface topography and residual stress measurements, the analyzed regions were located at least 3 mm away from the WEDM-cut edges.

The surface topography was measured using a white-light interferometer (ZYGO ZEGAGE PRO HR, ZYGO, Minato City, Tokyo). For each cutting condition, all three independently machined specimens were characterized, with a measurement area of 0.8×0.8 mm selected on each specimen. The resulting three-dimensional surface-height data were used for subsequent multiscale analysis based on wavelet decomposition. The measured surface topography contains the combined contributions of surface roughness, waviness, and form-related variations. Therefore, the wavelet scales were used to distinguish surface features with different spatial-frequency characteristics rather than being directly equated with the conventional roughness and waviness separation based on a standardized cutoff wavelength.

The cross-sectional microstructure was examined using a field-emission scanning electron microscope (Zeiss Gemini 300, Zeiss, Oberkochen, Germany) equipped with an Oxford Symmetry EBSD detector. EBSD measurements were performed at an accelerating voltage of 20 kV, a working distance of 14.5 mm, a specimen tilt angle of 70° , and a step size of 0.12 μm . The scanned area was 75.84×56.88 μm . EBSD data were processed using AZtecCrystal software (version 2.1). Grain boundaries were identified using a minimum misorientation angle of 5° , with a minimum grain size of 0.6 μm . Wild Spike correction and the Zero Solutions function were applied during data processing to improve the reliability of the indexed orientations. The EBSD analysis was conducted only at a cutting speed of 50 m/min; therefore, the resulting grain orientation, grain boundary, and misorientation characteristics are representative only of the investigated regions at this cutting speed and are not directly generalized to the 30 and 70 m/min conditions.

Surface residual stresses were measured using a Bruker D8 Advance residual stress analyzer (Bruker Corporation, Billerica, MA, USA), with the measurement parameters listed in Table 5. Residual stress analysis was conducted using the X-ray diffraction (XRD)

method. By integrating the surface morphology characterized using white-light interferometry, wavelet frequency-band characteristics, subsurface plastic deformation, EBSD-based microstructural characteristics, and residual stress measurements, the effects of different cooling strategies on the surface integrity of γ -TiAl alloy were systematically evaluated. For each cutting condition, one representative specimen was selected from the three independently machined specimens for residual stress measurement.

Table 5. Basic parameters for X-ray stress measurement.

Target	Bragg Angle	Wave-length	Diffraction Plane	Technique Time	X-Ray Tube Voltage	Electric Current
Cu-K α	139.2°	0.154 nm	220	2 s	40 KV	4.0 mA

Because the high-pressure cutting fluid was directly delivered to the tool–chip contact region in the form of a continuous high-velocity jet, it obstructed direct access to the cutting zone. In addition, the high-speed flow of chips, splashing of the cutting fluid, and limited space around the tool–workpiece contact region made it difficult for an infrared thermometer to accurately measure the actual temperature at the tool–chip interface. Contact-based temperature measurement methods, such as thermocouples, were also difficult to implement in the cutting zone without interfering with the machining process. Therefore, cutting temperature measurements were not performed in the present study. Instead, the effects of different cooling strategies on the surface integrity of γ -TiAl alloy were comprehensively evaluated based on the experimental results of surface morphology, subsurface microstructure, grain deformation characterized by EBSD, and residual stress.

3. Results and Discussion

3.1. Analysis of Surface Morphology Under Different Cooling Strategies

3.1.1. Wavelet Decomposition and Multiscale Surface Morphology Characteristics

The three-dimensional surface morphology signal generated during machining exhibits pronounced non-stationarity, multiscale superposition, and local abrupt variations. Conventional Fast Fourier Transform (FFT) analysis can provide the overall frequency distribution of a signal, but struggles to simultaneously characterize the spatial localization of different frequency components. In contrast, wavelet transform provides multiscale analysis and localized time–frequency characterization, making it more suitable for extracting the non-stationary morphological characteristics of machined surfaces [24].

The number of wavelet decomposition levels has a significant influence on the extraction of three-dimensional surface roughness. The maximum decomposition level of the wavelet transform is $j = [\log_2 n]$, while the number of sampling points obtained by the white-light interferometer in this study is $n \times n = 1000 \times 1000$. Based on the surface morphology data acquired by white-light interferometry, the reconstruction results at different decomposition levels were compared. When the decomposition level reached the 10th level, the reconstructed result tended to become stable and exhibited limited additional spatial variation in the surface morphology, indicating that the information content had approached saturation. Therefore, to ensure sufficient and effective representation of multiscale morphological information, nine decomposition levels were ultimately selected. Furthermore, the reconstruction errors of the Daubechies (db2–db10), Symlets (sym2–sym10), and Coiflets (coif1–coif5) wavelet families were compared, as presented in Table 6. The Sym9 wavelet exhibited the smallest root mean square error (RMSE); therefore, Sym9 was selected as the wavelet basis function for the decomposition and reconstruction of the three-dimensional machined surface morphology.

Based on the spatial-frequency characteristics of the wavelet decomposition, wavelet scales 1–3 were combined to reconstruct the high-frequency surface component, whereas scales 4–8 were combined to reconstruct the low-frequency surface component. The reconstructed components were defined as

$$Z_H(x, y) = \sum_{k=1}^3 D_k(x, y) \quad (1)$$

and

$$Z_L(x, y) = \sum_{k=4}^8 D_k(x, y) \quad (2)$$

respectively, where $D_k(x, y)$ denotes the detail component at wavelet scale k .

The Sa value of each reconstructed surface was calculated as

$$Sa = \frac{1}{MN} \sum_{m=1}^M \sum_{n=1}^N |z(m, n) - \bar{z}| \quad (3)$$

where z_{mn} is the reconstructed surface height at the sampling point (m, n) , $\bar{z}$ is the mean height of the corresponding reconstructed surface, and M and N are the numbers of sampling points in the two lateral directions.

The measured surface area was $0.8 \times 0.8 \text{ mm}^2$ with 1000×1000 sampling points, corresponding to a lateral sampling interval of approximately $0.8 \text{ }\mu\text{m}$. For the dyadic wavelet decomposition, the characteristic wavelength range of wavelet scale k can be approximately expressed as

$$2^k \Delta x \leq \lambda \leq 2^{k+1} \Delta x \quad (4)$$

Therefore, scales 1–3 approximately correspond to spatial wavelengths of $1.6\text{--}12.8 \text{ }\mu\text{m}$, whereas scale 4 begins at approximately $12.8 \text{ }\mu\text{m}$. The boundary between scales 3 and 4 can thus be regarded as an approximate equivalent cutoff wavelength. The high-frequency reconstructed component mainly characterizes short-wavelength surface irregularities, while scales 4–8 represent progressively longer-wavelength surface features. It should be noted that this wavelet-based separation is not strictly equivalent to Gaussian filtering because of the different frequency-response characteristics of the two methods.

To evaluate the reconstruction capability of different wavelet basis functions for the original surface topography, the root mean square error (RMSE) was employed to quantify the reconstruction accuracy. The RMSE was defined as the root mean square difference between the original surface topography measured by white-light interferometry and the corresponding surface reconstructed after wavelet decomposition and complete inverse wavelet reconstruction:

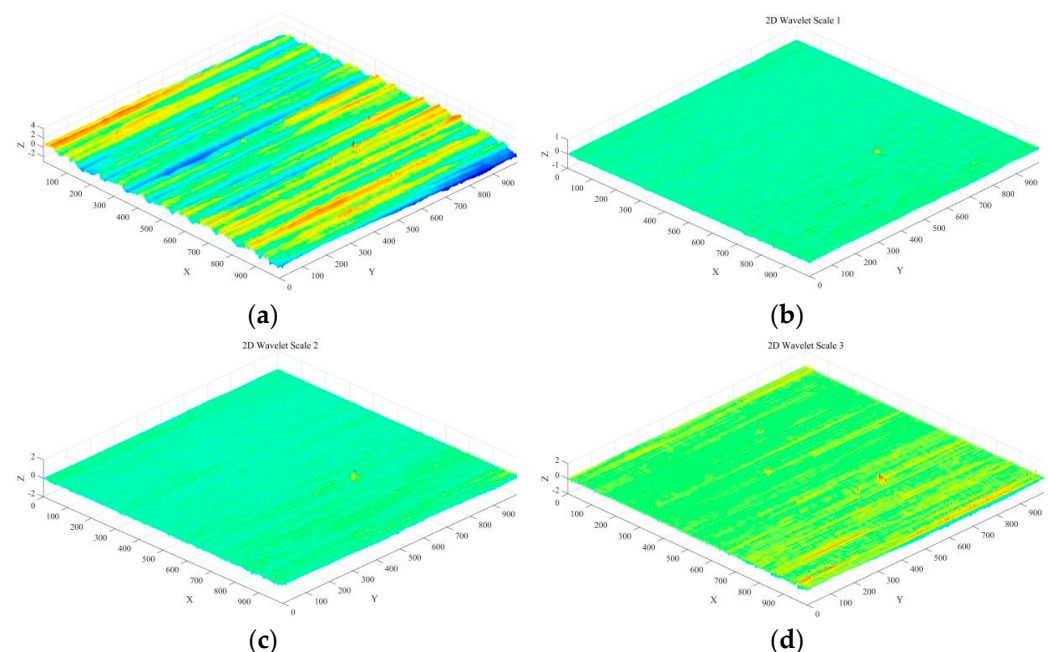
$$RMSE = \sqrt{\frac{1}{MN} \sum_{i=1}^M \sum_{j=1}^N [z(i, j) - \hat{z}(i, j)]^2} \quad (5)$$

where $z(i, j)$ is the original surface-height value at the sampling point (i, j) , $\hat{z}(i, j)$ is the corresponding reconstructed surface-height value, and (M) and (N) are the numbers of sampling points in the two spatial directions, respectively. In this study, $(M = N = 1000)$. All wavelet coefficients were retained during the reconstruction used for RMSE calculation; therefore, the RMSE represents the numerical reconstruction fidelity of each wavelet basis rather than the difference between the high- and low-frequency surface components. A lower RMSE indicates a higher degree of agreement between the reconstructed and original surfaces. The reconstruction errors of the Daubechies (db2–db10), Symlets (sym2–sym10), and Coiflets (coif1–coif5) wavelet bases were compared, as listed in Table 6. Among the tested wavelet bases, sym9 exhibited the smallest RMSE and was therefore selected as the wavelet basis for subsequent decomposition and reconstruction of the three-dimensional surface topography.

Table 6. Reconstruction errors of turning surfaces using different wavelet bases.

Wavelet Basis	Reconstruction Error	Wavelet Basis	Reconstruction Error	Wavelet Basis	Reconstruction Error
db2	9.16×10^{-13}	db10	5.26×10^{-12}	sym9	7.19×10^{-15}
db3	1.06×10^{-11}	sym2	9.16×10^{-13}	sym10	1.77×10^{-14}
db4	1.97×10^{-12}	sym3	1.06×10^{-11}	coif1	1.34×10^{-12}
db5	2.96×10^{-12}	sym4	6.95×10^{-13}	coif2	1.71×10^{-11}
db6	1.38×10^{-12}	sym5	2.37×10^{-13}	coif3	7.25×10^{-13}
db7	2.28×10^{-12}	sym6	1.11×10^{-12}	coif4	2.62×10^{-11}
db8	4.94×10^{-12}	sym7	8.59×10^{-13}	coif5	4.53×10^{-9}
db9	4.24×10^{-11}	sym8	2.65×10^{-13}		

The “Original 3D topography” in Figure 2 represents the directly measured surface topography obtained by white-light interferometry and contains the combined contributions of roughness, waviness, and form-related variations. The morphological signals at Scales 1–3 are dominated by small-amplitude and densely distributed microscopic fluctuations. Their variations are mainly concentrated around zero and exhibit typical high-frequency random characteristics. These components may be associated with local disturbances during cutting, such as machine-tool vibration, microscopic tool runout, and local material detachment [25]. In contrast, Scales 4–8 exhibit distinct periodic peaks and valleys and correspond to low-frequency profile components. These components are closely associated with the tool motion trajectory and the stability of the cutting process and constitute the major contribution to the waviness of the machined surface [25]. The reconstructed signal at Scale 9 becomes relatively smooth, with the overall morphology approaching a reference plane; therefore, it can be regarded as the reference morphological layer of the machined surface.



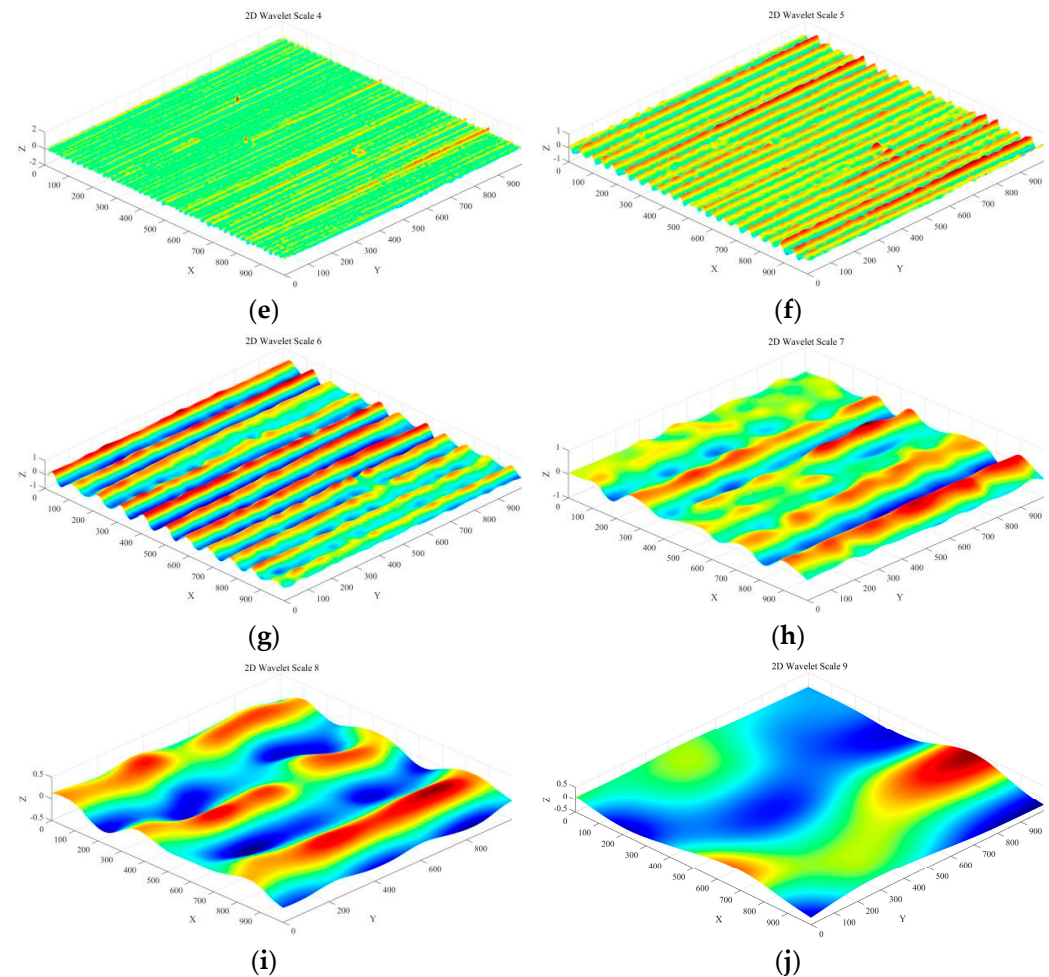


Figure 2. 3D surface morphologies at different scales using sym9 wavelet basis. (a) Original 3D topography. (b) First-level wavelet decomposition 3D topography. (c) Second-level wavelet decomposition 3D topography. (d) Third-level wavelet decomposition 3D topography. (e) Fourth-level wavelet decomposition 3D topography. (f) Fifth-level wavelet decomposition 3D topography. (g) Sixth-level wavelet decomposition 3D topography. (h) Seventh-level wavelet decomposition 3D topography. (i) Eighth-level wavelet decomposition 3D topography. (j) Ninth-level wavelet decomposition 3D topography.

Figure 3 further presents the reconstructed high- and low-frequency components. The reconstructed high-frequency surface is characterized by fine and densely distributed peaks and valleys and differs considerably from the original surface morphology. It mainly reflects microscopic texture characteristics and makes a relatively small contribution to the overall surface waviness [26]. The irregular protrusions in this component are mainly associated with hard particles on the surface, adhered built-up material, and transient vibration. In contrast, the low-frequency reconstruction retains the periodic profile of the original surface more effectively and therefore represents the dominant component governing the geometric characteristics of the machined surface. The irregular waviness observed in this component may be related to variations in tool condition, including tool wear, as well as other low-frequency disturbances during machining. In addition, the peak-and-valley characteristics almost disappear in the morphology reconstructed at Scale 9, making it incapable of effectively characterizing variations in the machined surface morphology. This component is mainly associated with machining errors of the machine tool and environmental disturbances.

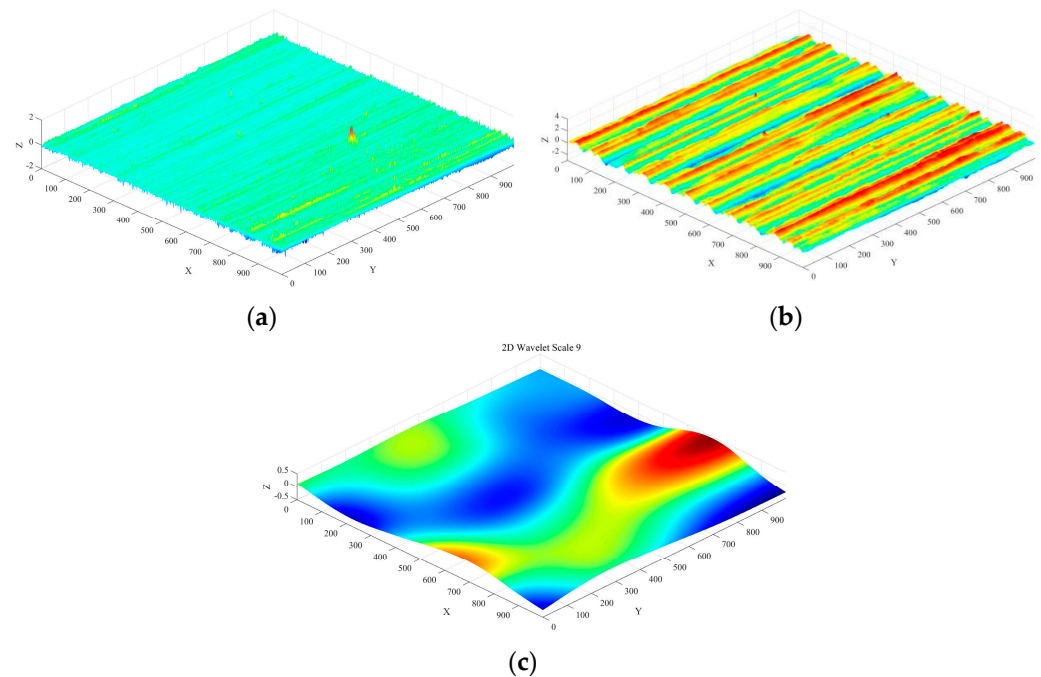


Figure 3. Signal reconstruction at different frequency bands using wavelet transform. (a) Reconstruction of high-frequency signal of machined surface. (b) Reconstruction of low-frequency signal of machined surface. (c) Reconstruction of reference plane signal of machined surface.

3.1.2. Effect of Cooling Strategy on Surface Morphology

Figures 4 and 5 present the variation in the areal surface roughness (S_a) of the high- and low-frequency components of the machined surfaces under conventional cooling and high-pressure cooling, respectively. For the high-frequency component, the S_a value increased slightly with increasing cutting speed under both cooling strategies. Under conventional cooling, the high-frequency S_a increased from $0.096 \mu\text{m}$ to $0.102 \mu\text{m}$, whereas under high-pressure cooling, it increased from $0.088 \mu\text{m}$ to $0.095 \mu\text{m}$. The values under high-pressure cooling remained consistently lower than those under conventional cooling. This indicates that high-pressure cooling can, to some extent, reduce microscopic random fluctuations on the machined surface and produce a more uniform distribution of fine-scale surface features, although the improvement is relatively limited. This finding is generally consistent with previous research [27].

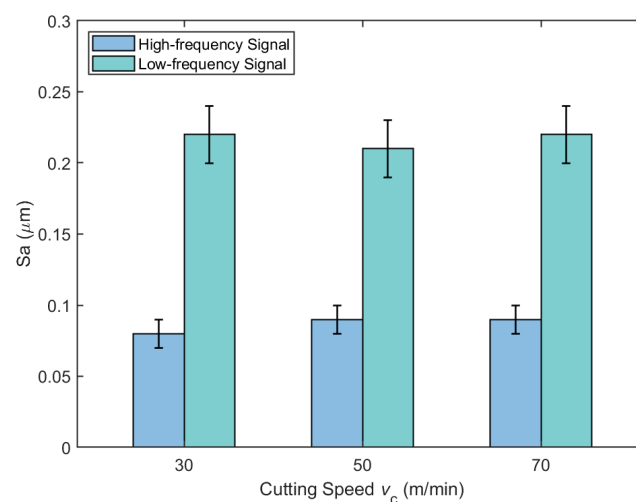


Figure 4. S_a values of reconstructed surfaces from high- and low-frequency signals under conventional cooling.

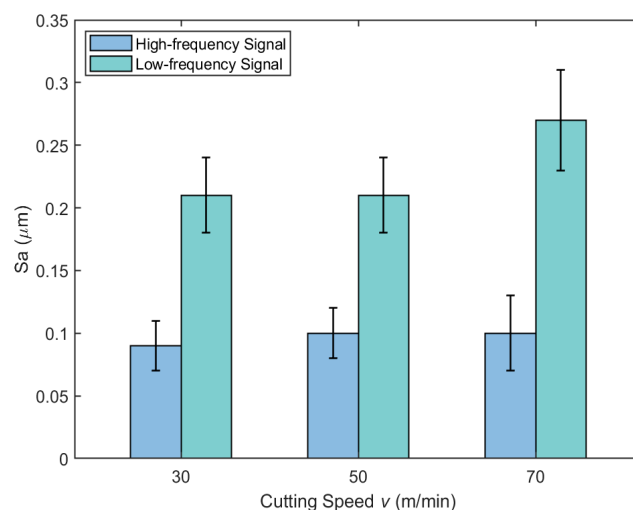


Figure 5. S_a values of reconstructed surfaces from high- and low-frequency signals under high-pressure cooling.

In contrast, the effects of different cooling strategies on the low-frequency profile characteristics were more pronounced. Under conventional cooling, the low-frequency S_a increased from $0.212\ \mu\text{m}$ to $0.272\ \mu\text{m}$, with a particularly pronounced increase at a cutting speed of $70\ \text{m/min}$. Under high-pressure cooling, the low-frequency S_a remained within a relatively narrow range of 0.212 – $0.226\ \mu\text{m}$, exhibiting only minor fluctuations. As the cutting speed increased, the difference between the two cooling strategies became increasingly pronounced, indicating that high-pressure cooling can effectively suppress the development of large-scale profile fluctuations on the machined surface.

Further examination of the reconstructed morphologies shown in Figures 6 and 7 reveals that the high-frequency components were mainly distributed within the range of $-2\ \mu\text{m}$ to $2\ \mu\text{m}$. The overall fluctuation ranges under the two cooling strategies were generally comparable, but the distribution of surface peaks and valleys was more uniform under high-pressure cooling. With increasing cutting speed, local protrusions gradually increased under conventional cooling, whereas relatively limited changes were observed under high-pressure cooling. The low-frequency reconstructed profiles exhibited more pronounced differences. At cutting speeds of 30 and $50\ \text{m/min}$, the differences between the two cooling strategies were relatively small. When the cutting speed increased to $70\ \text{m/min}$, the fluctuations of surface peaks and valleys became substantially more pronounced under conventional cooling, whereas the profile remained relatively smooth and continuous under high-pressure cooling. This indicates that high-pressure cooling may improve the stability of the machining process and thereby suppress the formation of large-scale profile fluctuations [28].

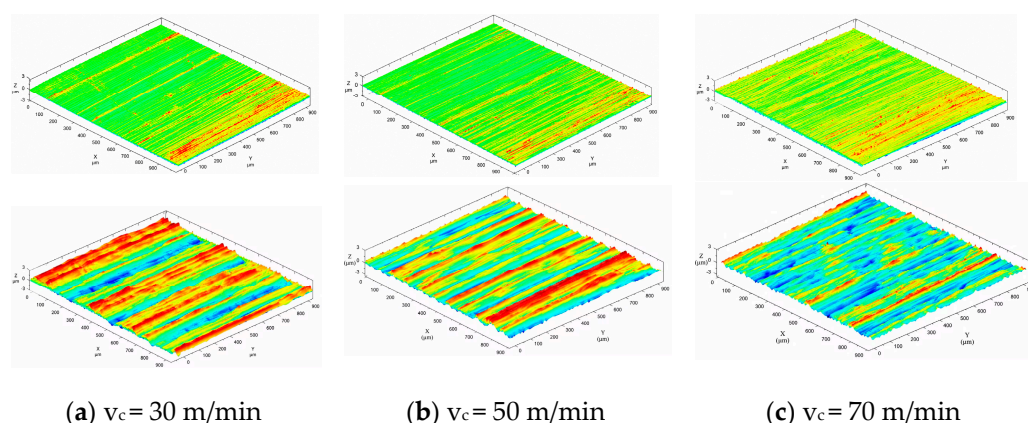


Figure 6. Reconstructed high- and low-frequency surface morphologies under conventional cooling at different cutting speeds.

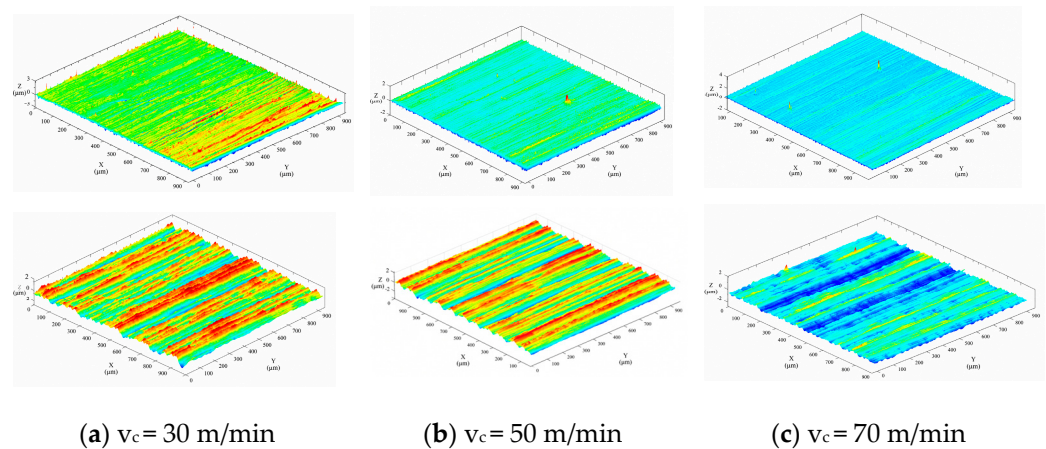


Figure 7. Reconstructed high- and low-frequency surface morphologies under high-pressure cooling at different cutting speeds.

Overall, the above results demonstrate that different cooling strategies regulate the surface morphology at multiple scales, with high-pressure cooling exhibiting a particularly pronounced improvement in the low-frequency profile characteristics. This effect can mainly be attributed to the enhanced penetration of the high-pressure jet into the tool–chip contact zone, which improves the interfacial lubrication condition [28,29]. Previous studies have experimentally demonstrated that high-pressure cooling can reduce the cutting temperature by enhancing heat dissipation from the cutting zone [30,31]. Therefore, the improved lubrication condition and reduced thermal accumulation under high-pressure cooling can contribute to more stable tool–workpiece interactions and reduce the influence of process disturbances on the formation of the machined surface profile, ultimately resulting in a more uniform and stable machined surface. It should be noted that the cutting temperature was not directly measured under the specific conditions of the present study; therefore, the temperature reduction is discussed based on the established mechanism and previous experimental evidence rather than as a directly measured result in this work.

3.2. Surface Plastic Deformation and Microstructural Characteristics Under Different Cooling Strategies

3.2.1. Surface Plastic Deformation

During machining, the combined effects of shear deformation and interfacial friction generated by continuous tool–workpiece contact govern the plastic flow behavior of the machined surface layer. Therefore, the subsurface plastic deformation layer can directly reflect the extent of material deformation under cutting loads [32]. Figures 8 and 9 show SEM images of the subsurface plastic deformation of γ -TiAl alloy machined at different cutting speeds under conventional cooling and high-pressure cooling, respectively. A distinct plastic deformation layer was formed under both cooling strategies, mainly manifested as bending, deflection, and local sliding of the lamellar structure of the γ -TiAl alloy.

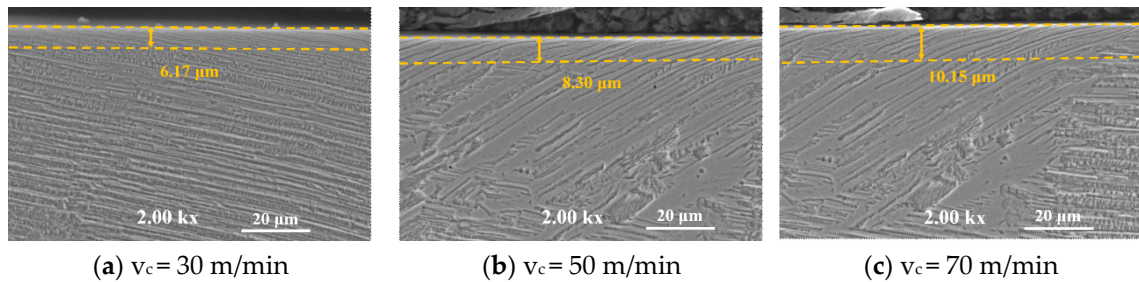


Figure 8. Subsurface deformation of γ -TiAl alloy under conventional cooling at different cutting speeds.

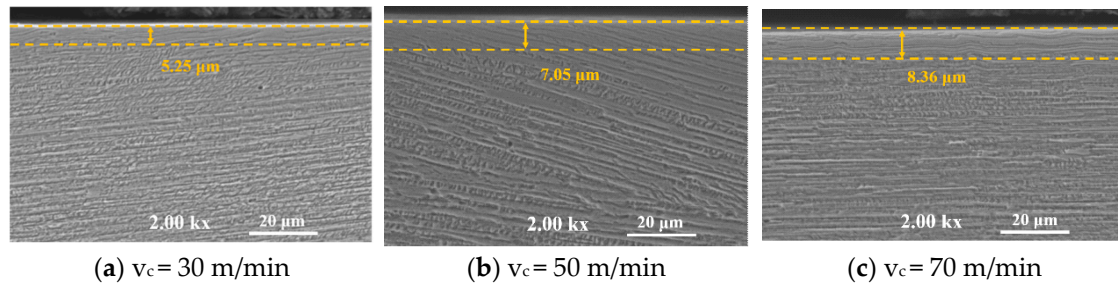


Figure 9. Subsurface deformation of γ -TiAl alloy under high-pressure cooling at different cutting speeds.

As shown in Figure 8, under conventional cooling, the thicknesses of the plastic deformation layer were 6.17, 8.30, and 10.15 μm at cutting speeds of 30, 50, and 70 m/min, respectively. Under high-pressure cooling, the corresponding thicknesses were 5.25, 7.05, and 8.36 μm , representing reductions of approximately 14.91%, 15.06%, and 17.64%, respectively, compared with conventional cooling. These results demonstrate that high-pressure cooling can effectively suppress machining-induced plastic deformation and maintain a more stable subsurface microstructure. This finding is generally consistent with previous studies [33].

The primary reason for the difference between the two cooling strategies is the distinct interfacial friction conditions and mechanical load-transfer characteristics. Under conventional cooling, the cutting fluid cannot effectively penetrate the tool–chip contact zone, resulting in relatively strong friction between the tool and the chip/workpiece and causing the machined surface layer to continuously experience substantial compressive and shear loads [34]. Under sustained mechanical loading, the γ/α_2 lamellar structure gradually undergoes bending, deflection, and sliding, with the deformation extending toward the interior of the material and consequently forming a relatively thick plastic deformation layer. Meanwhile, heat accumulation generated by interfacial friction may further facilitate local plastic flow and promote orientation deflection of the lamellar structure [35]. In contrast, high-pressure cooling enhances the penetration of the cutting fluid into the tool–chip contact zone through a high-velocity jet, thereby improving the interfacial lubrication condition. It also facilitates timely chip breakage and evacuation, resulting in a more stable tool–workpiece contact process [29,34]. The reduction in interfacial friction decreases the sustained compressive and shear loading imposed on the machined surface layer, thereby effectively suppressing material plastic flow. Consequently, the bending of the lamellar structure is substantially reduced, and plastic deformation is mainly confined to the region close to the machined surface, ultimately resulting in a significantly thinner plastic deformation layer.

The thickness of the plastic deformation layer was determined from the cross-sectional SEM images based on the depth over which the characteristic subsurface deformation features induced by machining were observed. The boundary of the deformation layer was identified where the microstructural morphology gradually recovered to that of the undeformed substrate. As the cutting speed increased from 30 to 70 m/min, the thickness of the plastic deformation layer increased under both cooling strategies. This can mainly be attributed to the increased material removal rate and the continuously increasing contact frequency and shear strain rate between the tool and workpiece at higher cutting speeds. The resulting enhancement of interfacial friction causes the machined surface layer to experience greater plastic deformation, thereby promoting the extension of the plastic deformation layer toward the subsurface region [36]. Although the rate of increase in the deformation-layer thickness decreased at higher cutting speeds within the investigated range, the present study only concludes that increasing the cutting speed promotes the development of the plastic deformation layer within the investigated range.

Overall, the cooling strategy not only affects the thickness of the plastic deformation layer but also alters the deformation mode of the material during machining. Compared with conventional cooling, high-pressure cooling produced a thinner deformation layer under all investigated cutting speeds. This difference may be associated with the altered tool–workpiece interaction and thermal conditions provided by the high-pressure cooling system. The specific contributions of interfacial friction, mechanical loading, and thermal effects require further investigation through direct measurements of cutting force, cutting temperature, and tool wear.

3.2.2. Microstructural Characteristics of the Machined Surface Layer

It should be noted that the EBSD analysis in this section was performed under the typical condition of a cutting speed of $V_c = 50$ m/min. Consequently, the following discussions on grain orientation, grain boundary characteristics, and dynamic recrystallization are only applicable to the regions tested at this cutting speed and cannot be directly generalised to the conditions of 30 and 70 m/min.

To further elucidate the microstructural characteristics of the machined surface layer of γ -TiAl alloy under different cooling strategies, EBSD analyses were performed on both the substrate and machined surface regions. Figures 10–12 present the inverse pole figure (IPF) maps, pole figures, grain size distributions, and misorientation angle distributions of the substrate and machined surface regions under different cooling strategies.

Figure 10 presents the IPF maps and pole figures of the γ -TiAl alloy substrate and subsurface regions machined under the two cooling strategies at a cutting speed of 50 m/min. As shown in Figure 10a, the substrate exhibits a typical as-cast microstructure, consisting primarily of lamellar γ/α_2 colonies and a small fraction of equiaxed γ phase. The grain boundaries are distinct, and the crystallographic orientations are relatively randomly distributed. The IPF map shows a relatively uniform distribution of grain colors without pronounced concentration, indicating that the overall texture intensity of the as-cast microstructure is relatively weak. The pole figure further shows that the γ -phase orientations are relatively dispersed without a pronounced preferred orientation, whereas the α_2 phase exhibits a certain degree of orientation concentration along the $\langle 0001 \rangle$ direction, indicating a degree of orientation selection during solidification.

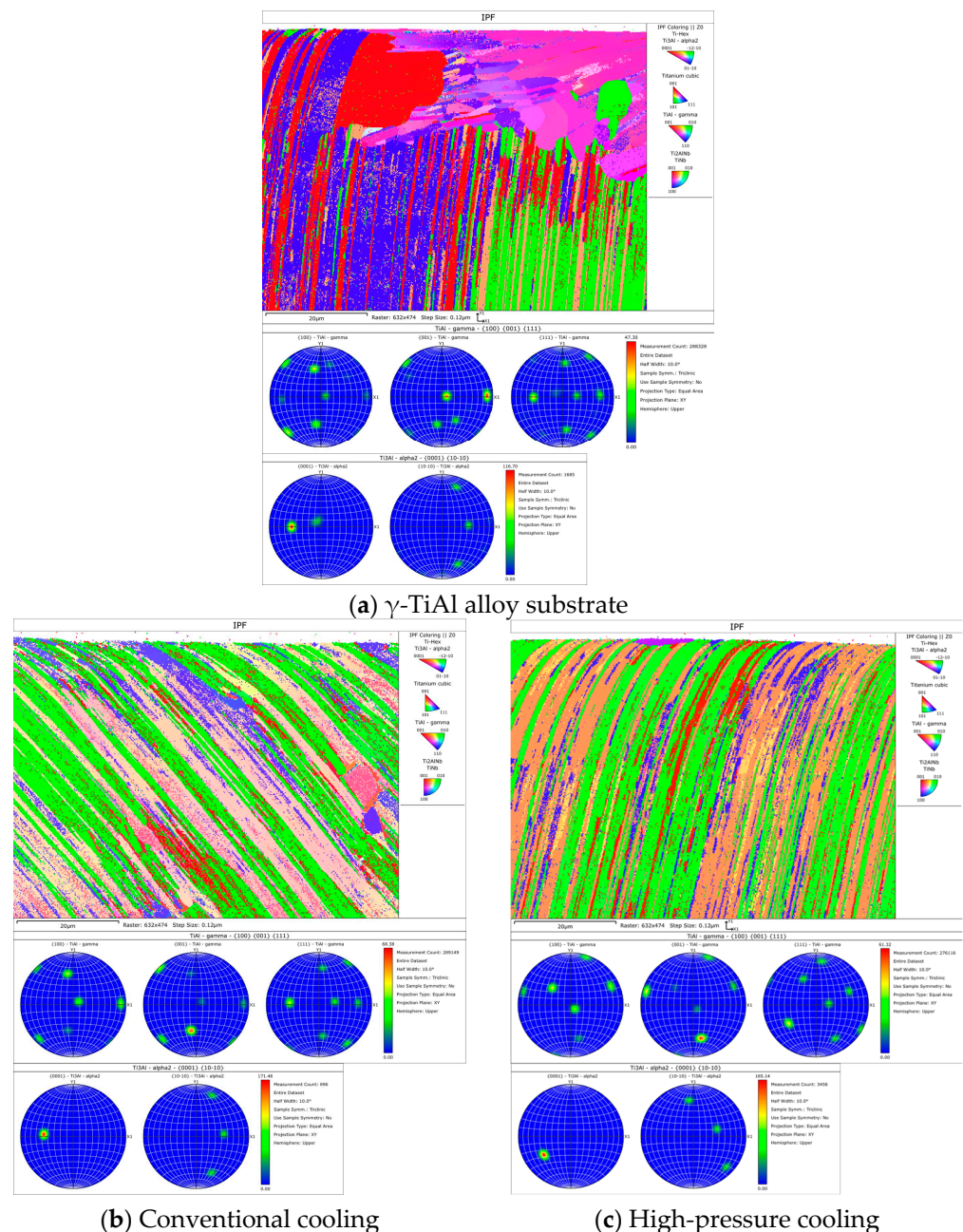


Figure 10. IPF and pole figures of γ -TiAl alloy under two cooling strategies and in the bulk.

After machining, the surface layers under both cooling strategies exhibited different degrees of crystallographic orientation adjustment, indicating that the cutting load induced grain rotation and texture evolution. Under conventional cooling, the peak orientation intensity of the γ phase decreased from 46.33 in the as-cast substrate to 41.32, indicating that the original grain orientations were disturbed during machining. Some grains underwent orientation deflection and redistribution, resulting in a reduced degree of preferred γ -phase orientation and a decrease in texture intensity. In contrast, the peak orientation intensity of the α_2 phase increased to some extent, indicating that the α_2 grains underwent a certain degree of orientation adjustment during cutting deformation and that their orientation distribution became more concentrated.

Because the γ phase has relatively greater deformation compatibility, whereas the α_2 phase exhibits limited plasticity at room temperature, the γ phase can more readily accommodate the applied load through slip deformation under cutting-induced shear, whereas strain concentration is more likely to occur in the α_2 phase and at γ/α_2 interfaces.

Therefore, under conventional cooling, the stronger interfacial friction and less stable mechanical loading promote local accumulation of plastic strain, resulting in more dispersed grain rotation and weakening of the original γ -phase texture.

Under high-pressure cooling, the peak orientation intensity of the γ phase increased significantly, exceeding not only that under conventional cooling but also the level of the as-cast substrate. This indicates that the cutting stress promoted the development of a more pronounced preferred orientation. This phenomenon suggests that high-pressure cooling alters the deformation mode of the surface layer. Under the high-pressure jet, the lubrication condition at the tool–workpiece interface is improved, while frictional resistance and fluctuations in cutting loads are reduced, resulting in more continuous and coordinated material deformation [29,36]. Meanwhile, the number of valid data points for the γ phase increased significantly, suggesting that high-pressure cooling favors the preservation of γ -phase crystallographic integrity and reduces machining-induced lattice distortion and microstructural damage.

In contrast, the peak orientation intensity of the α_2 phase increased further under high-pressure cooling, indicating more pronounced orientation adjustment and texture evolution, whereas its number of valid data points continued to decrease. This suggests that under high-pressure cooling, local deformation tends to concentrate mechanically in the α_2 phase and at phase-boundary regions. Because of the limited deformation compatibility of the α_2 phase, the local strain is difficult to release through homogeneous plastic flow, resulting in relatively large orientation gradients and lattice distortion.

To further characterize the degree of microstructural evolution in the machined surface layer under different cooling strategies, statistical analyses of the grain size and misorientation angle distributions were performed for the substrate and machined surface regions, as shown in Figures 11 and 12. Figure 11 presents the grain size distributions under the different conditions. The average grain size in the substrate was 4.23 μm , with a relatively broad grain size distribution, characteristic of the lamellar microstructure of the as-cast γ -TiAl alloy. After machining, the average grain sizes were 4.03 and 4.17 μm under conventional cooling and high-pressure cooling, respectively. Although the grain size decreased under both cooling conditions compared with the substrate, the magnitude of the change was relatively small, and no significant grain refinement was observed.

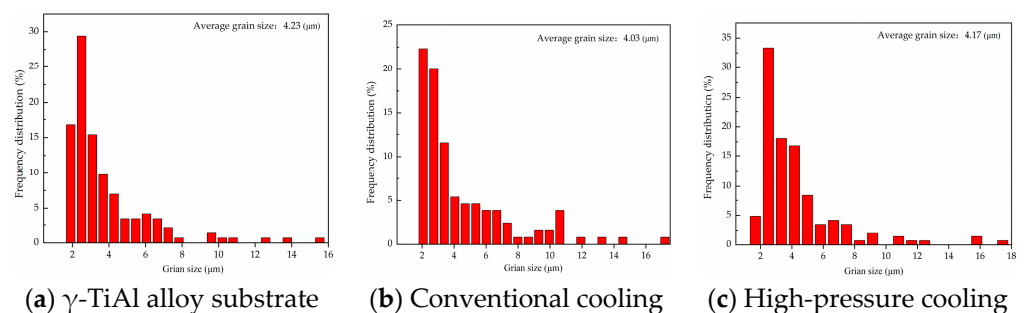


Figure 11. Grain size distribution of γ -TiAl alloy in the bulk and under two cooling strategies.

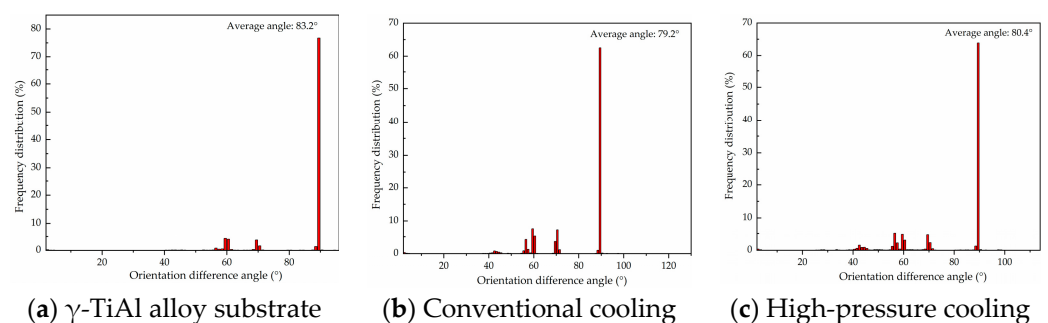


Figure 12. Grain boundary misorientation distribution of γ -TiAl alloy in the bulk and under two cooling strategies.

In general, dynamic recrystallization requires relatively high thermal input and sufficient accumulation of plastic strain, with typical characteristics including the formation of new grains, a significant reduction in grain size, and redistribution of grain boundary structures [37,38]. However, in the present study, the EBSD observations provide no clear evidence of significant dynamic recrystallization in the investigated machined regions. First, the IPF maps did not reveal an obvious population of newly formed fine equiaxed grains near the machined surface. Second, the average grain size changed only slightly, from 4.23 μm in the substrate to 4.03 μm and 4.17 μm under conventional and high-pressure cooling, respectively, indicating that substantial grain refinement did not occur. Third, the overall grain-boundary characteristics remained dominated by high-angle grain boundaries, without an obvious microstructural feature indicative of extensive grain-boundary reconstruction. Therefore, the observed EBSD characteristics are more consistent with machining-induced grain rotation and crystallographic orientation adjustment than with significant dynamic recrystallization. These observations suggest that the machining conditions investigated here did not produce sufficient microstructural modification to generate clear EBSD evidence of significant recrystallization. However, because cutting temperature was not directly measured, the thermal conditions responsible for this response cannot be quantitatively determined. Therefore, the present results do not allow the thermal contribution to dynamic recrystallization to be independently evaluated. The observed microstructural characteristics are therefore more consistent with mechanically induced plastic deformation and crystallographic orientation adjustment than with significant recrystallization. Accordingly, under the investigated conditions, the observed microstructural changes are mainly characterized by machining-induced plastic deformation and crystallographic orientation adjustment, while no clear evidence of significant dynamic recrystallization was observed.

A further comparison of the two cooling conditions shows that the average grain size under conventional cooling was slightly smaller than that under high-pressure cooling. This difference is consistent with the greater thickness of the plastic deformation layer observed under conventional cooling, indicating a greater extent of machining-induced microstructural modification. Previous studies have reported that high-pressure cooling can improve coolant penetration, lubrication, and heat removal during machining [39,40]. These effects may contribute to the relatively limited microstructural modification observed under high-pressure cooling, under which the average grain size remained closer to that of the as-cast substrate. The relatively small difference in grain size between the two cooling conditions also indicates that substantial grain refinement did not occur under the investigated conditions. However, because cutting force and cutting temperature were not directly measured, the respective contributions of mechanical and thermal effects to these microstructural differences cannot be quantitatively separated.

To further analyze the changes in grain boundary structure, the misorientation angle distributions under different conditions are presented in Figure 12. The microstructures of the substrate and the specimens machined under both cooling strategies were dominated by high-angle grain boundaries (HAGBs), indicating that machining did not fundamentally alter the overall grain boundary characteristics of the material. The average misorientation angle of the substrate was 83.2°, indicating a relatively random crystallographic orientation distribution in the as-cast microstructure and substantial orientation differences between neighboring grains. After machining, the average misorientation angles decreased to 79.2° and 80.4° under conventional cooling and high-pressure cooling,

respectively. The decrease in average misorientation angle indicates that machining-induced deformation caused partial grain rotation, reducing the orientation differences between neighboring grains and resulting in a reorganization of grain-boundary orientation relationships. This result is consistent with the orientation concentration observed in Figure 10, indicating that a certain degree of deformation-induced texture evolution occurred during machining.

The more pronounced reduction in average misorientation angle under conventional cooling indicates that stronger interfacial friction and mechanical loading promoted dislocation accumulation and grain rotation, leading to more significant crystallographic adjustment in the machined surface layer [41]. In contrast, the average misorientation angle under high-pressure cooling was higher than that under conventional cooling and remained closer to that of the as-cast substrate. This indicates that high-pressure cooling restricted excessive crystallographic reconstruction. Combined with the pole figure analysis, these results demonstrate that although high-pressure cooling promoted grain rotation toward preferred orientations, it did not induce significant grain boundary migration or microstructural reconstruction. This further confirms that the beneficial effect of high-pressure cooling on the machined microstructure does not rely on high-temperature microstructural reconstruction. Instead, it is achieved by optimizing the interfacial load-transfer mode, allowing plastic strain to be accommodated more uniformly and thereby limiting excessive dislocation accumulation and grain-boundary orientation adjustment.

The combined SEM and EBSD results demonstrate that different cooling strategies fundamentally alter the evolution pathway of the machined surface microstructure. Under conventional cooling, stronger interfacial friction and shear loading induce greater plastic flow in the surface layer, promoting dislocation accumulation, random grain rotation, and texture weakening, ultimately resulting in a thicker plastic deformation layer and more pronounced microstructural disturbance. In contrast, high-pressure cooling improves the interfacial lubrication condition and stabilizes the mechanical load distribution, promoting coordinated grain rotation toward preferred orientations while suppressing excessive strain accumulation and grain-boundary reconstruction. Therefore, under the cutting conditions investigated in this study, the microstructural evolution of the machined γ -TiAl surface layer is characterized by mechanically dominated deformation, controlled thermal effects, crystallographic orientation adjustment as the primary microstructural response, and suppression of dynamic recrystallization. High-pressure cooling modifies the interfacial interaction conditions and thereby promotes improved surface integrity characterized by a thinner plastic deformation layer, enhanced crystallographic integrity, and greater microstructural stability.

3.3. Residual Stress Under Different Cooling Strategies

Residual stress is an important indicator for evaluating machined surface integrity. It originates from the redistribution of elastoplastic stresses following machining-induced plastic deformation and is jointly affected by mechanical loading and thermal effects [42]. In this study, residual stress was measured on one representative specimen selected from the three independently machined specimens for each cutting condition. Therefore, the residual stress values reported in this study represent the selected specimens under the investigated conditions and are not statistical averages across the three machining repetitions.

Figure 13 presents the residual stress distributions at different cutting speeds under the two cooling strategies. It can be observed that the machined surfaces exhibited residual compressive stresses under both cooling strategies, with the maximum magnitude of residual stress occurring at the machined surface. Combined with the SEM and EBSD results discussed above, no significant dynamic recrystallization was observed under either

cooling strategy within the investigated conditions. The microstructural changes in the machined surface layer was mainly characterized by grain rotation, crystallographic orientation adjustment, and localized lattice distortion induced by plastic deformation. Therefore, the residual stress was primarily associated with stress self-equilibration following machining-induced plastic deformation, while the cooling strategy mainly affected the development and stability of the residual stress field by regulating the frictional state at the tool–workpiece interface, the mechanical load-transfer mode, and local thermal effects [43].

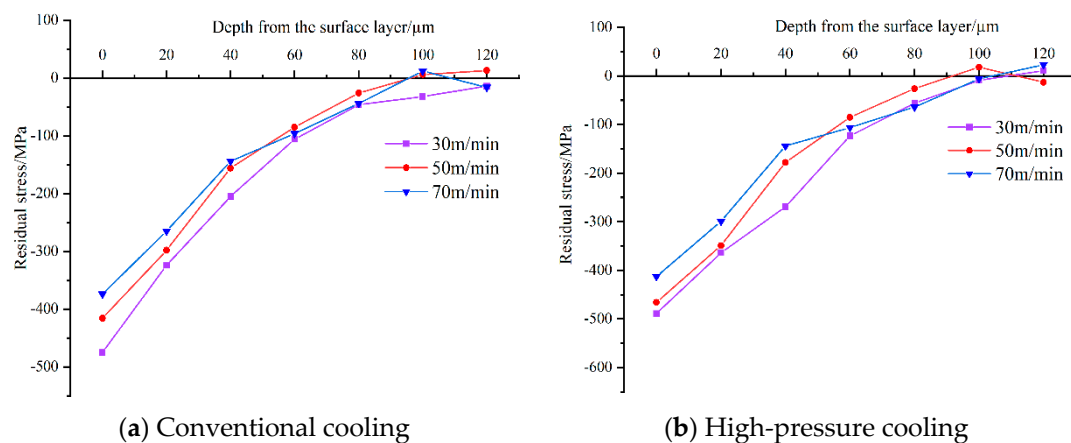


Figure 13. Surface residual stress distribution of γ -TiAl alloy under different cooling strategies.

Under conventional cooling (Figure 13a), the surface residual stresses were −475, −416, and −374 MPa at cutting speeds of 30, 50, and 70 m/min, respectively. In comparison, under high-pressure cooling, the corresponding surface residual compressive stresses were −489, −466, and −413 MPa, respectively, representing increases in compressive stress magnitude of 2.9%, 12.0%, and 10.4%, respectively. These results indicate that, under identical cutting parameters, high-pressure cooling can establish a stronger residual compressive stress state in the machined surface layer and maintain relatively high compressive stress levels even as the cutting speed increases.

Combined with the plastic deformation layer and EBSD analyses presented above, these results indicate that the thermal input generated during cutting was insufficient to dominate microstructural reconstruction, and that residual stress formation remained primarily governed by mechanically induced plastic deformation. During cutting, mechanical loading induces plastic flow, dislocation accumulation, and grain rotation in the surface layer, which tend to generate residual compressive stress. Although localized thermal effects associated with cutting can cause thermal expansion and contraction of the material and thereby promote the development of residual tensile stress, the final residual stress state is determined by the competition between these mechanical and thermal effects.

Under conventional cooling, relatively greater heat accumulation in the cutting zone partially counteracts the residual compressive stress generated by mechanical deformation, resulting in a relatively lower magnitude of surface compressive stress. In contrast, high-pressure cooling improves the tool–workpiece contact condition, resulting in more uniform and stable mechanical load transfer and more coordinated accommodation of plastic strain within the surface layer [44]. The EBSD results indicate that, under high-pressure cooling, the grains mainly underwent limited and coordinated rotation and crystallographic orientation adjustment, while the grain boundary structure remained relatively stable without significant dynamic recrystallization or grain boundary reconstruction. This suggests that plastic strain was accommodated more uniformly within the

grains rather than being concentrated in severe localized damage. Consequently, although the spatial extent of plastic deformation was reduced, the machining-induced compressive stress could be retained more effectively within the surface layer, leading to a more stable elastoplastic stress equilibrium and, ultimately, a higher magnitude of residual compressive stress.

It is noteworthy that no significant dynamic recrystallization was observed under either cooling strategy, indicating that the local thermal input during cutting was insufficient to drive substantial microstructural reconstruction. Therefore, thermal effects primarily contributed to stress relaxation rather than determining the formation of residual stress. Accordingly, the higher residual compressive stress obtained under high-pressure cooling may not result from a change in the fundamental residual stress formation mechanism, but rather from the reduced influence of thermal effects on stress relaxation and the improved coordination of plastic deformation. These effects allow the mechanically dominated compressive stress field to be retained more effectively in the machined surface layer. This further indicates that, under the cutting conditions investigated in this study, mechanical loading remained the dominant factor governing residual stress formation, whereas thermal effects played a secondary regulatory role.

In addition, the magnitude of the surface residual compressive stress decreased with increasing cutting speed under both cooling strategies. This can mainly be attributed to the more intense tool–workpiece interaction at higher cutting speeds, which increases both the rate of plastic deformation and local thermal effects. The resulting enhancement in stress relaxation weakens the residual compressive stress generated by mechanical plastic deformation [45]. Consequently, the residual compressive stress decreased at higher cutting speeds under both cooling strategies. Nevertheless, high-pressure cooling consistently maintained a higher magnitude of residual compressive stress, demonstrating its effective capability for regulating the stress state of the machined surface layer over the investigated cutting-speed range.

Figure 14 further presents the depth-wise distribution of residual stress at a cutting speed of 50 m/min. Under both cooling strategies, the residual compressive stress gradually decreased in magnitude with increasing depth and eventually approached the stress state of the substrate. The most pronounced variation in residual stress occurred within the depth range of 0–60 μm , whereas the stress distribution became relatively stable beyond 60 μm . This indicates that the influence of machining loads on the residual stress field was mainly concentrated in the machined surface region. With increasing depth, the extent of plastic deformation and microstructure gradually decreased, and the residual stress field progressively returned toward the initial state of the material.

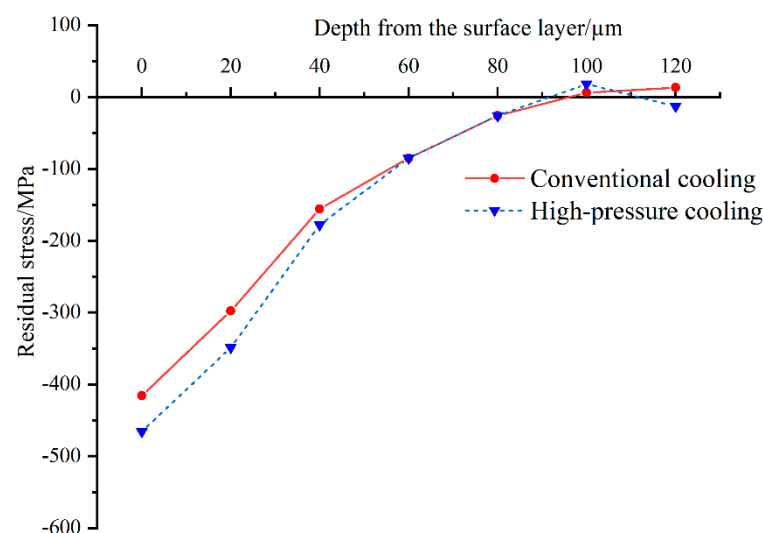


Figure 14. Effect of cooling strategies on residual stress of γ -TiAl alloy.

Notably, the depth of the residual stress-affected layer was substantially greater than the thickness of the plastic deformation layer. As shown by the results in Figures 8–12, although significant plastic deformation was mainly confined to a few micrometers beneath the machined surface, the stress field generated during machining could continuously propagate into the material interior. The stress concentration generated by severe plastic deformation in the surface layer was progressively transmitted toward the subsurface through elastoplastic compatibility, inducing a certain degree of elastic deformation and stress redistribution in the underlying material. Consequently, a residual stress-affected layer considerably deeper than the plastic deformation layer was formed [46,47]. Combined with the EBSD results, the absence of significant dynamic recrystallization in the machined surface layer indicates that the residual stress was not substantially released through microstructural reconstruction, but was instead retained in the machined surface and near-surface regions through elastoplastic self-equilibration.

As summarized in Table 7, high-pressure cooling was associated with reduced surface fluctuations, a thinner subsurface plastic deformation layer, microstructural characteristics closer to those of the substrate, and a higher magnitude of compressive residual stress under the investigated conditions.

Table 7. Comparison of the machined surface and subsurface characteristics under conventional and high-pressure cooling.

Characteristic	Conventional Cooling	High-Pressure Cooling	Change Under High-Pressure Cooling
High-frequency Sa	0.096–0.102 μm	0.088–0.095 μm	Reduced by approximately 6.9–8.3%
Low-frequency Sa	0.212–0.272 μm	0.212–0.226 μm	Maximum Sa reduced from 0.272 to 0.226 μm
Plastic deformation layer	6.17–10.15 μm	5.25–8.36 μm	Reduced by 14.91–17.64%
Average grain size	4.03 μm	4.17 μm	Closer to substrate value of 4.23 μm
Average misorientation angle	79.2°	80.4°	Closer to substrate value of 83.2°
Surface residual compressive stress	−475 to −374 MPa	−489 to −413 MPa	Compressive-stress magnitude increased by 2.9–12.0%

Although high-pressure cooling can effectively improve the surface integrity of machined γ -TiAl alloys, its engineering application is still constrained by the equipment investment required for high-pressure fluid supply, operation and maintenance costs, energy and cooling-fluid consumption, and adaptability to different machining environments. Therefore, for conventional material machining or processes with relatively low requirements for surface integrity, the overall economic benefits of high-pressure cooling may be limited. In contrast, high-pressure cooling is more suitable for the precision machining of high-value, difficult-to-machine components in fields such as aerospace and energy equipment. It should be noted that the energy consumption, cooling-fluid consumption, and economic costs associated with the two cooling strategies were not quantitatively evaluated in the present study. Therefore, a comprehensive assessment of the economic benefits and engineering applicability of high-pressure cooling requires further techno-economic investigations.

4. Conclusions

This study systematically investigated the machined surface morphology, subsurface microstructure, and residual stress during the turning of γ -TiAl alloy under different cooling strategies. The results demonstrate that different cooling strategies do not alter the fundamental formation mechanisms of the machined surface layer of γ -TiAl alloy, but regulate plastic deformation, microstructure, and residual stress development by modifying the contact conditions and mechanical load-transfer characteristics at the tool–workpiece interface. Compared with conventional cooling, high-pressure cooling improves the interfacial lubrication condition and machining stability, thereby achieving controlled plastic deformation, enhanced crystallographic integrity, and increased residual compressive stress without inducing dynamic recrystallization, ultimately resulting in improved surface integrity. The main conclusions are as follows:

(1) Wavelet-based multiscale analysis effectively separates morphological information at different scales on the machined surface. The high-frequency components mainly reflect random disturbances associated with machine-tool vibration, microscopic tool runout, and local material detachment, whereas the low-frequency components correspond to the periodic profile generated by the tool motion trajectory and constitute the dominant contribution to the geometric characteristics of the machined surface. Compared with conventional cooling, high-pressure cooling provides limited improvement in high-frequency random fluctuations but significantly suppresses low-frequency profile fluctuations, resulting in a more uniform and stable surface morphology.

(2) High-pressure cooling effectively reduces the thickness of the machining-induced plastic deformation layer. As the cutting speed increased from 30 to 70 m/min, the thickness of the plastic deformation layer gradually increased under both cooling strategies. However, high-pressure cooling reduced the thickness of the plastic deformation layer by approximately 14.91–17.64% compared with conventional cooling. By improving the lubrication condition at the tool–workpiece interface, reducing friction, and enhancing machining stability, high-pressure cooling confines plastic deformation more effectively to the machined surface region, thereby suppressing the continued bending of the lamellar structure and the propagation of plastic deformation into the subsurface.

(3) EBSD analysis indicates that no significant dynamic recrystallization occurred in the machined surface layer under either cooling strategy. The microstructural evolution was primarily characterized by grain rotation, crystallographic orientation adjustment, and localized lattice distortion rather than grain reconstruction. Compared with conventional cooling, high-pressure cooling promoted more coordinated grain rotation toward preferred orientations and reduced localized microstructural damage, thereby maintaining higher crystallographic integrity and grain-boundary stability in the machined surface layer. These results indicate that, under the cutting conditions investigated in this study, microstructural evolution in the machined surface layer was predominantly controlled by mechanical deformation, while thermal effects mainly regulated the extent of microstructural evolution and were insufficient to dominate microstructural reconstruction.

(4) The machined surfaces exhibited residual compressive stress under both cooling strategies, and the magnitude of the residual compressive stress gradually decreased with increasing cutting speed. Although high-pressure cooling reduced the thickness of the plastic deformation layer, the magnitude of the surface residual compressive stress remained consistently higher than that under conventional cooling. Combined with the subsurface deformation and EBSD results, this difference is considered to be associated primarily with the different mechanical deformation and strain-accommodation responses under the two cooling strategies.

Overall, the above conclusions are limited to the investigated cutting speeds of 30, 50, and 70 m/min, with the feed rate and depth of cut kept constant, and to the cooling

conditions examined in this study. Further investigations involving a broader range of cutting parameters, together with direct measurements of cutting force, cutting temperature, tool wear, and other relevant variables, are required to further clarify the underlying mechanisms and assess the general applicability of these findings to γ -TiAl machining.

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