The robot grinding and polishing of additive aviation titanium alloy blades: a review

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Abstract

Purpose – The purpose of this review is to comprehensively consider the material properties and processing of additive titanium alloy and provide a new perspective for the robotic grinding and polishing of additive titanium alloy blades to ensure the surface integrity and machining accuracy of the blades.

Design/methodology/approach – At present, robot grinding and polishing are mainstream processing methods in blade automatic processing. This review systematically summarizes the processing characteristics and processing methods of additive manufacturing (AM) titanium alloy blades. On the one hand, the unique manufacturing process and thermal effect of AM have created the unique processing characteristics of additive titanium alloy blades. On the other hand, the robot grinding and polishing process needs to incorporate the material removal model into the traditional processing flow according to the processing characteristics of the additive titanium alloy.

Findings – Robot belt grinding can solve the processing problem of additive titanium alloy blades. The complex surface of the blade generates a robot grinding trajectory through trajectory planning. The trajectory planning of the robot profoundly affects the machining accuracy and surface quality of the blade. Subsequent research is needed to solve the problems of high machining accuracy of blade profiles, complex surface material removal models and uneven distribution of blade machining allowance. In the process parameters of the robot, the grinding parameters, trajectory planning and error compensation affect the surface quality of the blade through the material removal method, grinding force and grinding temperature. The machining accuracy of the blade surface is affected by robot vibration and stiffness.

Originality/value – This review systematically summarizes the processing characteristics and processing methods of aviation titanium alloy blades manufactured by AM. Combined with the material properties of additive titanium alloy, it provides a new idea for robot grinding and polishing of aviation titanium alloy blades manufactured by AM.

Keywords Additive manufacturing, Robot grinding, Titanium alloy blade, Precision control

Paper type Literature review

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1. Introduction

1.1 Background

Aviation blade is a key component of aero-engine, which provides power for aviation equipment. A series of blades are installed together to form a bladed disk to provide power for the engine. Blades are usually in extreme working environments, such as high temperature, high pressure and cyclic loading (Sinha *et al.*, 2022). In order to improve the thrust-weight ratio of aero-engine and obtain good heat dissipation conditions, aero-engine blades usually adopt hollow structure (Zhou *et al.*, 2014). Superplastic forming/diffusion bonding (SPF/DB) process can be used to fabricate engine blades with cavity structure. This process is to coat the spacer between the two blanks of the blade, combine them by DB, obtain the cavity structure of the blade by SPF and then obtain the expected shape by hot forming (Akula *et al.*, 2023). Hollow blades with complex surfaces can be manufactured by SPF/DB process (Wang *et al.*, 2022a), but the process is complex and difficult to control and the hollow structure and shape cannot achieve good manufacturing accuracy. With the increasing demand for material utilization and production efficiency in the manufacturing process, green manufacturing processes are gradually adopted in the production process of high-performance aero-engine blades. These processes should make hollow blades have high service performance and ensure the reliability of engine operation even in high temperature environments. Therefore, more stable and efficient production technology is needed to manufacture high-performance aero-engine blades. Additive manufacturing (AM), as an alternative to traditional technologies, can solve these problems and produce better performance blades with higher production efficiency.

AM is a technology that directly converts a digital model into a physical model by continuously adding the required materials layer by layer. Among them, laser additive manufacturing (LAM) is widely used in the production of parts in the aerospace industry (Tan *et al.*, 2021). Because the process of machine tool placement and mold design is required before production, the production and manufacturing of traditional parts takes a long time. However, the original manufacturing time can be reduced by about 50% through AM technology. Siemens used AM technology to produce turbine blades, combined with 3D printing technology to develop and test gas turbine blades, reducing the overall development time from the expected two years to the final two months (EOS Turbine Blade). Advantages of AM include design freedom, high material utilization and significant reduction in part weight. These advantages are crucial for aerospace applications, which make AM selected for the manufacture of aviation parts. AM can also realize the integration of multiple parts, making the design and assembly process of parts simpler. Jiang *et al.* (2017) pointed out in the report that AM can enable 855 single parts to be merged into 12 parts, which significantly reduces the weight of the parts by 45 kg, increases the fuel consumption by 20% and increases the power output by 10%. This shows that AM can promote the use of resources, thereby reducing the production cost of parts (Richardson *et al.*, 2016). The complex curved surface, hollow structure and internal cooling pipe of turbine blades make it almost impossible to manufacture turbine blades by traditional process. Therefore, after recognizing the potential of the AM industry, the aerospace sector has put AM technology into the production of engine parts, including turbine blades. With the increase in the market size of the AM industry, the market size of the aerospace industry sector grew rapidly in 2019 to nearly USD 200 million (Tan *et al.*, 2021) and is expected to reach USD 8 billion in 2026 (GE). Among them, selective laser melting (SLM) has become a mainstream AM process for titanium alloy blades due to its short production cycle, high processing accuracy and high material utilization. However, the material has manufacturing defects such as residual stress, internal pores and rough surfaces (Zhang *et al.*, 2023a). It is easy to cause processing damage and needs to be improved through subsequent processing.

Abrasive belt is widely used in precision machining of complex surfaces due to its advantages of flexibility, adaptability and high grinding efficiency (Xiao *et al.*, 2023). Research has shown that abrasive belt grinding can effectively improve the surface integrity of the processed material and reduce surface damage and defects (Zhou *et al.*, 2023; Xiao *et al.*, 2022a; He *et al.*, 2023). Robots have made great progress in the past few years and have attracted more attention in the field of grinding (Ferraguti *et al.*, 2019). The robot-assisted grinding system improves the polishing efficiency and surface quality. In order to achieve high process efficiency without affecting the grinding accuracy, the correct attitude and path generation algorithm is very important (Wang *et al.*, 2014; Lin, 2014). Robots need to use a variety of sensors to monitor, process and collect information and use intelligent algorithms to predict surface roughness, determine the stop time of grinding and avoid over-grinding (Beatriz *et al.*, 2018; Segreto *et al.*, 2015). Although robot-assisted polishing has been widely studied, many key issues still need to be further explored. For example, the motion accuracy (positioning accuracy/positioning repeatability/motion accuracy) of the robot is lower than the actual demand, and the stiffness is relatively low, which limits the application of ultra-precision polishing to the nanometer level, so it is necessary to compensate the error of the robot trajectory.

1.2 Research significance

The "*Made in China 2025*" plan lists aerospace equipment as vigorously promoting breakthroughs in key areas (Zhou, 2015). Among them, titanium alloy blades are important key parts for the development of a new generation of aero-engines, and their surface quality and profile accuracy have a profound impact on their service performance (Zhao *et al.*, 2023). As a green manufacturing process, AM can greatly shorten the manufacturing cycle and improve the utilization rate of materials. Titanium alloy blades produced by AM process have good manufacturing accuracy, but the surface quality needs to be improved through subsequent processing. Robotic machining technology meets the processing requirements of additive titanium alloy and also conforms to the development trend of automation. Therefore, the realization of robot low-damage machining of additive titanium alloy blades can reduce the influence of material defects in the AM process on the service performance of aviation blades and greatly promote the application of AM technology in the aerospace field. It is of great significance to improve the automation, precision and high-quality development of Chinese aerospace manufacturing field by robot trajectory planning and precision control to make blade machining meet the requirements of machining accuracy and surface integrity.

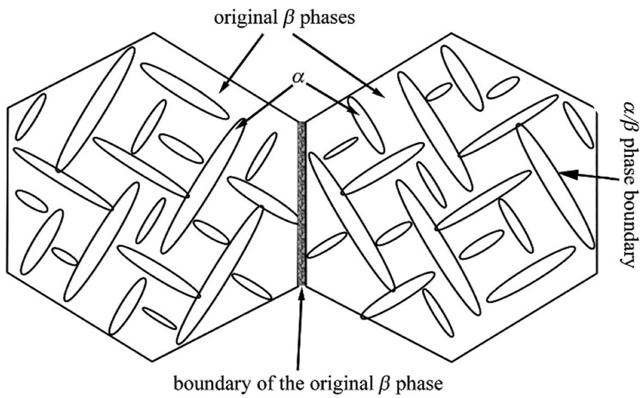
2. Material properties of additive titanium alloy

In thermo-mechanically processed titanium alloys, especially in two-phase alloys, the microstructure of the material is very diverse. The grain size and morphology are influenced by temperature, cooling rate, mechanical processing and heat treatment (Zhou *et al.*, 2008). Titanium alloys can be divided into two categories according to their microstructure and composition: one is a single-phase alloy composed of α phase or β phase, and the other is a two-phase titanium alloy composed of α/β structure. The α phase or β phase of the single-phase alloy is the coarse grain microstructure of the polyhedral grains. Most of the additive titanium alloys are the microstructure of polyhedral grains characterized by lamellar α and β phase grains, which are distributed in the large grain boundary of the pre-β phase of the two-phase alloy (Cao *et al.*, 2004). In general, the uniform fine grain microstructure corresponds to the high mechanical properties of titanium alloys (Wang *et al.*, 2018). The α/β two-phase titanium alloy is characterized by a granular microstructure composed of pre-β phase grains, and there is a α phase network on its boundary. There is a grain group of α-phase laths inside the grains, which nucleates during the phase transformation, mainly on the grain boundaries

(Liang *et al.*, 2014), as shown in Figure 1. Due to the inhomogeneity of the microstructure and the incompatibility of the deformation of the two phases, the boundary regions of the α grains in the organization of the two-phase titanium alloys and the α/β interfaces in the basketweave microstructure are considered to be relatively fragile because internal cracks in the material tend to sprout and expand in these regions (Zuo *et al.*, 2008).

Due to the low thermal conductivity and mechanical properties of titanium alloys, Ti-6Al-4V performs differently during machining, especially when using a round-edged tool for micro-scale machining (Pratap *et al.*, 2022). Zhao and Liu (2020) observed the plastic flow on the machined surface during the ultrasonic assisted roll polishing of Ti-6Al-4V. It is found that accumulation and deformation are the main material flow mechanisms, and the height of the workpiece changes little after polishing. Wang *et al.* (2020a) studied the chip formation and surface formation mechanism considering the progressive wear of cermet cutting tools. The main forms of surface defects are feed marks, metal debris, plastic deformation, stains and grooves. The cross-sectional geometry of the chip is jagged, the minimum chip thickness is 6.31 μm and the segmentation degree is 0.24. The transition from α-Ti to β-Ti occurs during tool wear in microchips. Chen *et al.* (2021) carried out high-speed cutting of Ti-6Al-4V and observed the material removal mechanism related to time-related microstructure changes. Ductile shear parabolic pits and tensile ellipsoid pits were observed on the free surface of the u-HSC (ultra-high-speed cutting) segmented chips of Ti-6Al-4V alloy, indicating that there were severe shear and tensile plastic deformation along the adiabatic shear band (ASB) and the free surface of the segmented chips.

Although metal AM technology has greatly promoted the development of the manufacturing industry, there are still many defects and anomalies in the actual manufacturing process (Fu *et al.*, 2022). These defects and anomalies will reduce the mechanical properties of materials. Strantza *et al.* (2019) studied the residual stress distribution of different layers of Ti-6Al-4V material fabricated by laser metal deposition (LMD) and proposed a quantitative method for the meso-scale and directional changes of residual stress. Emminghaus *et al.* (2021) pointed out that powder recovery will lead to the increase of surface roughness of the top and side of Ti-6Al-4V fabricated by PBF-LB/M (laser-based powder bed fusion of metals) process. Walker *et al.* (2017) pointed out that when the laser energy density is insufficient, a cavity structure will be formed inside the metal fabricated by AM, which may wrap the unmelted metal powder to form a lack of melting (LOF). Moreover, during the melting process of the powder, the air in the metal powder will expand to form pores in the material. Romanenko *et al.* (2022) studied the residual stress and



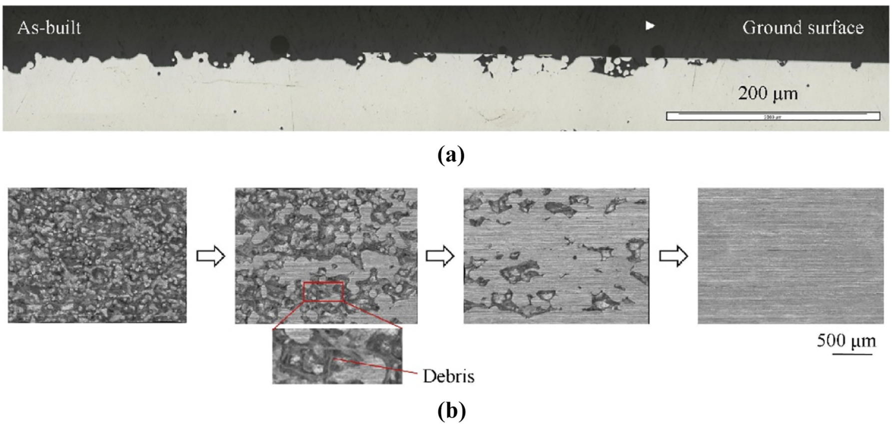
Source(s): Figure courtesy of Liang *et al.* (2014)

Figure 1. Microstructure diagram of two-phase (α/β) titanium alloy

deformation of Ti-6Al-4V parts generated under various powder-based directed energy deposition (DED) process parameters and strategies and found that the residual stress and deformation of the layer near the substrate were larger.

The microstructure characteristics of titanium alloy in AM and the defects left inside the material during the AM process bring new challenges to the grinding process of additive titanium alloy. Guo *et al.* (2021) found that part of the melt particles in the surface area of the additive metal were the main reason for the large surface roughness. During the grinding process, this part of the melt layer is gradually removed, and the change of roughness is closely related to the grinding depth. When part of the melt layer is completely removed, the surface roughness is stabilized, and the tool trace becomes the main component influencing factor. In addition, long and thin fragments were observed in the pits on the surface. This is due to the intermittent grinding between particles during the grinding process, as shown in Figure 2. The material of this layer will bring instability to the integrity of the grinding surface, so it is necessary to control the grinding depth to exceed the thickness of the partially melted layer during the grinding process. The surface roughness of SLM-processed parts is about 20% lower than that of forged parts (Polishetty *et al.*, 2017). This is due to the high hardness and reduced ductility of AMed materials, which limits the peak transverse plastic flow on the machined surface. In a study, Shunmugavel *et al.* (2016) also compared the machinability between forged and SLMed Ti6Al4V. It is found that the cutting force is high when machining AMed Ti6Al4V, which increases the cutting temperature and tool/chip wear, resulting in severe viscous abrasive wear. Rotella *et al.* (2018) studied the surface integrity of AMed Ti6Al4V fabricated by Electron Beam Melting (EBM) and Direct Metal Laser Sintering (DMLS). After turning at different cutting speeds, it is found that the roughness of AMed parts is about 10–20% higher than that of forged parts, which is different from the results of Polishetty *et al.* (2017). The affected layer with plastically deformed grains was found on the machined surface, and the thickness of the layer increased with the increase of cutting speed. At each cutting speed, the thickness of the affected layer of the EBM processed part is the largest (21–24 μm), followed by the DMLSed parts (18–22 μm) and the forging part (less than 17 μm). Therefore, how to reduce the defects in the process of metal AM through process parameter optimization and how to reduce the influence of defects on materials through subsequent processing have become an urgent problem for Metal Additive Manufacturing Technology (MAMT).

The thermo-mechanically processed titanium alloy exhibits a hierarchical structure of macro-sized β-axis grains, including α/β grain structure, composed of finer α and β lamellar



Source(s): Figure courtesy of Guo *et al.* (2021)

Figure 2. Topography evolution of the grinding process from the tip of the protrusion particle to the surface of the material: (a) Cross-sectional view of surface evolution and (b) Top views

grains (Nath *et al.*, 2022), while the martensitic α' microstructure is common in the additively manufactured Ti-6Al-4V sample, showing high strength and low ductility (Spigarelli *et al.*, 2022), as shown in Figure 3. There are differences in the microstructure of titanium alloy manufactured by the two processes. The size effect of Ti-6Al-4V submillimeter structure fabricated by SLM is crucial for metal mechanical metamaterials with unique mechanical properties, such as negative Poisson's ratio and ultra-high modulus. Compared with forging materials, the hardness, yield strength and ultimate tensile strength of additively manufactured titanium alloys are higher. These enhanced mechanical properties significantly affect the tool-workpiece interaction and the plastic deformation process of chip formation, thereby affecting the cutting force and ultimately affecting the integrity of the machined surface. Kishawy *et al.* (2023) pointed out that the increase in the hardness of titanium in AM leads to faster tool wear, especially when processed at higher feed and speed, which eventually leads to higher cutting force. However, at low feed and low speed, forging and AM titanium machining produce almost similar cutting forces. It was also found that the machining direction and the printing direction had no significant effect on the cutting force or tool wear. Compared with forged titanium, the adiabatic shear in AM titanium sheet is proved to be more obvious, resulting in deeper shear bands. At present, many scholars have studied the grinding process of titanium alloy (Handa *et al.*, 2021; Zhao *et al.*, 2021; Huang *et al.*, 2021), and some scholars have studied the surface microstructure and properties of titanium alloy obtained by AM (Yang *et al.*, 2022; Wang *et al.*, 2022b). However, the existing research does not reveal the relationship between grinding parameters and surface integrity of additive titanium alloy, and the grinding process of AM titanium alloy is still a research direction.

3. Robot grinding method for blades

3.1 Grinding trajectory planning and accuracy control of robots

Abrasive belt grinding is an excellent finishing method. Its characteristics of low grinding heat, small grinding force and flexible processing can help robots achieve low damage processing of titanium alloy blades. In the aspect of abrasive belt grinding mechanism, Zhou *et al.* (2023) studied the relationship between the wear of electroplated diamond abrasive belt and the surface integrity of Cr-Ni-Fe alloy 718. The research shows that with the wear of abrasive grains, the roughness of the grinding surface is significantly reduced. Xiao *et al.* (2022a) found a set of suitable abrasive belt grinding parameters through experiments, which can reduce the surface roughness and residual stress of GH4169 super alloy and effectively improve the fatigue performance of the alloy. He *et al.* (2023) obtained the surface of high-strength titanium alloy by laser abrasive belt collaborative processing, which effectively reduced the defects of the grinding surface. Traditional abrasive belt grinding is usually carried out by computer numerical control (CNC) grinding machine to remove the material on

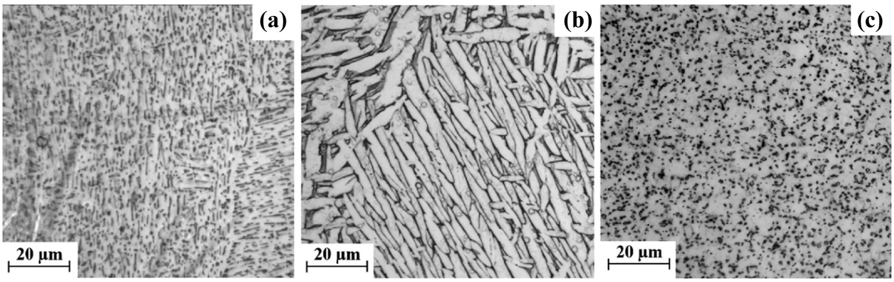
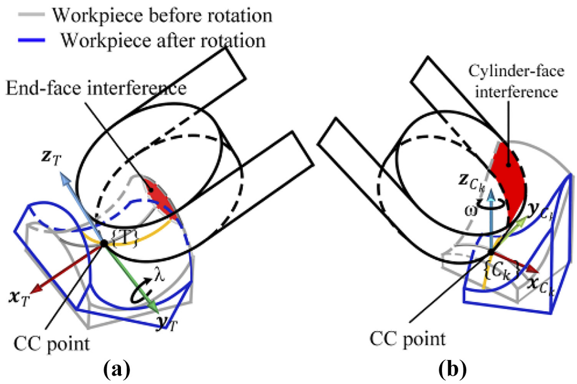


Figure 3. Microstructure of titanium alloy under different processes: (a) EBM, (b) DMLS and (c) forging titanium alloy

Source(s): Figure courtesy of Rotella *et al.* (2018)

the surface of the part. However, for parts with complex structures or large changes in surface shape, it is difficult for CNC grinding machines to accurately grind along the surface trajectory, and the system for generating trajectory programs is usually more complex. Because of its high degree of freedom and good adaptability, robot is widely used in the processing of complex curved surface parts.

The complex surface of the blade generates a robot grinding trajectory through trajectory planning. The quality of the trajectory planning method has a profound impact on the surface integrity and machining accuracy of the blade surface. Scholars have carried out a lot of research on robot trajectory planning methods. Wang *et al.* (2023) proposed an offline-online planning framework that combines the offline generation of the shortest grinding path and the online control of the contact force. In the case of unknown workpiece size and arbitrary distribution of grinding points, the shortest grinding path is adaptively generated by size estimation and optimal sorting algorithm based on double ant colony system (DACS). Xie *et al.* (2022) established two common interference correction spaces with grinding methods (grinding wheel surface grinding and grinding wheel edge grinding) and modeled various types of interference and their correction strategies. Then, two b-spline attitude curves for the rotational motion and translational motion of the workpiece used to correct the interference in the entire tool contact curve are given. Using these two b-spline curves, a tool path planning algorithm for robotic belt grinding of complex parts based on surface division, iterative correction interference and grinding position smoothing is further proposed, as shown in Figure 4. Wen *et al.* (2022) proposed a tool path planning strategy, which can provide a completely uniform coverage of free-form surfaces or surfaces with minimal overlap and provide an efficient path generation method based on dichotomy. The spacing between adjacent path segments is determined by the contact area, which is related to the position and changes along the surface according to its principal curvature, as shown in Figure 5. Du *et al.* (2023) modeled the D-H kinematics of the robot and used the pose separation method to solve the inverse kinematics of each path point. Then, the traditional cubic spline interpolation is improved, and the midpoint of the starting and ending segmentation interval time is corrected. At the same time, it is effectively combined with the improved particle swarm optimization algorithm, which shortens the movement time of the robot by about 30% and greatly improves the work efficiency. Gao *et al.* (2023) proposed a method of robot flexible polishing system instead of manual polishing blade. A trajectory planning algorithm based on cross-section method and nonuniform rational basis spline (NURBS) curve fitting is proposed to reverse the polishing trajectory of the robot. The algorithm is used to extract the



Source(s): Figure courtesy of Xie *et al*. (2022)

Figure 4. Robot trajectory correction: (a) Rotate the workpiece along the axis y_T and (b) rotate the workpiece around the axis z_{Ck}

Algorithm 1: Path Generation Algorithm.

Input : Surface description (as NURBS) and overall boundary of the entire surface
Output: Continuous path segments that provide uniform coverage and surface normals

Initialization: seed curve with base points $\boldsymbol{p}_{i,0}$ for $i = 0, \dots, n$ and set $j = 1$;
while *End of surface boundary not reached* **do**
  for $i = 0 : n_j$ **do**
    $\boldsymbol{p}_{i,j}$ = Bisection($\boldsymbol{S}_{i,j} \cdot \vec{\boldsymbol{j}}, \boldsymbol{S}_{i,j} \cdot \vec{\boldsymbol{j}} + 2r$);
    Calculate contact area at $\boldsymbol{p}_{i,j}$;
    Extract upper boundary at $\boldsymbol{p}_{i,j}$ as $\boldsymbol{b}_{u,i,j}$;
  end
  Interpolation: $\boldsymbol{b}_{u,:,j} \rightarrow \boldsymbol{S}_j$;
  Calculate arc-length of $\boldsymbol{S}_j$ and determine n_j;
  $j = j + 1$;
  Side-step interpolation;
end
Extract surface normal vectors along the path.

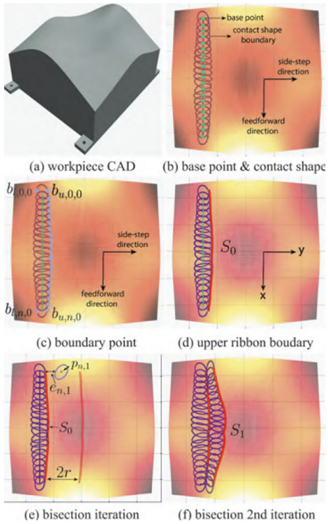


Figure 5.
Curved surface machining trajectory planning

Source(s): Figure courtesy of Wen *et al.* (2022)

key tool contact points, which can control the fitting error within a given range and improve the machining quality of the blade.

For the higher hardness, yield strength and ultimate tensile strength of AM titanium alloy, the grinding force in the grinding process will be different from that of traditional forged titanium alloy. Song *et al.* (2023) analyzed the relationship between grinding force and grinding depth in robot belt grinding in detail and established the robot processing pose error model considering the deformation of grinding head. As shown in Figure 6, the Inconel 718 alloy processing experiment of robot belt grinding was designed and the mapping relationship between grinding force and grinding depth was obtained, so as to obtain the relationship between grinding force and grinding depth of additive material. For the problem of uneven distribution of blade grinding allowance, Lv *et al.* (2022) proposed a geometric algorithm for dynamic calculation of tool contact points based on modified calculation model and dichotomy. Subsequently, an off-line machining program is generated based on the

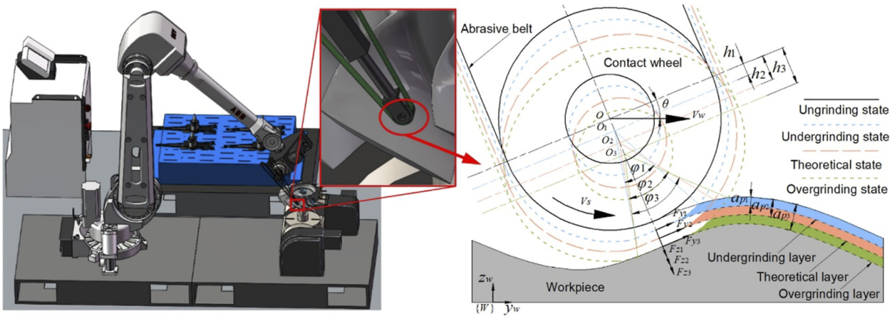


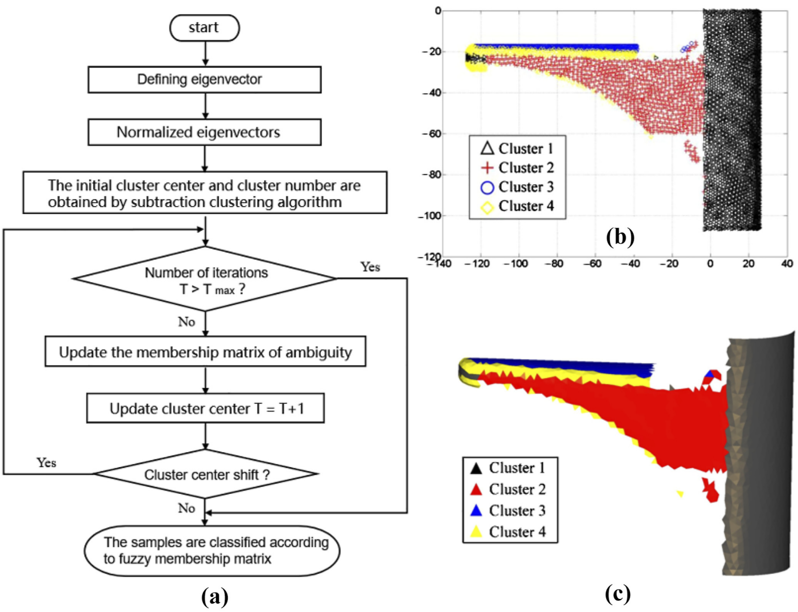
Figure 6.
Robot belt grinding force depth model

Source(s): Figure courtesy of Song *et al.* (2023)

double vector control method to obtain the best contact posture and perform robot grinding experiments on titanium alloy blades to obtain higher machining quality and machining efficiency.

In the manufacturing process of additive materials, the surface morphology and microstructure characteristics of different material stacking directions are also different, and the curved surface structure of the additive blade will inevitably lead to different material characteristics of the blade surface. For this feature, Xie *et al.* (2020) proposed a region-based robotic belt grinding method. The surface to be ground is divided into different regions, and then by imitating the behavior of experienced workers in manual grinding to avoid gouging, an algorithm for selecting a compatible belt grinding mode for the partitioned region is proposed, as shown in Figure 7. Lv *et al.* (2020) proposed an equal scallop height algorithm based on material removal profile (MRP) model, constructed an adaptive trajectory planning algorithm based on MRP model and proposed an improved equal chord height error method considering the influence of elastic deformation to improve the contour accuracy in robotic belt grinding. Xu *et al.* (2021) proposed an active force control method based on a six-axis force/torque sensor and a PI/PD controller to eliminate wear marks and traces. The over-cutting and under-cutting phenomena in the robot processing system are reduced by the passive control of the PID controller of the one-dimensional force sensor. The Kalman filter information fusion method is used to combine the active and passive control methods to improve the accuracy and efficiency of the controlled force.

In order to realize the precision control of robot belt grinding and polishing, it is also necessary to build a robot surface belt grinding model. Ren *et al.* (2023) established a material removal depth profile (MRDC) prediction model for curved belt grinding based on material removal rate (MRR), using MRR, the normal force of the workpiece and the grinding tool at the contact point, the feed rate and the physical and geometric parameters to establish a model to predict MRDC. Zhang *et al.* (2022) proposed a nonlinear material removal depth



Source(s): Figure courtesy of Xie *et al.* (2020)

Figure 7.
Grinding area division of complex surface: (a) Program for fine surface partition, (b) clustering results of center points of triangular surface and (c) corresponding clustering results of triangular surface

model, which is applied to the robot automatic grinding aviation blade system. Considering the non-linear relationship between contact force and other grinding parameters (belt speed, feed rate and contact force), the parameters of MRD model are solved and evaluated by multiple linear regression method, as shown in Figure 8.

3.2 Low damage grinding and polishing method for robots

Due to the characteristics of laser additive titanium alloy, there are micropore enrichment layers on its surface, which are prone to cracks during grinding. Micro-cracks may also be generated during the abrasive belt grinding process. These micro-cracks usually extend continuously during the working process of the workpiece, which eventually leads to the failure of the workpiece. Therefore, in the process of machining, not only the machining accuracy of the workpiece should be considered, but also the surface machining quality should be considered. At the same time, the titanium alloy structure will produce plastic flow on the grinding surface, as shown in Figure 9. Zhu *et al.* (2020) used single-grained scratch simulation based on an improved chip thickness model, combined with the tool-workpiece meshing elastic module, to explore the damage mechanism from the aspects of micro-crack initiation, propagation and suppression. The critical depth of cut for the transition from brittleness to ductility of zirconia ceramics was determined to be 0.42 μm. When the

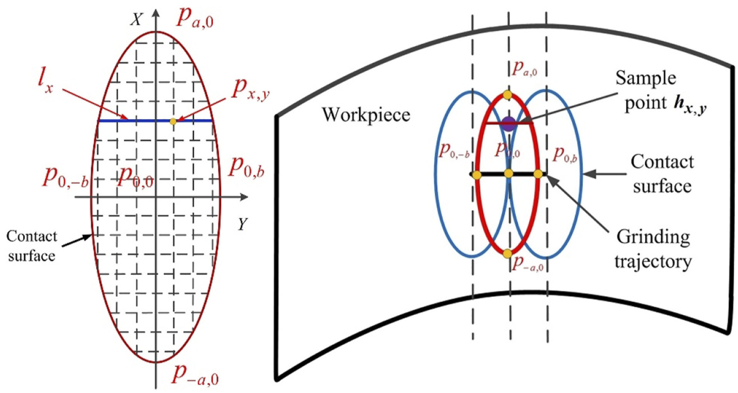


Figure 8. MRD model

Source(s): Figure courtesy of Zhang *et al.* (2022)

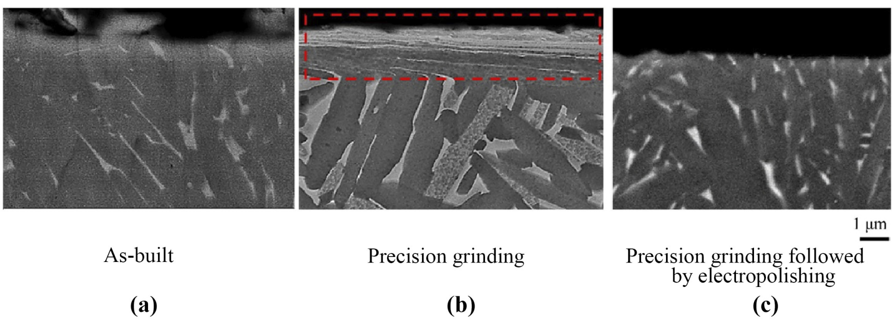


Figure 9. Subsurface morphology of additive titanium alloy: (a) As-built, (b) precision grinding and (c) precision grinding followed by electropolishing

Source(s): Figure courtesy of Guo *et al.* (2021)

maximum UCT (undeformed chip thickness) exceeded 0.42 μm, transverse cracks began to appear and brittle removal became dominant. In brittle grinding, high abrasive particle velocity can help significantly improve the surface integrity of the workpiece by inhibiting the median/radial cracks generated when the maximum UCT is close to 0.8 μm.

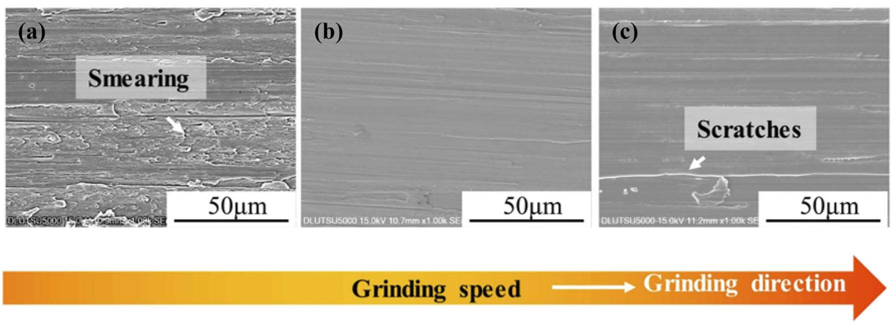
Grinding parameters have a significant effect on the low damage processing of materials. Qiao *et al.* (2023) found that at a grinding speed of 28.75 m/s, due to severe plastic deformation at low strain rates, serious stains appeared on the grinding surface of titanium alloy samples (Figure 10a) manufactured by AM. With the increase of grinding speed, the adhesion area of grinding surface decreases obviously. More severe grinding scratches occur at higher grinding speeds (Figure 10c), which leads to embrittlement of the material at high strain rates (Yang and Zhang, 2019). Therefore, in order to realize the low damage grinding and polishing of robot abrasive belt, it is necessary to control the grinding speed within the appropriate range.

Due to the existence of pores in the additive blade is inconsistent with the material properties, the grinding force tracking of the robot in the grinding process is usually in a nonlinear and time-varying environment. Accurate force and trajectory tracking is challenging in nonlinear and time-varying environments. Considering the inherent uncertainties and environmental factors in the process of robot grinding and polishing, the dynamic tracking of contact force becomes a key challenge. Based on the uncertain environment, many researchers have proposed different control strategies. Zhou *et al.* (2021) proposed a hybrid control strategy of grinding and polishing robot based on adaptive impedance control, which realized adaptive stress control and position tracking control under impact conditions. The experimental results show that the motion curve is consistent with the surface morphology of the workpiece, and the contact force is stable at 103 N. The established adaptive impedance control is shown in Figure 11. Chen *et al.* (2005) proposed a high-precision impedance control method of fuzzy controller with self-regulating quantitative factor. This method can not only realize real-time control by adjusting impedance parameters, but also enhance system stability and dynamic characteristics. The feasibility and effectiveness of the strategy are verified by the simulation of the free-form surface polishing manipulator. The established control model is shown in Figure 12.

4. Processing methods for additive blades

4.1 Model reconstruction method of additive blades

In addition to shape accuracy, the machined surface state (surface integrity) of complex thin-walled components in aero-engines is another core factor affecting their performance in



Source(s): Figure courtesy of Qiao *et al.* (2023)

Figure 10. SEM images of the surface morphology of additive manufacturing samples at different grinding speeds of 28.75–232.66 m/s

actual operation. The manufacturing quality problems of key components can be attributed to the lack of clear surface state generation mechanism, insufficient research on the relationship between manufacturing surface state and service performance, lack of relevant basic data and failure to grasp process control rules. After Field and Callus proposed the concept of surface integrity in 1964, they published the national standard of surface integrity and then formulated the relevant process specifications and acceptance criteria for key components, that is, the machined surface state is usually characterized by stress concentration factor (SCF), surface residual stress, surface microstructure and surface three-dimensional morphology. Cheng *et al.* (2017) used the fractal function to reconstruct the contour of the machined surface and used the SCF to evaluate the stress concentration of the machined surface. They also applied polynomial functions and sine decay functions to determine the gradient distribution of surface micromechanical properties using parameter characterization methods. Imran *et al.* (2011) divided the cutting surface layer into nanostructured surface layer, deformed secondary surface layer and material matrix and then evaluated the cutting surface layer by grain size, nano-hardness, plastic deformation and crystal orientation difference.

Reverse engineering (RE) is mainly used to redesign components to obtain CAD models for rapid prototyping (RP) or rapid manufacturing (RM) and most RE applications are focused on surface modeling to adapt to CAD/CAM systems for product design, replication, manufacturing or inspection. Because the reconstruction of the new theoretical processing model will inevitably produce errors, the defect area calculated by comparing the actual model with the theoretical processing model is very unstable. The existing method of locating defect regions based on point cloud features is suitable for point clouds with different boundary features. Since the materials of AM usually face many defects, the reconstruction process of its model faces challenges. In view of the fact that the scanning data of the wear area is not suitable for the creation of nominal geometry, Wang *et al.* (2020b) used RE to

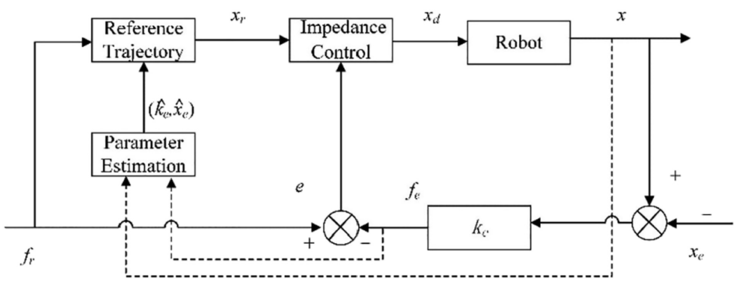


Figure 11. Adaptive impedance control model

Source(s): Figure courtesy of Zhou *et al.* (2021)

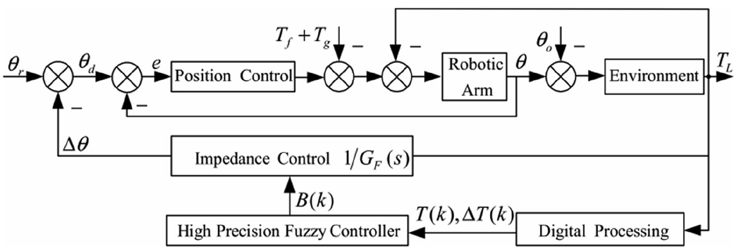


Figure 12. Flow chart of high precision fuzzy impedance controller

Source(s): Figure courtesy of Chen *et al.* (2005)

reconstruct the geometry of the defect area with damaged original geometry and developed a reconstruction method based on non-defect area data to reconstruct the geometry of the defect area. In this paper, a nominal geometric reconstruction method for subsequent repair processes that include AM process and mechanical processing is proposed. Based on the created nominal geometry, the tool paths generated during welding and machining can be adaptively adapted to the geometry of a single blade to achieve accurate repair of curved blades. Chen and Medioni (1992) obtained the point cloud data at the defect by comparing the design model with the real model and then superimposed it on the design model to obtain a new theoretical processing model. The dense point cloud data obtained by scanning the whole blade profile is huge and the background point cloud must be removed in other ways in the later stage. Zhao *et al.* (2017) proposed a measurement-based free form deformation (FFD) method for geometric reconstruction of the final nominal shape. Firstly, the original shape is cut into several sections according to the design method. Then, each section is modified by FFD based on a set of organized measurement points. Finally, the final nominal shape is reconstructed by lofting these modified sections. Zhao and Xu (2021) used the registration algorithm to find the best position between the design shape and the measuring point on the machine and then established a nonlinear constrained optimization model to find the feasible point within the tolerance range, considering the contour occupancy rate, thickness occupancy rate and machining allowance inhomogeneity. Finally, a new process shape is constructed based on these feasible points, which can be used for adaptive machining of curved thin-walled parts. This method is also applicable to parts with complex surfaces such as blades.

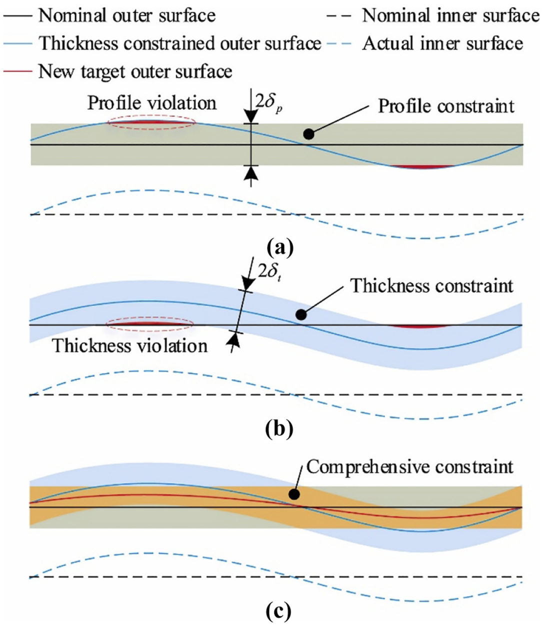
4.2 Residual extraction technology

Due to the deviation between the actual processing model and the theoretical model, and in order to ensure the machining accuracy of the blade and reduce the scrap rate of the parts, the blade needs to be reconstructed before processing. The model reconstruction is obtained by the blade section curve. The measurement strategy of these section curves determines the measurement accuracy and the distribution of measurement points, which has a great influence on the calculation accuracy and efficiency of the constrained optimization solution. Model reconstruction requires registration, that is, model matching. Registration plays an important role in the proposed model reconstruction strategy. Due to the misalignment of each coordinate system, there are some displacement and rotation errors between the measurement point and the corresponding design model. The purpose of registration is to find the appropriate position and obtain the rotation matrix R and the translation matrix T between the measurement point and the design model. In 1992, Besl and Mckay proposed to use the iterative closest point (ICP) method to solve the registration problem. The model registration is realized by two steps: the nearest point calculation and the transformation matrix solution. The essence of the ICP algorithm is to find the associated point set between the target point cloud and the reference point cloud according to the Euclidean distance minimization criterion and then calculate the transformation matrix that can maximize the overlap of two point clouds. At the same time, the Tangent-squared Distance Minimization (TDM) (Chen and Medioni, 1992) algorithm is also widely used to match the output of 3D scanners. TDM studies the calculation of rigid body transformation from the perspective of geometry and optimization. The constraints based on instantaneous kinematics and the quadratic approximation of the squared distance function are used in conjunction with the tangent plane of the nearest point.

Due to the existence of a partially melted layer on the surface of the additive material, the surface of the additive blade is usually faced with many bumps and pits, which will make the margin extraction process of the blade face many noise points. Tian *et al.* (2023) proposed a technical framework for robot profiling of blade edges based on the measurement-processing integrated manufacturing strategy. Firstly, the leaf model is reconstructed. A hand-eye calibration method based on robot relocation is proposed to obtain the conversion relationship between the robot base coordinate system and the scanner. This paper proposes an improved dynamic threshold constrained ICP matching algorithm to avoid the matching process falling into the local optimal solution. Combined with point cloud splicing and denoising, the blade model is accurately reconstructed. Then the trajectory is re-planned and processed. In the case of fully considering the dynamic problem between the pulley and the blade, a trajectory re-planning method based on the equal scallop height algorithm of MRP model and an optimized constant chord height error algorithm are proposed. The path and grinding point of the edge area of the blade to be machined are adaptively planned according to the blade curvature. The trajectory re-planning processing method using the self-developed closed-loop control software can effectively eliminate the margin of the blade edge without over-cutting. Li *et al.* (2011) proposed a new point-plane distance based on the distance function described by point representation, in which the point-plane shortest distance iterative registration algorithm is considered, and a nonlinear optimization model is established to calculate the optimal transformation. The convergence of the proposed algorithm is derived and analyzed from the perspective of geometric optimization. Sun *et al.* (2022) extracted important process features of blade parts to improve the matching efficiency with point clouds and used the normal direction of the contour after fine grinding as the normal direction of registration. The objective function of minimizing the residual variance is constructed to improve the uniformity of grinding depth. The overall uniformity of the calculation results is also considered. By constraining the shape center of the two point cloud models, the effect of non-tangential distance tampering is achieved.

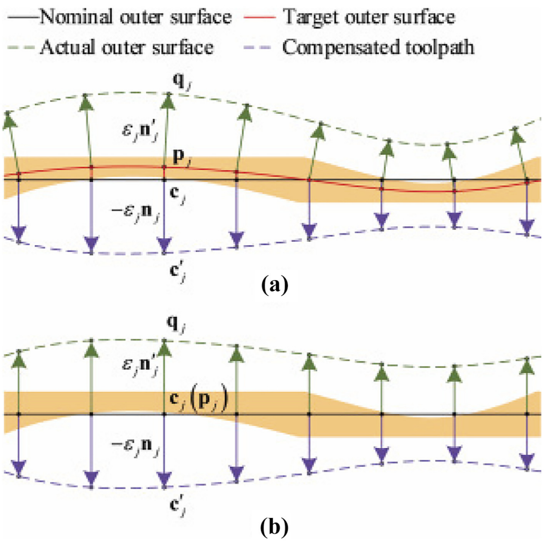
4.3 Grinding error compensation technology of blades

As a comprehensive manufacturing technology, adaptive machining integrates functions such as state perception, real-time analysis, autonomous decision-making and precise execution. By comparing the measured data, the state of the machining process can be determined, and then the machining strategy can be independently formulated according to the results, and finally, the machining program suitable for the current machining state can be generated (Gao *et al.*, 2008). In addition, once the shape and position of the processing object changes, the numerical control (NC) processing scheme can be customized for each individual processing object by adjusting the processing program. For the complex thin-walled parts of aero-engine, the adaptive machining method should also be integrated with deformation prediction and error compensation. Before the machining process, the current state of the blank is obtained by measurement, and the following NC machining parameters are adjusted by comparing the blank design model. Subsequently, adaptive machining technology is used for further digital measurement, adaptive workpiece clamping, positioning and positioning, process model construction and NC machining programming. Many scholars have tried to find an error compensation method to ensure the surface integrity during blade grinding. Zhang *et al.* (2023b) proposed a comprehensive compensation method for machining curved surface parts with contour and thickness tolerance constraints. Based on this method, the actual outer surface and inner surface of the workpiece are reconstructed. Then, based on the reconstructed workpiece geometry, a comprehensive constraint considering both contour and thickness constraints is established, as shown in Figures 13 and 14. Xu *et al.* (2021) proposed a grinding allowance extraction method considering the double size constraints of the inner and outer contours of the hollow blade. The two sizes of the inner and outer contours of the hollow blade were constrained, and the machining model of the blade was modified to obtain a more reasonable grinding



Source(s): Figure courtesy of Zhang *et al*. (2023b)

Figure 13.
Contour and thickness constraints: (a) Contour constraints, (b) thickness constraints and (c) comprehensive constraints



Source(s): Figure courtesy of Zhang *et al*. (2023b)

Figure 14.
Tool path error compensation: (a) Reconstructed outer surface as the target surface and (b) nominal outer surface as the target surface

allowance distribution. Xiao *et al.* (2022b) proposed a profile error reverse compensation strategy based on the robotic abrasive belt grinding process and the blisk structure. Based on the proposed contour error compensation strategy, a new step-row spacing optimization adaptive trajectory planning method is proposed to reduce the contour error of the blisk surface.

5. Summarized and prospected

In summary, the additive titanium alloy blade is easy to cause processing damage due to its material properties, and the molten metal particles adhere to form a rough surface of the material, which requires subsequent low-damage processing to improve its surface quality. In addition to the difficulty of material processing, the complex surface of the blade is also difficult to carry out traditional numerical control processing. In this regard, robot belt grinding can solve the processing problem of additive titanium alloy blades. The complex surface of the blade generates a robot grinding trajectory through trajectory planning. The trajectory planning of the robot profoundly affects the machining accuracy and surface quality of the blade. Subsequent research needs to solve the problems of high machining accuracy of blade profile, complex surface material removal model and uneven distribution of blade machining allowance. In the process parameters of the robot, the grinding parameters, trajectory planning and error compensation affect the surface quality of the blade through the material removal method, grinding force and grinding temperature. The machining accuracy of blade surface is affected by robot vibration and robot stiffness. Therefore, the robot belt grinding of additive titanium alloy blade requires correct trajectory planning method and its precision control. With the development of intelligent manufacturing, robot grinding of additive titanium alloy may be able to obtain the optimal process parameters through accurate prediction models in the future and obtain better surface quality and machining accuracy.

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