Article

Plane Machining by Inner-Jet Electrochemical Milling of TiB₂/7050 Aluminum Matrix Composite

Binsen He , Hansong Li *, Xin Ma, Jie Li and Shukai Fan

College of Mechanical & Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China; hebinsen1209@163.com (B.H.); xinma24@nuaa.edu.cn (X.M.); lj960301@163.com (J.L.); arienfan@126.com (S.F.)

* Correspondence: hsl@nuaa.edu.cn

Abstract: Electrochemical milling (ECM) is an ideal technique for machining thin-walled structural parts of aluminum matrix composites. Adopting a reasonable tool cathode structure, feed rate, and processing method can improve the machining efficiency. In this study, a tool cathode with a reasonable structure was selected through flow field simulation. Then, the material removal rate (MRR) and surface roughness were studied using various ECM parameters. Finally, the transverse movement and processing method in which the starting position was rotated 90° were studied, and a plane of 59 × 59 mm was machined. The experimental results show that using an appropriate tool cathode can create a more uniform flow field. The MRR was 168.6 mm³/min and the surface roughness (Ra) was 3.329 μm at a feed rate of 30 mm/min. For machining larger plane structures, a transverse movement of 7 mm is verified to be the most suitable because of the best smoothness in the middle of the two processes. By using the same machining method and rotating the starting position 90°, the flatness of the processing plane decreased from 0.296 mm to 0.251 mm, a reduction of 15.2% compared to that obtained in the first processing.

Keywords: TiB₂/7050; electrochemical milling; flow field simulation; material removal rate

Citation: He, B.; Li, H.; Ma, X.; Li, J.; Fan, S. Plane Machining by Inner-Jet Electrochemical Milling of TiB₂/7050 Aluminum Matrix Composite. *Appl. Sci.* **2021**, *11*, 8087. <https://doi.org/10.3390/app11178087>

Academic Editors: Alexey S. Prosviryakov, Alexey N. Solonin, Kotov Anton and Andrea Paglietti

Received: 20 July 2021

Accepted: 28 August 2021

Published: 31 August 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The TiB₂/7050 aluminum matrix composite has received intensive attention because of its high specific strength, high wear resistance, fatigue resistance, and low cost [1–4]. These properties make it potentially suitable for various structural applications such as aerospace, automobile industry, and even in medical fields owing to its remarkable characteristics in comparison with conventional alloys [5–8].

During the traditional process, owing to the presence of hard ceramic particles, the tools are worn out at the initial tool wear stage, which indicates that the wear of the tool is rapid [9,10]. In addition, monolithic parts are usually manufactured directly from the entire blank, and the material removal rate (MRR) of some parts exceeds 70% [11], which leads to a high cost of machined aluminum matrix composite monolithic parts. For this reason, it is necessary to explore efficient and low-cost processing methods for monolithic aluminum matrix composites. Electrochemical machining is a special manufacturing method that is based on the principle of electrochemical anode dissolution and produces no tool wear, no residual stress on the machined surface, and no burr, among other advantages [12,13]. Thus, the processing efficiency associated with electrochemical machining is high and it is suitable for processing difficult-to-cut materials. Electrochemical milling (ECM) uses an electrode with a simple shape and forms a machined surface along its path of movement under the control of a numerical control system. Electrochemical machining combines the low cost and high efficiency of electrochemical machining for difficult-to-cut materials with the numerical control technology and avoids the complicated design and manufacture of forming cathodes. The flexibility of electrochemical machining has been improved, and its application scope has been expanded [14].

According to the electrolyte supply, electrolytic milling can be divided into inner and outer sprays. In the electrochemical milling process, the electrolyte flow pattern has a large effect on process stability and efficiency. Initially, the outer spray electrolyte supply mode is applied. Kozak et al. [15] used a spherical tool electrode with an external nozzle to machine alloy tool steel NC6, and the thickness of material removal was 0.05 mm in a single pass. A. Ruszaj et al. [16] electrochemically machined alloy tool steel NC6 with a flat rectangular universal electrode and found that when machining with a flat electrode it was possible to reach higher metal removal rate and smaller machined surface waviness than in the case of machining with a ball-ended electrode. The machining depths were about 0.1 mm in a single pass when the feed rates were 59 mm/min. Hinduja et al. [17] electrochemically machined a simple square pocket and a pocket with a human-being shaped protrusion with tools having circular and square electrodes. The experimental results indicated that the groove width and depth of the cylindrical electrode were smaller than those of the square electrode. The machining depths were about 0.021 mm in one pass using a square cross-section electrode when the feed rates were 9 mm/min.

Subsequently, the inner spray electrolyte supply mode was introduced in electrochemical milling instead of the outer spray electrolyte supply mode. Compared with the external spray type, the internal spray can provide greater flow and higher pressure of the electrolyte, which can improve the removal energy of the electrolytic products attached to the anode, thereby improving the processing efficiency. M. Hackert-Oschätzchen et al. [18] used a continuous electrolytic free jet to obtain a high localization of the removal area and electrochemically machined a cavity with a depth of approximately 180 μm and a width of approximately 190 μm . M. Kang [19] presented the flow channel of a spherical electrode for electrochemical milling of stainless steel in which the electrolyte was ejected from seven holes at the bottom of this rotating electrode. When the feed rate was 50 mm min⁻¹, the machining depth was about 0.2 mm for a single pass. K. Mishra [20] machined a simple slot with length of 30 mm and depth of 1.2 mm, fabricated from Nimonic-263 alloy. The MRR were 0.23 g/min when the feed rates were 8 mm/min. H.S. Li and S. Niu et al. [21,22] proposed a flow channel structure for a rotating electrode with a dead-end tube used for the ECM of nickel-based alloy GH4169/Inconel 718. A sample with thin-walled structures was produced stably at a feed rate of 2.1 mm/min and a machining depth of 3 mm. The MRR was 282.9 mg/min at the maximum feed rate.

The above research results show that ECM can be used as a feasible process method for machining TiB₂/7050 aluminum matrix composites. However, the above-mentioned studies used either tube electrodes for electrochemical machining of planes or large-diameter hollow tools for electrochemical machining of grooves, cavities, etc. The smaller diameter tool results in a smaller conductive area. Therefore, the MRR was not high and the depth of the structure was also shallow. For large thin-walled parts, more materials must be removed during processing. If the tube electrode is used for processing, it will result in a long processing time and significant processing problems. Thus, the purpose of this work was to study the machining of large planes with hollow tools on a macroscopic scale. The present research proposed the design and development of a tool cathode suitable for large material removal, and a scheme optimization study was carried out through numerical simulation of the flow field. Subsequently, the MRR and surface roughness associated with various machining parameters were studied. In addition, the influence of different transverse movements on the machining surface topography was studied. Finally, with the appropriate transverse movement and processing route, a complete plane was processed.

2. Simulation Analysis

2.1. Flow-Field Simulation Model

The layout form of the liquid outlet on the end face of the tool cathode has an important influence on the distribution of the electrolyte flow rate in the processing area. Two layout forms of the liquid outlet are designed, and as shown in Figure 1 six liquid outlets are set on the end face of tool A with a diameter of 1 mm, and one outlet is located in the center

of the circle. The centers of the remaining liquid outlets are all located at the intersection of the bisector and concentric circle. There are two concentric circles on the end face with diameters of 5 mm and 8 mm, respectively. Because here, only the influence of the layout form on the flow field distribution is studied, it is necessary to avoid the influence of inconsistent discharge areas. Therefore, the measure of the area of the liquid outlets on tools A and B should be consistent. Tool B also has six outlets with a diameter of 1 mm, and the center of each outlet is located at the intersection of the bisector and concentric circles. There are three concentric circles on the end face, with diameters of 4, 6, and 8 mm. In addition, the tool cathode has an outer diameter of 10 mm, inner diameter of 9 mm, side wall thickness of 0.5 mm, and end wall thickness of 1 mm.

Figure 1. Design of the liquid outlet form of different cathode tools. (A) Tool A electrolyte outlet layout; (B) Tool B electrolyte outlet layout.

During ECM, the electrolyte enters the machining gap from the liquid outlet at the bottom of the tool cathode and finally flows out from the upper surface and back of the groove. Figure 2 shows the distribution of the electrolyte inside the tool cathode and the machining gap. The tool cathode moves in the three-dimensional space according to the set path and rotates with the spindle at a constant speed. Therefore, here, the sliding grid model is used to simulate the periodic rotation at a certain instant, which divides the calculation zone into two parts: the rotation zone and the stationary zone. The interface between the rotating and stationary domains is the grid interface. In the calculation process, the rotating domain rotates around the rotation axis with a change in the calculation steps, whereas the stationary domain remains stationary. The two regions realize the coupling of the flow field through kinetic transfer at the grid interface.

Figure 2. Schematic of electrolyte distribution.

According to the above analysis, a three-dimensional model of the machining flow field was established, as shown in Figure 3. The model consisted of two parts: a stationary

zone and a rotation zone. The electrolyte inside the tool cathode was the rotation zone, and the electrolyte outside the tool cathode was the stationary zone. An observation surface was set up in the flow field model, which coincided with the machined surface. The geometric parameters of the flow field model were as follows: the outer diameter of the tool cathode was 10 mm, the width of the groove was 10.4 mm, the gap between the tool cathode and the surface to be machined was 0.2 mm, and the gap between the tool cathode and the machined surface was 0.7 mm. In addition, to reduce the amount of grid calculation, the length of the groove was set to 7 mm and the height of the fluid inside the tool cathode was set to 2 mm. The FLUENT 18.0 module of the WORKBENCH software was adopted for the simulation calculation of the flow field in the machining gap. The boundary conditions and the calculation parameters are listed in Table 1. After the calculation, the machined surface was selected as the observation surface to examine the flow rate distribution of the electrolyte in the machining area.

Figure 3. Geometric model of flow field simulation.

Table 1. Flow field simulation parameters.

Parameter	Value
Inlet pressure (MPa)	0.6
Outlet pressure (MPa)	0
Side and bottom gap (mm)	0.2
Spindle speed (rpm)	500
Step times (s)	0.01
Total simulation times (s)	0.25

To simplify the calculation process of the flow field simulation, the following assumptions were made for the physical model [23]:

1. The fluid is a viscous continuous incompressible fluid. That is, the influence of changes in pressure and temperature on the density and volume of the fluid is ignored.
2. There is no slip between the fluid and the boundary. That is, there is no relative movement between the fluid and the solid boundary.
3. The fluid viscosity is constant.
4. The fluid is a Newtonian fluid, that is, the shear stress and shear strain of the fluid conform to Newton's law of internal friction.

The standard k - ϵ turbulence model is chosen for the liquid turbulence model because the fluid velocity is very high and the flow field is complex. Based on the above assumptions, the momentum and mass conservation equations, which are generally used for turbulent flow in ECM, are described next.

$$\rho \nabla \cdot u = 0, \quad (1)$$

$$\rho(u \cdot \nabla)u = \nabla \cdot \left\{ -pI + (\mu + \mu_T) [\nabla u + (\nabla u)^T] - \frac{2}{3} \rho K I \right\} + \rho g, \quad (2)$$

where p is the pressure, ρ is the density of the electrolyte, μ is its dynamic viscosity, u is the velocity vector along the x -axis, and g is the acceleration due to gravity.

2.2. Analysis of Simulation Results

To explore the influence of the outlet layout on the flow field distribution in the machining gap, a geometric model is established and the boundary conditions are set according to Section 2.1, and then the simulation calculation and post-processing are carried out. Figure 4 shows the distribution of the electrolyte flow rate in the machining gap at different times when tool A is used. From the simulation results, the distribution of the electrolyte flow rate is directly related to the layout of the tool cathode outlet. At the time of 0.06 s (180° rotation) and 0.12 s (360° rotation), the high flow rate region of the electrolyte is concentrated in the location of the liquid outlet. The flow field of the liquid outlet at the center of the tool cathode is relatively concentrated. Because the liquid outlet is at the center of the circle, even if the tool cathode rotates at different angles, the high-flow-rate area always acts on the center of the tool cathode [24]. In electrochemical machining, the flow field has a significant impact on the conductivity. The high-velocity flow zone can enhance product transport, decrease stray corrosion, and improve the machined surface quality. Further, electrolytic products accumulate at low flow rates, resulting in a significant change in the composition and concentration of the local electrolyte in the machining area, thus reducing the processing reaction rate [25]. Under the action of a non-uniform flow field for a long time, the difference between the high and low flow rates will lead to different MRRs. In long-period processing, the center of the groove corresponding to the center of the tool may be particularly concave.

Figure 4. Electrolyte velocity distribution in the machining gap at different times using tool A.

Figure 5 shows the distribution of the electrolyte flow rate in the machining gap at different times when tool B is used. The figures reveal that because of the influence of the layout of the tool cathode outlet, the high flow rate area in the machining gap is no longer always concentrated in the center of the tool cathode but is more dispersed around the center of the tool cathode as the tool cathode rotates. At the times of 0.06 s (180° rotation) and 0.12 s (360° rotation), the position of the liquid outlet changes, and correspondingly the position of the high velocity region is quite different. During the rotation of the tool cathode, the position of the electrolyte outlet facing the center of the tool cathode constantly changed, and the high flow velocity area was always concentrated near this position. Under different rotation angles of the tool cathode, the area suffering from high-speed electrolyte flow is enlarged to avoid the concentration of the high-velocity area in a small range. The flow field simulation shows that the flow field uniformity in the machining gap can be

improved in the center of the tool cathode during the rotation of tool B. Therefore, tool B was thus more suitable for performing the ECM testing study.

Figure 5. Electrolyte velocity distribution in the machining gap at different times using tool B.

3. Experimental

3.1. Experimental Set Up

Figure 6 shows photographs of tool A and tool B. The material of the tools was 304 stainless steel and the sizes of the tools were similar to the design part. The outer diameter was about 10 mm, inner diameter was 9 mm, side wall thickness was 0.5 mm, and end wall thickness was 1 mm. The side wall is treated with electrophoresis insulation to reduce the corrosion of the side wall electric field to the workpiece. The length of the insulated area was 40 mm, the uninsulated area was 20 mm, and the thickness of the insulating layer was 60 μm .

Figure 6. Photographs of tool A and tool B.

The test material was a TiB_2 /7050 aluminum matrix composite, and Table 2 presents the chemical composition of the TiB_2 /7050 aluminum matrix composite used in this study.

Table 2. TiB_2 /7050 aluminum matrix composite composition.

Element	Al	Zn	Ti	Mg	Cu	B	Zr
Wt.%	balance	6.7	3.78	2.27	2.24	1.55	0.13

In the present study, we imaged the macro-morphologies of machined surfaces using both a high-resolution camera and an optical microscope (DVM5000, Leika, Wetzlar, Germany). The cross-sectional profiles of the grooves were measured using a coordinate measuring machine (CONTURA RDS VAST XXT10126, ZEISS, Oberkochen, Germany). In addition, the surface roughness (R_a) of some machined surfaces was measured using a surface-finish instrument (Perthometer M1, Mahr GmbH, Göttingen, Germany).

3.2. Groove-Machining Experiment

In order to further study the influences of tools A and B on the groove machining, a set of contrast tests was carried out and the main test parameters are listed in Table 3.

Table 3. Main parameters of groove-machining experiment.

Parameter	Value
Electrolyte	NaCl aqueous solution
Concentration (wt%)	20%
Electrolyte temperature (°C)	30
Spindle speed (rpm)	500
Processing voltage (V)	30
Electrolyte pressure (MPa)	0.6
Initial machining gap (mm)	0.2
Feed rate (mm/min)	30

Figure 7 shows the grooves machined by different tools. For tool A, the material removal in the processing area is non-uniform, and obvious depressions can be observed in the middle of the groove. The reason is that the high flow rate region of the electrolyte is concentrated in the location of the liquid outlet. Even if the tool cathode rotates at different angles, the high-flow-rate area always acts on the center of the tool cathode, so the middle of the groove corrosion is rapid. As such, the processing depth of this region is deeper. Therefore, the adoption of tool B can obtain a relatively smooth machining surface. Based on the flow-field simulation and experimental results, tool B was selected to perform the next ECM testing study.

Figure 7. Grooves machined by different tool A and tool B.

In the cathode ECM process of bar tools, the feed rate has an important effect on the machining depth, machining efficiency, and surface quality. A feeding speed of 10–30 mm/min was selected to carry out the machining test, and the other main test parameters were the same as Table 3.

At 0.6MPa electrolyte pressure, the flow rate of the electrolyte is about 5.53 L/min, and the product can be almost conveyed from the machined surface at this flow rate. Figures 8 and 9 show cross-sectional photographs and profiles, respectively, of grooves machined using a variety of feed rates.

Figure 8. Cross-sectional photographs of machined grooves under different feed rates.

Figure 9. Cross-sectional profiles of machined grooves under different feed rates.

As can be observed from Figure 9, the machined slots gradually decrease with the increase in feed rate. When the feed rate was increased from 10 to 30 mm/min, the maximum groove depth decreased from 1.216 to 0.669 mm. However, a deeper processing depth does not necessarily imply a higher MRR, which is defined as follows:

$$MRR = \frac{\Delta M}{\rho t}, \quad (3)$$

where ΔM is the quality removed during machining, t is the total machining time, and ρ is the density of material, about 2.9g/cm³. The workpieces were ultrasonically cleaned before and after each experiment, and after drying, they were weighed with an analytical balance (accuracy 0.01 g) to calculate the weight of the quality. Figure 10 shows how the MRR and surface roughness vary with the feed rate. The MRR increases from 94.4 mm³/min to 168.6 mm³/min as the feed rate increases from 10 mm/min to 30 mm/min. The surface roughness (R_a) decreases from 5.787 μ m to 3.329 μ m over the same feed rate range. It can be concluded that increasing the feed rate within the 10 mm/min to 30 mm/min range serves to improve the processing efficiency and surface roughness.

Figure 10. Material removal rate and surface roughness with the feed rate.

3.3. Gear Mark Machining Experiment

Through the above flow field simulation and test verification, tool cathode B was selected to process the groove. However, it is difficult to use this tool to machine large plane structures. Plane structures need to be fed several times, and the flatness of the plane is related to the transverse movement of the two feed paths. The groove shape of the workpiece is low in the middle and high on both sides when it is processed once. If the amount of transverse movement of the two feed paths is large, the machining plane will appear as a convex shape of the gear mark because there is less overlap between two feed paths and less material was removed in the middle part of two feed paths. If the amount of transverse movement of the two feed paths is small, the overlap of two feed paths will be larger and the tool cathode will cause secondary corrosion on the bottom surface, which generates a pit on the machining plane. Therefore, the amount of transverse movement between the two feed paths is very important and the process parameters are presented in Table 4. Figures 11 and 12 show the gear marks corresponding to different transverse displacements.

Table 4. Main processing parameters for gear mark machining experiment.

Parameter	Value
Electrolyte	NaCl aqueous solution
Concentration (wt%)	20%
Electrolyte temperature (°C)	30
Spindle speed (rpm)	500
Processing voltage (V)	30
Electrolyte pressure (MPa)	0.6
Initial machining gap (mm)	0.2
Feed rate (mm/min)	30
Transverse displacement (mm)	6–9

Figure 11. Different transverse movements of the corresponding gear marks.

Figure 12. Cross-sectional profiles of machined grooves under different transverse movements.

As can be observed from Figures 10 and 11, when the transverse movement was 6 mm, the machining mark was concave. This is because the second processing of the first processing groove for the second corrosion caused excessive material removal and destroyed the bottom surface of the first processing groove. When the transverse movement was 9 mm, the machining mark had a convex shape. Because of the large transverse displacement, part of the anode workpiece material between the two feed paths cannot be completely covered by the tool cathode surface. Thus, it is not dissolved and removed, resulting in the anode workpiece surface bulge. With a decrease in the transverse displacement, the area of the undissolved material on the anode workpiece surface gradually decreased, and the side wall of the groove for the first time began to be corroded but not completely removed. Thus, the height of the bulge gradually decreased. When the transverse movement was 7 mm, the gear mark was the smallest. This is because the round angle of the side wall of the groove processed in the first time was completely removed by the second processing, and the bottom surface of the groove machined for the first time was not damaged.

3.4. Sample Fabrication

In this experiment, we used tool B and transverse displacement of 7 mm studied for the flat machining of the $\text{TiB}_2/7050$ aluminum matrix composite. The other process parameters are the same as Table 4. The processing path adopted in the experiment is shown in Figure 13, where the single processing length in the Y direction was 49 mm, and the single processing length in the X direction was 7 mm, and a rectangular plane with a length and width of 59 mm was processed.

Figure 13. Diagram showing firstly processing path.

To observe the flatness of the machined plane more clearly, the three-dimensional profilometer (VR-5000, Keyence, Osaka, Japan) was used to scan the contour of the machined surface, and the results are shown in Figure 14. It can be observed from the figure that the

first machining path cannot completely cover the entire processing area, so there are some unprocessed areas at the edge of the processing area.

Figure 14. Diagram of electrochemical milling of a flat surface.

To eliminate the unprocessed area produced after the first processing, the machined surface is leveled by rotating the direction of the cutter 90° . The secondary processing path adopted in the experiment is shown in Figure 15, where the single processing length in the X direction is 49 mm, and the single processing length in the Y direction is 7 mm. After secondary processing, the flatness of the processing plane was improved. The flatness of the processing plane decreased from 0.296 to 0.251 mm, a reduction of 15.2% compared to that of the first processing. The final processing results are shown in Figure 16.

Figure 15. Diagram showing secondary processing.

Figure 16. Diagram of secondary Processing of a flat surface.

4. Conclusions

The present research proposes the development of two types of tool cathodes for the efficient machining of the difficult-to-machine TiB₂/7050 aluminum matrix composite, with a processing plane of 59 × 59 mm. Experiments were performed using a flow-field simulation analysis and validated using the ECM test. The major conclusions of this study are as follows.

1. The flow field simulation results showed that the high-flow-rate area always acts on the center of the circle even if tool A rotates at different angles, which lead to different MRRs. For tool B, the position of the electrolyte outlet facing the center of the tool cathode constantly changed avoid the concentration of the high-velocity area in a small range.
2. When the feed rate is increased from 10 mm/min to 30 mm/min, the maximum groove depth decreases from 1.216 mm to 0.669 mm, the MRR increases from 94.4 mm³/min to 168.6 mm³/min, and the surface roughness (Ra) decreases from 5.787 μm to 3.329 μm. Therefore, by machining TiB₂/7050 aluminum matrix composite using a feed rate of 30 mm/min, the processing efficiency and surface roughness can be improved.
3. When the transverse movement is 6 mm, the cutting mark is concave, and when the transverse movement is 9 mm, the cutting mark is convex. When the transverse movement is 7 mm, the gear mark is the smallest because the round angle of the side wall of the groove processed in the first time is completely removed by the second processing, and the bottom surface of the groove machined for the first time is not damaged.
4. The TiB₂/7050 aluminum matrix composite sample is processed twice using the same cutting method and rotating the starting position 90°, which eliminates the unprocessed area and the flatness of the processing plane is improved. The flatness of the processing plane decreases from 0.296 to 0.251 mm, a reduction of 15.2% compared to that of the first processing.

Author Contributions: B.H. was responsible for the design of the experiment, conducted all the experimental testing, and wrote the first draft of this paper; H.L. was responsible for a detailed review of this journal paper; X.M. were responsible for the experimental data analysis; J.L. was responsible for the design of the flow-field simulation; S.F. contributed to the interpretation of the results. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (51875286).

Institutional Review Board Statement: This paper does not involve humans or animals.

Informed Consent Statement: This paper does not involve humans or animals.

Data Availability Statement: The data published in this research are available upon request from the first author and corresponding authors.

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

References

1. Liu, G.; Geng, J.; Li, Y.; Cai, L.; Wang, M.; Chen, D.; Ma, N.; Wang, H. Effects of Pre-Strain on the Microstructural Evolution and Mechanical Strength of In Situ TiB₂/7050 Al Composite. *Adv. Eng. Mater.* **2019**, *21*, 1900042. [\[CrossRef\]](#)
2. Yu, W.; Li, Y.; Chen, J.; Zuo, Z.; Chen, D.; An, Q.; Chen, M.; Wang, H. Experimental study on chip formation and surface quality in milling of TiB₂/Al alloy composites. *Mater. Manuf. Process.* **2020**, *35*, 1671–1679. [\[CrossRef\]](#)
3. Ma, Y.; Chen, Z.; Wang, M.; Chen, D.; Ma, N.; Wang, H. High cycle fatigue behavior of the in-situ TiB₂/7050 composite. *Mater. Sci. Eng. A* **2015**, *640*, 350–356. [\[CrossRef\]](#)
4. Gangadhar, T.G.; Girish, D.P.; Sathesh, J.; Chandra, A. Study on mechanical properties of Al7050 alloy hybrid composites by stir casting method. *Mater. Today Proc.* **2021**, *46*, 5980–5985. [\[CrossRef\]](#)
5. Aurich, J.C.; Zimmermann, M.; Schindler, S.; Steinmann, P. Effect of the cutting condition and the reinforcement phase on the thermal load of the workpiece when dry turning aluminum metal matrix composites. *Int. J. Adv. Manuf. Technol.* **2015**, *82*, 1317–1334. [\[CrossRef\]](#)

6. Lin, K.; Wang, W.; Jiang, R.; Xiong, Y. Effect of tool nose radius and tool wear on residual stresses distribution while turning in situ TiB₂/7050 Al metal matrix composites. *Int. J. Adv. Manuf. Technol.* **2018**, *100*, 143–151. [[CrossRef](#)]
7. Bian, R.; He, N.; Li, L.; Zhan, Z.B.; Wu, Q.; Shi, Z.Y. Precision milling of high volume fraction SiCp/Al composites with monocrystalline diamond end mill. *Int. J. Adv. Manuf. Technol.* **2013**, *71*, 411–419. [[CrossRef](#)]
8. Ramasamy, M.; Daniel, A.A.; Nithya, M. A review on aluminium (Al7050) metal matrix composite characteristics reinforced with titanium. *Mater. Today Proc.* **2020**, *43*, 1720–1723. [[CrossRef](#)]
9. Anandakrishnan, V.; Mahamani, A. Investigations of flank wear, cutting force, and surface roughness in the machining of Al-6061–TiB₂ in situ metal matrix composites produced by flux-assisted synthesis. *Int. J. Adv. Manuf. Technol.* **2010**, *55*, 65–73. [[CrossRef](#)]
10. Xiong, Y.; Wang, W.; Jiang, R.; Lin, K.; Song, G. Tool wear mechanisms for milling in situ TiB₂ particle-reinforced Al matrix composites. *Int. J. Adv. Manuf. Technol.* **2016**, *86*, 3517–3526. [[CrossRef](#)]
11. Wang, T.; Zha, J.; Jia, Q.; Chen, Y. Application of low-melting alloy in the fixture for machining aeronautical thin-walled component. *Int. J. Adv. Manuf. Technol.* **2016**, *87*, 2797–2807. [[CrossRef](#)]
12. Liu, G.; Li, H.; Niu, S.; Yue, X.; Qu, N. Combined Machining of Ti-6Al-4V Alloy Using Electrochemical Milling and Electrochemical Grinding. *Int. J. Electrochem. Sci.* **2019**, *14*, 9876–9887. [[CrossRef](#)]
13. Wang, D.; Zhu, Z.; Wang, H.; Zhu, D. Convex shaping process simulation during counter-rotating electrochemical machining by using the finite element method. *Chin. J. Aeronaut.* **2016**, *29*, 534–541. [[CrossRef](#)]
14. Liu, Y.; Qu, N. Investigation on the performance of macro electrochemical machining of the end face of cylindrical parts. *Int. J. Mech. Sci.* **2020**, *169*, 105333. [[CrossRef](#)]
15. Kozak, J.; Chuchro, M.; Ruszaj, A.; Karbowski, K. The computer aided simulation of electrochemical process with universal spherical electrodes when machining sculptured surfaces. *J. Mater. Process. Technol.* **2000**, *107*, 283–287. [[CrossRef](#)]
16. Ruszaj, A.; Zybura-Skrabalak, M. The mathematical modelling of electrochemical machining with flat ended universal electrodes. *J. Mater. Process. Technol.* **2001**, *109*, 333–338. [[CrossRef](#)]
17. Hinduja, S.; Pattavanitch, J. Experimental and numerical investigations in electro-chemical milling. *CIRP J. Manuf. Sci. Technol.* **2016**, *12*, 79–89. [[CrossRef](#)]
18. Hackert-Oschätzchen, M.; Meichsner, G.; Zinecker, M.; Martin, A.; Schubert, A. Micro machining with continuous electrolytic free jet. *Precis. Eng.* **2012**, *36*, 612–619. [[CrossRef](#)]
19. Fu, X.Q.; Kang, M.; Zheng, Q.Y. Research on Flow Field Simulation and Experiment of Numerical Control Electrochemical Machining. *Key Eng. Mater.* **2011**, *458*, 63–68. [[CrossRef](#)]
20. Mishra, K.; Sarkar, B.R.; Bhattacharyya, B. Influence of different featured tools on machining accuracy in electrochemical milling. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2019**. [[CrossRef](#)]
21. Niu, S.; Qu, N.; Fu, S.; Fang, X.; Li, H. Investigation of inner-jet electrochemical milling of nickel-based alloy GH4169/Inconel 718. *Int. J. Adv. Manuf. Technol.* **2017**, *93*, 2123–2132. [[CrossRef](#)]
22. Li, H.; Niu, S.; Zhang, Q.; Fu, S.; Qu, N. Investigation of material removal in inner-jet electrochemical grinding of GH4169 alloy. *Sci. Rep.* **2017**, *7*, 3482. [[CrossRef](#)] [[PubMed](#)]
23. McGeough, J.A. *Principles of Electrochemical Machining*; Springer: New York, NY, USA, 1974.
24. Li, J.; Li, H.; Hu, X.; Niu, S.; Xu, G. Simulation Analysis and Experimental Validation of Cathode Tool in Electrochemical Mill-Grinding of Ti6Al4V. *Appl. Sci.* **2020**, *10*, 1941. [[CrossRef](#)]
25. Riggs, J.B.; Muller, R.H.; Tobias, C.W. Prediction of work piece geometry in electrochemical cavity sinking. *Electrochim. Acta* **1981**, *26*, 961–969. [[CrossRef](#)]