# A Review on Non-Traditional Machining of Titanium Alloys

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**Abstract**

Titanium is a most desirable material for the automotive, aerospace, petroleum, chemical, marine and biomedical industries for its excellent mechanical properties. But machining of titanium and its alloys is a quiet challenging process as it is a difficult-to-cut material. Therefore, It has always been a matter of concern to analyse the non-conventional machining process of titanium and its. A number of research works has been carried out in this direction. However, most of them are specifically in any of the one machining process only. It's quiet important to have a clear data about all type of non-conventional machining of titanium and its alloys. Therefore, this review aims to study the machining parameters of Titanium and its alloys in most of the non-conventional machining processes.

## 1 Introduction

Unique material properties makes titanium alloys to a widely used alloys in the automotive, aerospace, petroleum, chemical, marine and biomedical industries. It's commonly used in aeronautic industry due to the characteristics like low density, strength and high temperature resistance. However, it also considered as an expensive material because of deformation and fabrication process. In many cases, it's required ma- chining works where titanium alloys categorized as difficult-to-cut materials. There are several materials, mechanical and machining properties that influence to the titanium alloys machining process Gupta and Laubscher (2016); Niknam et al. (2014); RAHMAN et al. (2003) such as low thermal conductivity which leads heat concentration on the cutting edge; high chemical reactivity causes rapid wear, chipping or cutting tool failure; continuously high temperature and stress generation in between chip and cutting edge (within 0.5mm); low elastic modulus. To solve these problems, research studies is being carried out into new tool developments considering tool design and tool materials; optimization of cutting parameters(cutting force, speed, depth of cut, feed rate etc.) Niknam et al. (2014); and development of advanced material removing processes e.g. Ultrasonic Vibration Assisted Machining(UVAM)Muhammad et al. (2014), Laser Assisted Machining(LAM)Dandekar et al. (2010), Electric Discharge Machining(EDM)Hasçalık and Çaydaş (2007).

A number of advanced machining process performance investigation in hard-to-machine materials includ- ing titanium alloys machining has taken part of the research concern due to the capability for overcom- ing existing problems. The 1 shows the research works on non-traditional machining of titanium alloys. In this case, ultrasonic machining, electrochemical machining (ECM), electrical discharge machining, laser assisted machining, abrasive water jet machining (AWJM) are considered as non-traditional machining pro- cess. The graph represents the number of research articles has published in major journals in the year 2009 to present. It is clearly indicates that increasing of research in the field of titanium machining. The growth in USM, ECM and EDM significantly higher than LAM and AWJM. However, number of research works is uplift- ing for the LAM and AWJM. In addition, research issues in non-traditional machining processes can be seen as machinability in term of comparison between conventional and non-traditional machining; modelling and optimization; influence of process parameters; performance such as surface quality after machining process completed, temperature during machining process etc. (see 2). For machining process like USM,

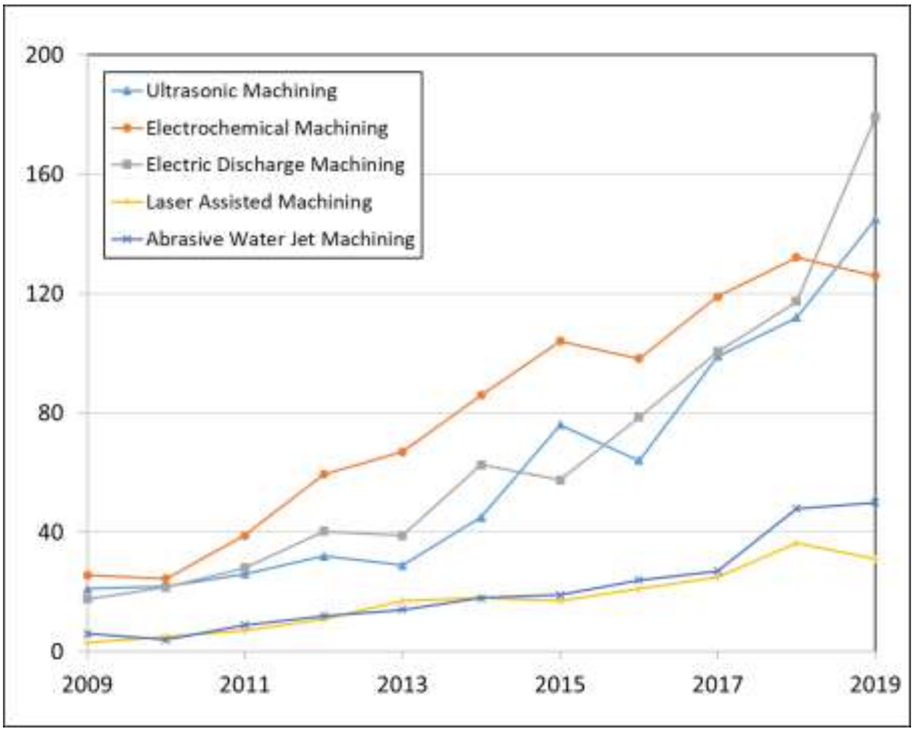



Figure 1: Number of articles on non-traditional machining of titanium alloys extracted from different jour- nals database.

ECM and LAM, data shows that research works are carried out to investigate influence of process param- eters and machining performance such as surface quality of machined workpiece much more than the investigation of machinability and modelling and optimization. Moreover, for EDM the graph indicates the highest research works done in machining performance. For AWJM, surprisingly research on modelling and optimization has taken place the top among the others. Overall, the graph reveals the research focus in non-traditional machining process.

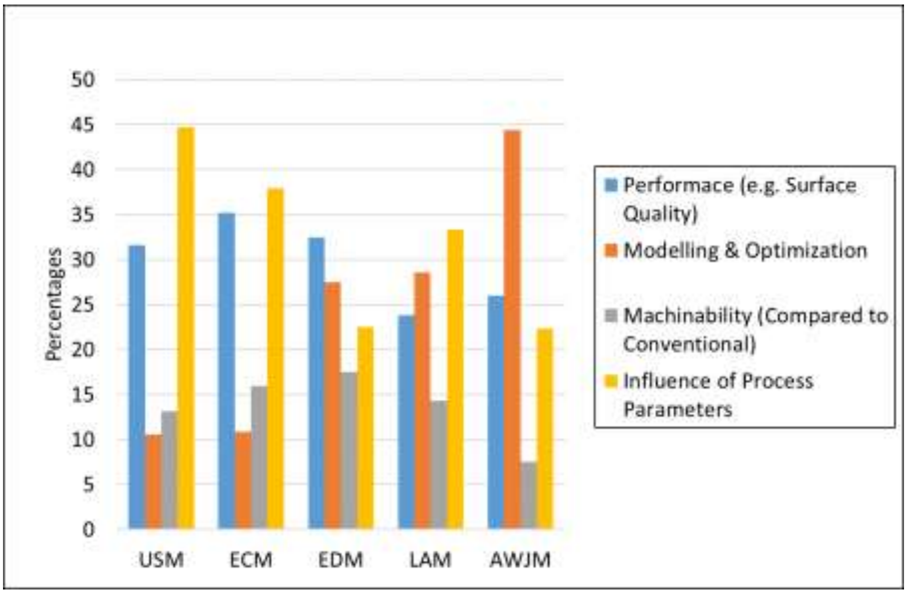



Figure 2: Percentages of studies categorized by types of non-traditional machining extracted and summa- rized from different journals database.

There are several research works has been done in every year that shows research direction or trends. However, most of them are specific in one machining process. Sometime that create complexities for new research direction. In addition, it’s important to have a clear picture of a research area for further research consideration. Therefore, this study aim to review last ten years articles in non-traditional machining pro- cess of titanium and its alloys. The focus of this review will be on the contribution for solving existing problems by using non-traditional machining processes mentioned earlier. This article organized with the start of introduction, secondly, recent works of non-traditional machining and thirdly, improvement com- pared to conventional machining process. Then, finally concluded with the suggestions of most efficient machining process for titanium alloys machining. In this study, most of the articles are collected from major journals.

## 2 Ultrasonic Machining (USM)

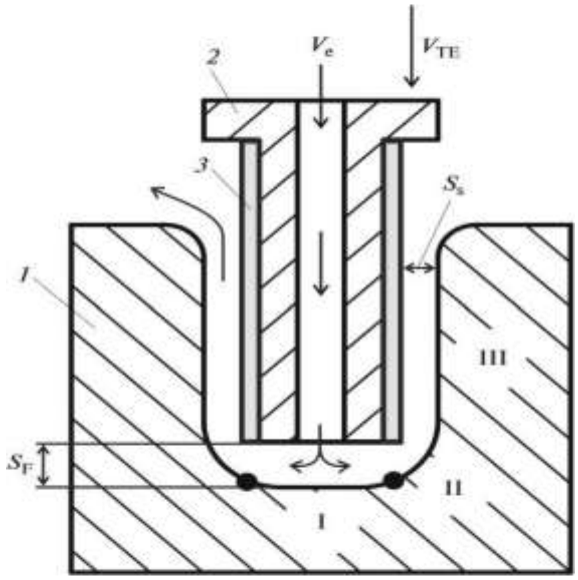
Ultrasonic machining or ultrasonic vibration assisted machining process remove materials from workpiece through high frequency and low amplitude vibrations, piezoelectric actuator used as the source of vibra- tion. The frequency is about 20 to 40 kHz. This machining process used as an alternative option of EDM and good choice for hard materials machining. USM considered as one of the high efficient machining process for titanium alloysXu and Zhang (2015). Result of Maurotto et al. (2012) shown that at least 75% of cutting can be reduced compare to conventional machining of titanium alloys while using USM. He also provides a comparison of surface quality which revealed a clear statement on advantage of USM in term of surface quality compare to conventional machining. In the study of Koshimizu (2008), shows a reduction of 33–50% cutting force. At the same time, the study states that semi-dry cutting condition is suitable for ultrasonic assisted turning. Similar improvement results found in different studies using USM in term of surface quality, cutting force and cutting temperature Maurotto et al. (2013); Muhammad et al. (2014); Maurotto et al. (2012); Patil et al. (2014); Wu et al. (2013).
It can be seen from the previous section that most of the research output concluded about the comparison and improvement. Among them, surface quality, cutting force, cutting temperature was the main concern in their studies. However, some other issues such as influence of cutting fluid, ultrasonic parameters also has been considered. Dixit et al. (2019) concluded in his review article that it is important to have research focus on influence of friction in ultrasonic vibration assisted machining process. He also found less stud- ies from economic and power consumption perspectives. So, the further study can be to emphasize on sustainable manufacturing for titanium alloys machining process.

## 3 Electrochemical Machining (ECM)

The electrochemical machining (ECM) is a modern nontraditional method of machining based on the elec- trochemical dissolution of metal aimed at the production of parts of prescribed shape, dimensions, and surface finish McGeough (1974); Rumyantsev and Davydov (1989); Wilson (1971). There are several ap- plication of it in titanium part preparations such as gas turbine engine parts, engine blades etc. Figure 3 gives a scheme of one type of ECM, the formation of a hole of circular cross-section using a tubular tool- electrode (TE). A hole is formed by deepening TE into the workpiece at a constant rate equal to the rate of metal dissolution at the bottom of the hole. Thereby, the inter electrode distance (the machining gap SF) is held constant. To enhance the accuracy of replication of TE onto the workpiece (WP), the inter electrode distance should be as small as possible, frequently, less than 100 µm. To remove the products of electro- chemical and possible chemical reactions from the working zone and refresh the electrolyte composition in the working zone, an intense electrolyte flow is organized.

Many specific features of ECM depend on the type of workpiece, type of required operation, and the tech- nology applied. For example, the machining of large-sized parts and complex-shaped parts on special ma- chines, the machining with the removal of large amounts of metal and application of powerful sources and large volumes of electrolyte differ significantly from the micro- and nanomachining with simple-shaped TE in the form of a needle or plate on small machines with the dissolution of small amounts of metal Davydov et al. (2017). In addition, ECM does not cause heat-affected zones and internal stresses on the machining surface Xu et al. (2016), therefore it can produced parts with high accuracy and better surface quality for hard-to-cut material like titanium.




| | Type | Mode | |
|---|---|---|---|
| Chen et al. (2018) | UVM | 1D cut- | Reduction of 22.8% in cutting temperature near the ting zone |
| Sofuoğlu et al. (2018) | UVT | 1D stress | Reduction of cutting force 70%; Maximum effective at least 25% |
| Ni et al. (2018) | UVM | 21.5- 1D 25.9% | Cutting force components Fx and Fy reduced by 37.24% and 31.02-46.30%; Surface roughness Ra and 48.3% |
| Llanos et al. (2018) | UVT | 1D axial | Reduction of 4.76% for tangential force, 8.62% for force 9.04% for radial force |
| Wang et al. (2019) | UVM | 1D decreased | Radial force, axial force, and tangential force by 60%, 27.7%, and 33% |
| Tan et al. (2019) | UVT | 2D | Surface roughness value reduced about 31% |
| Puga et al. (2019) | UVT | 1D | Cutting force in feed direction decreased by 24.8% and in the width of cut direction decreased by 29.9% |
| Zheng et al. (2018) | UVM | 1D 35% | Average friction coefficient wear volume decrease and 67%, in oil lubrication |
| Hu et al. (2019) | UVT | 1D | 42% of cutting force decreased |
| Bai et al. (2017) | UVM | 1D in | In CT, grain size beneath machined surface was larger at lower depth and smaller at higher depth; grain size shear band was bigger in case of UAT. Vibration amplitude had insignificant effect on grain size |
| Chen et al. (2019) | UVM | 1D roughness re- | cutting forces reduced by 64%, the surface duced, compressive residual stress increased by 85% |

Figure 3: Scheme of ECM of workpiece (1) by tubular tool-electrode (2) with insulated side surface (3). The arrow at VTE shows the direction of TE feed, the arrows from Ve show the direction of electrolyte flow, SF is the end face inter electrode gap, Ss is the side inter electrode gap, I denotes the machining zone (working zone), II denotes area adjacent to the working zone, and III denotes the zone of passive titanium Davydov et al. (2017).

There are different types of ECM, however, micro-ECM is become very popular in recent years due to the high accuracy, small amount of material removal with a low current which better than conventional ECM. Unfortunately, this method can't be applied for the titanium as highly prone to passivation metal when coated with thick passive resistive oxide films, because the oxide films exhibit significantly higher resis- tance than the solution layer in the inter electrode gap. In addition, it is important to choose an appro- priate electrolyte and relevant current parameters. Xu et al. (2016) concerned that self-passivation is one of the problem in ECM process, which inhibits the dissolution process. Therefore, he suggested to select corresponding process parameters. Influence of process parameters Anasane and Bhattacharyya (2017) is given below:

1. Electrolyte: Electrolyte plays an important role in term of surface quality, texture, accuracy, mate- rial removal rate etc. for example methanol electrolyte is better for shape and surface; Solution of methanol sulfuric acid has effective in electro polishing of titanium.
2. Machining Voltage: voltage between cathode and anode is also critical for controlling anodic disso- lution. Different amount of voltage has influence to remove material in different rate.
3. Pulse Duty Ratio: Duty ratio represents the percentage of time for which pulse remains on i.e. per- centage of time available for both faradic and non-faradic current. Increase in duty ratio in turn increases time available for faradic current. Hence, the amount of faradic effect and current density increases results in more material removal.

## 4 Electric Discharge Machining (EDM)

Electric discharge machining (EDM) is one of non-traditional material removing process, which is success- fully used in difficult-to-machine materials like titanium. Many industry used the process due to the high accuracy, ease of cutting complex shape and better surface roughness. EDM process introduce a residual stress free material because of the tool (electrode) and workpiece material untouched condition Qudeiri et al. (2018). The principle of the EDM technique is to use thermo-electric energy to erode a workpiece by rapidly recurring electrical discharges (sparks) between the untouched electrode and workpiece. The small distance between tool (electrode) and workpiece named discharge gap, which filled with dielectric fluid. Flushing the dielectric fluid during the machining process carries away debris (removed solid particles) and restores the sparking condition in the gap. As no cutting forces are used in between tool and the workpiece results an untouched condition which helps to eliminates vibration or stresses during machining.

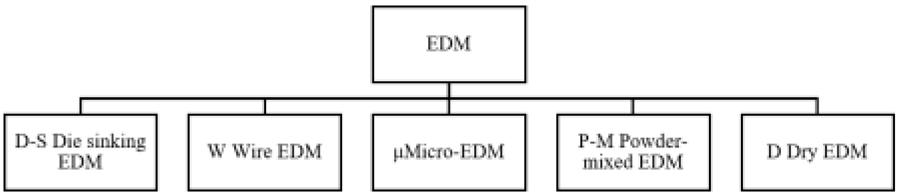



Figure 4: Classification of Electric Discharge Machining Process

In EDM process there are several process parameters such as peak current, pulse off time, discharge volt- age, pulse on time, polarity, pulse wave form, discharge gap, flushing of the dielectric fluid, and workpiece rotation; which are affected the EDM performance e.g., surface quality, material removal rate and elec- trode wear rate(EWR). MRR is one of the concerning issue in EDM due to the low material removal rate compare with the other non-traditional machining process Qudeiri et al. (2018). EDM forms in different name with basic principles in various process. Qudeiri et al. classified EDM process in 5 category shown in figure 4.

Many research has been carried out to investigate the effect of process parameters on performance of tita- nium alloys in EDM process. Moreover, several methods has been introduced to improve the performance such as surface quality, machining accuracy and material removal rate. Bhaumik and Maity investigated effect of electrode material in different EDM aspect of titanium alloys. They concluded that copper and brass electrode provides good surface finish Bhaumik and Maity (2018). In addition, zing electrode re- sulted higher defects. Some of recent studies of titanium alloys in EDM process is shown in the Table 2. In the EDM process, several research objective reported in recent works namely modelling and optimiza- tion; surface quality; dielectric fluid research; electrode materials used in EDM process; Machinability and process performance.

| Author(s) | EDM | Objective | Remarks |
|---|---|---|---|
| Pramanik et al. (2019) | W | Optimization | Investigates geometrical errors and trend found that influence of tension in wire on the flexibility of wire, the dependence of heat generation and dissipation on pulse on time, and ability of the flushing pressure to control the cooling, as well as debris removal from the machining zone. |
| Sahu and Mahap- atra (2018) | D-S | Optimization | Material removal rate (MRR), tool wear rate (TWR) and average surface roughness (Ra) are used to ana- lyze optimized by GRA method combined with Firefly algorithm |
| Tonday and Tigga (2019) | W | Characterization of Surface In- tegrity | cutting factors of wire EDM significantly influences the surface characteristics of machined samples |
| Ahmed et al. (2018) | D | Machinability and performance | Al electrode: the lowest surface roughness Graphite electrode: maximum material removal rate Negative tool polarity: rough machining Positive tool polarity: fine machining. |
| Kumar et al. (2018) | W | Process perfor- mance | EDM performance is assessed in terms of MRR and TWR. Surface integrity of the machined specimen is evaluated in purview of surface morphology and topographical features including surface roughness, surface crack density, white layer thickness, mate- rial migration, phase transformation, residual stress, and micro indentation hardness |
| Ramamurthy and Muthu- ramalingam (2018) | W | Machinability and performance | Conventional brass wire electrode has produced higher material removal rate. The zinc diffused brass wire electrode can produce lower surface rough- ness. |
| Shabgard and | | Machining | Surface micro cracks reduced in carbon nanotubes |

| | | | |
|---|---|---|---|
| Khosrozadeh (2017) | D-S | performance | (CNT) particles in dielectric. Addition of CNTs into dielectric exhibited advantages in reducing MRR and TWR |
| Kumar et al. (2017) | D | Electrode Mate- rial | Effect of deep cryogenic treatment (DCT) on tool wear rate during electric discharge machining of Ti-5Al-2.5Sn titanium alloy process parameters namely cryogenic treatment of electrode material, peak cur- rent, pulse-on off time and flushing pressure. |
| Chen et al. (2014) | μ | Performance and Dielectric | Adding concentration of Ti powder into dielectric solvent prevent the formation of surface cracks and micro-cracks, raise the wettability on the surfaces of Ti |
| Kolli and Kumar (2014) | D | Performance and Dielectric fluid | Addition of B4C powder in various concentrations has influenced the material removal rate, surface roughness and tool wear rate. |
| Jabbaripour et al. (2013) | D | Performance and Dielectric fluid | Different powders such as aluminum, chrome, sili- con carbide, graphite and iron is performed to in- vestigate the output characteristics of surface rough- ness and topography, material removal rate (MRR), electrochemical corrosion resistance of machined samples and also the machined surfaces are inves- tigated by means of EDS and XRD analyses |

Table 2: Studies of titanium alloys in EDM process.

## 5 Laser Assisted Machining (LAM)

The idea of laser assisted machining (LAM) has come with the concept of localized heat for reducing cutting force during machining process, and ultimately it results decrease in yield strength Dandekar et al. (2010). In this process, workpiece material heated by laser (e.g., CO2 and Nd:YAG) and material removed with traditional cutting tools Venkatesan et al. (2014). For titanium alloys treatment Nd:YAG and CO2 usually used, characteristics of this laser type shown in table 3. Most of the research is concerning advantages of LAM and challenges in traditional machining process. However, the performance of LAM depends on various parameters such as laser parameters and machining process parameters. Laser power and spot diameter of laser beam are main parameters of LAM. In term of influence of process parameters and it performance, many studies has been conducted. As a hybrid machining process, investigation of LAM provides various results. Table 4, shows a summary of LAM machining process and performance of titanium and its alloys.

| Properties | Nd:YAG | CO2 |
|---|---|---|
| Wavelength (μm) | 1.06 | 10.6 |
| Overall efficiency (%) | 1-3 | 5-10 |
| Output power in CW mode | =16 kW | =20 kW |
| Focused power density (W/cm2) | 105-7(flash lamp), 106-9(diode) | 106-8 |
| Pulse duration (sec) | 10-8-10-3 | 10-4 |
| Fiber coupling | - | x |

Table 3: Characteristics of laser in titanium alloys machining process Lee et al. (2016).

| Author(s) | Objective | Remarks |
|---|---|---|
| Rashid et al. (2012) re- | Effect of laser power | Higher laser power(1.2-1.6kW) effective for ducing cutting |
| Ayed et al. (2014) dur- | Physical properties ing | Distance between the axis of the laser beam and the tool rake face is the most important parameter that can reduce 50% of the cutting force |
| Oh et al | Machining characteristic and energy efficiency | Specific cutting energy reduced 6% than con- ventional milling |
| Abdollahi et al. (2019) vibration amplitude, laser power, | | Process optimization pulse frequency and gas Increase of |
| Chatterjee et al. (2018) i | Performance | Laser energy and pulse width significantly influ- ence on circularity, taper and spatter area |
| Character- Bermingham et al. (2015) | Performance of Tool | At low cutting speeds, LAM offered a marginal improvement in tool life compared to room temperature dry machining |
| Habrat (2017) im- | Machinability | Tangential cutting force reduced 60%. No provement in chips |
| Hedberg et al. (2015) performance | Machining | Cutting force reduced by 30-50%; Cutting speed can be increased 30% without reducing tool life; Compressive residual stress reduced by 10%; A 33% cost can be reduced using LAM |

Table 4: Studies of LAM on titanium alloys.

Among the types of machining process, some important issues, challenges and opportunities exist. For hybrid conventional laser assisted machining process it can be categorized by machining cost, tool life, and flow stress. At the same time the challenges are to overcome by solving the problem of complex control system and application to material with various shapes.

## 6 Abrasive Water Jet Machining (AWJM)

Abrasive water jet machining (AWJM) is one of the flexible material removal method that become popular among other machining process. The reason behind this is elimination of thermal effect and minimum stress in workpiece Kartal (2016). In this machining process, mechanical energy of water with the abrasive particle used to cut the material by erosion Li and Wang (2015). The water pumped to high pressure (400- 600 MPa) and exit through the nozzle (ranging from 0.1 to 1.0 mm) Shukla (2013). The velocity of water is about 1000m/s which used to cut materials like metals, ceramics, glass etc. To improve the machining performance for abrasive water jet process, many research works has been conducted. As hard-to-cut material and thermal characteristics of titanium alloys, number of research has been done. Most of the research focus on the influence of machining process parameters, machining performance such as surface quality and the modelling and simulations. Table 5, shows the summary of the recent work on titanium and its alloys using abrasive water jet machining.

| Author(s) | Process Parame- | Objective | Remarks |
|---|---|---|---|
| Pahuja and M. (2019) | Pressure, Speed | Modelling | Power-to-speed ratio is effective lumped control parameter which physically represented the en- ergy deposited per unit linear distance moved by the jet. |
| Kumar and Shukla (2012) | particle impact angle, velocity, depth, erosion rate | Modeling Simula- tion | Significant variation of crater geometry for impact of up to the first 17 particles, depending on impact- ing velocity and angle. |
| Vasanth et al. (2016) | Water pressure, abrasive flow rate, feed rate, standoff distance | Effect of process parame- ters | Abrasive flow rate and standoff distance has the most significant role on determining surface qual- ity. Higher abrasive flow rate with higher standoff distance produces higher surface roughness ow- ing to larger and random energy distribution. |
| Bui et al. (2017) | Gaussian curve, feed | Modelling | The model rapid and effective as the accuracy of the models obtained over a number of configura- tions was to within the order of 5% |
| Hlaváč et al. (2015) | Traverse speed, limit depth of cut, limit angle | | The theoretical model and the experiment show a very good correlation. |
| Perec (2018) | Traverse speed, concentration of abrasive | stack configura- tion, the traverse | Abrasive material |

| | | | |
|---|---|---|---|
| The garnet abrasive material gave the greatest cutting depth, Olivine caused the | greatest abra- sive wear of the focusing tube, Crushed glass abra- sive caused | the smallest value of wear coefficient. The most significant factors | for the taper angle on both materials are the pressure and the stack con- |
| Alberdi et al. (2015) | feed rate, the cutting tool and the pressure over the kerf profile | Machinability perfor- mance | figuration, followed by the traverse feed rate. To minimize the taper angle and the roughness, it is recommended to use high-pressure, low traverse feed rates. |
| Li and Wang (2015) | Water pressure drilling time | Effect of process parame- ters | It was found that both the hole depth and diam- eter increased as drilling time increased but in a decreasing rate. An increase in water pressure in- creased both the hole depth and the hole diame- ter. |

Table 5: Summary of recent works on titanium alloys.

Some other researchers also focus on surface quality and classifying the surface of workpiece material. Pal and Choudhury (2014) generated pocket on titanium surface with adjusting parameters namely pressure, standoff distance and abrasive size. Surface waviness, roughness and crater has been measured. Results shown that small abrasive size provides good surface quality. In another work, Kerf geometry, surface roughness (Ra), microstructural analyses and material removal rate (MRR) of Ti-6Al-4v were investigated using Abrasive water jet machining Gnanavelbabu et al. (2018). He mentioned surface roughness is affected by high pressure of water jet. Results of Babu and Muthukrishnan (2014) also provides conclusion for surface quality.

## Sustainable issues in Non-Traditional Machining

Sustainability is one of the important issue in modern machining process. For some complex production, it is impossible to produce the product without non-traditional machining process. The concerning issues can be affected health, environment or even economy. Table 6 shows the most common issue regarding non-traditional machining process and the properties that are responsible for that.

| Process | Properties | Sustainable issue |
|---|---|---|
| USM | Hard Particles. | Environmental problems; Health problems due to ECF, ul- trasound and slurry fluids causing acoustic trauma, tinnitus, dermatitis. |
| ECM | High dissolution rate at very large current densi- ties. | Corrosions risk; High energy consumption; Complex waste management; Electrolyte disposal issues; Liver, kidney and skin irritation; Handling and storage difficulty. |
| EDM | Volatility, Odorless, flash point, environment friendly, viscosity. | Gas, noise, magnetic field. Chips, liquid, Noise, Vi- bration. |

| | |
|---|---|
| Harmful vapor, skin irritation, odor, risk of fire and explo- sions, high oxidation rate, high rate of sludge accumulation. | Health problems. |
| | High energy consumption, recycling issue, health issue. |

Table 6: Sustainable issue in non-traditional machining process Rajurkar et al. (2017); Saxena et al. (2018).

## 7 Conclusion

Non-traditional machining process for titanium alloys due its capability to solve existing problems. Research works in the field of non-traditional machining is still going on. This paper reviewed several articles on different types of non-traditional machining process. Therefore, this section can be arranged with some conclusions.

1. First section of this paper presented current trends on non-traditional machining process. Its shows EDM has the first priority for the research work as the number of published articles in last 10 years. Moreover, the research focuses specifically on investigation of machining process parameter and performance.
2. Ultrasonic machining has successfully reduced cutting force, temperature and improve surface qual- ity for titanium alloys. However, more research need to have in term of cutting mechanics and solving sustainable issues such as energy consumption and economic aspects.
3. For electric discharge machining, review shows that dielectric fluid has significant effect on machining performance. In addition, low discharge energy provides better surface with less defects. Integration of other hybrid process resulted better outcome. Future research can be focused on combining EDM with other process like laser assisted machining.
4. As the main problem of electrochemical machining on titanium is prone to passivation in the aque- ous electrolyte solutions. Which is required for high amount of dissolution of titanium. Therefore, electrolyte solutions can be the focused for the further research. In addition it's important to have focus for sustainable issue as ECM machining process used much more chemical compared to other non-traditional machining process.
5. Laser assisted machining has already achieve great attention for the capability of overcome by reduc- ing cutting energy and improve surface roughness of titanium alloys. The review reveals that LAM significantly improve the product quality by decreasing cost.
6. In Abrasive water jet machining Garnet, silicon carbide dust, and aluminum oxide are most commonly used as abrasive materials, however more research work need to do for further development of this process. Sustainability is most common issue in modern manufacturing process. Specially, for non-traditional machining process, there are not many studies has been carried out. Therefore, more research should be focused on environmental and economic issues.

## References

Abdollahi, H., Shahraki, S., and Teimouri, R. (2019). Empirical modeling and optimization of process param- eters in ultrasonic assisted laser micromachining of ti–6al–4v. *International Journal of Lightweight Mate- rials and Manufacture*, 2(4):279–287, DOI: 10.1016/j.ijlmm.2019.08.008, https://doi.org/10. 1016/j.ijlmm.2019.08.008.

Ahmed, N., Ishfaq, K., Moiduddin, K., Ali, R., and Al-Shammary, N. (2018). Machinability of titanium al- loy through electric discharge machining. *Materials and Manufacturing Processes*, 34(1):93–102, DOI: 10.1080/10426914.2018.1532092, https://doi.org/10.1080/10426914.2018.1532092.

Alberdi, A., Artaza, T., Suárez, A., Rivero, A., and Girot, F. (2015). An experimental study on abrasive waterjet cutting of CFRP/ti6al4v stacks for drilling operations. *The International Journal of Advanced Manufactur- ing Technology*, 86(1-4):691–704, DOI: 10.1007/s00170-015-8192-x, https://doi.org/10.1007/ s00170-015-8192-x.

Anasane, S. S. and Bhattacharyya, B. (2017). Electrochemical micromachining of titanium and its alloys. In *Materials Forming, Machining and Tribology*, pages 337–365. Springer International Publishing, DOI: 10.1007/978-3-319-52009-4_9, https://doi.org/10.1007/978-3-319-52009-4_9.

Ayed, Y., Germain, G., Salem, W. B., and Hamdi, H. (2014). Experimental and numerical study of laser- assisted machining of ti6al4v titanium alloy. *Finite Elements in Analysis and Design*, 92:72–79, DOI: 10.1016/j.finel.2014.08.006, https://doi.org/10.1016/j.finel.2014.08.006.

Babu, M. N. and Muthukrishnan, N. (2014). Investigation on surface roughness in abrasive water-jet ma- chining by the response surface method. *Materials and Manufacturing Processes*, 29(11-12):1422–1428, DOI: 10.1080/10426914.2014.952020, https://doi.org/10.1080/10426914.2014.952020.

Bai, W., Sun, R., Leopold, J., and Silberschmidt, V. V. (2017). Microstructural evolution of ti6al4v in ultra- sonically assisted cutting: Numerical modelling and experimental analysis. *Ultrasonics*, 78:70–82, DOI: 10.1016/j.ultras.2017.03.005, https://doi.org/10.1016/j.ultras.2017.03.005.

Bermingham, M., Sim, W., Kent, D., Gardiner, S., and Dargusch, M. (2015). Tool life and wear mechanisms in laser assisted milling ti–6al–4v. *Wear*, 322-323:151–163, DOI: 10.1016/j.wear.2014.11.001, https://doi.org/10.1016/j.wear.2014.11.001.

Bhaumik, M. and Maity, K. (2018). Effect of electrode materials on different EDM aspects of tita- nium alloy. *Silicon*, 11(1):187–196, DOI: 10.1007/s12633-018-9844-x, https://doi.org/10.1007/ s12633-018-9844-x.

Bui, V. H., Gilles, P., Sultan, T., Cohen, G., and Rubio, W. (2017). A new cutting depth model with rapid calibration in abrasive water jet machining of titanium alloy. *The International Journal of Ad- vanced Manufacturing Technology*, 93(5-8):1499–1512, DOI: 10.1007/s00170-017-0581-x, https://doi.org/10.1007/s00170-017-0581-x.

Chatterjee, S., Mahapatra, S. S., Bharadwaj, V., Choubey, A., Upadhyay, B. N., and Bindra, K. S. (2018). Drilling of micro-holes on titanium alloy using pulsed nd:YAG laser: Parametric appraisal and prediction of performance characteristics. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 233(8):1872–1889, DOI: 10.1177/0954405418805604, https://doi.org/ 10.1177/0954405418805604.

Chen, G., Ren, C., Zou, Y., Qin, X., Lu, L., and Li, S. (2019). Mechanism for material removal in ultrasonic vibration helical milling of ti 6al 4v alloy. *International Journal of Machine Tools and Manufacture*, 138:1– 13, DOI: 10.1016/j.ijmachtools.2018.11.001, https://doi.org/10.1016/j.ijmachtools. 2018.11.001.

Chen, J., Xu, M., Xie, C., Du, J., Dai, H., and Fang, Q. (2018). A nonuniform moving heat source model for temperature simulation in ultrasonic-assisted cutting of titanium alloys. *The International Jour- nal of Advanced Manufacturing Technology*, 97(5-8):3009–3021, DOI: 10.1007/s00170-018-2174-8, https://doi.org/10.1007/s00170-018-2174-8.10.1016/j.mspro.2014.07.346, https://doi.org/10.1016/j.mspro.2014.07.346.

Patil, S., Joshi, S., Tewari, A., and Joshi, S. S. (2014). Modelling and simulation of effect of ultrasonic vi- brations on machining of ti6al4v. *Ultrasonics*, 54(2):694–705, DOI: 10.1016/j.ultras.2013.09.010, https://doi.org/10.1016/j.ultras.2013.09.010.

Perec, A. (2018). Experimental research into alternative abrasive material for the abrasive water-jet cutting of titanium. *The International Journal of Advanced Manufacturing Technology*, 97(1-4):1529–1540, DOI: 10.1007/s00170-018-1957-2, https://doi.org/10.1007/s00170-018-1957-2.

Pramanik, A., Islam, M. N., Basak, A. K., Dong, Y., Littlefair, G., and Prakash, C. (2019). Optimizing dimen- sional accuracy of titanium alloy features produced by wire electrical discharge machining. *Materials and Manufacturing Processes*, 34(10):1083–1090, DOI: 10.1080/10426914.2019.1628259, https://doi.org/10.1080/10426914.2019.1628259.

Puga, Grilo, and Carneiro (2019). Ultrasonic assisted turning of al alloys: Influence of material processing to improve surface roughness. *Surfaces*, 2(2):326–335, DOI: 10.3390/surfaces2020024, https:// doi.org/10.3390/surfaces2020024.

Qudeiri, J. E. A., Mourad, A.-H. I., Ziout, A., Abidi, M. H., and Elkaseer, A. (2018). Electric discharge machining of titanium and its alloys: review. *The International Journal of Advanced Manufacturing Technology*, 96(1-4):1319–1339, DOI: 10.1007/s00170-018-1574-0, https://doi.org/10.1007/ s00170-018-1574-0.

RAHMAN, M., WONG, Y. S., and ZAREENA, A. R. (2003). Machinability of titanium alloys. *JSME International Journal Series C*, 46(1):107–115, DOI: 10.1299/jsmec.46.107, https://doi.org/10.1299/jsmec. 46.107.

Rajurkar, K., Hadidi, H., Pariti, J., and Reddy, G. (2017). Review of sustainability issues in non-traditional machining processes. *Procedia Manufacturing*, 7:714–720, DOI: 10.1016/j.promfg.2016.12.106, https://doi.org/10.1016/j.promfg.2016.12.106.

Ramamurthy, A. and Muthuramalingam, T. (2018). Analysis of machinability on WEDM processed titanium alloy with coated electrodes. In *Lecture Notes in Mechanical Engineering*, pages 279–285. Springer Singa- pore, DOI: 10.1007/978-981-13-1724-8_27, https://doi.org/10.1007/978-981-13-1724-8_ 27.