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Anomalous influence of polarity in sink EDM of titanium alloys

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Abstract: An anodic tool polarity is generally adopted in sink electrical discharge machining (EDM) to maximize material removal relative to tool wear. Sink EDM of Ti and Ti6Al4V is however atypical in that these materials necessitate a cathodic tool polarity. Adding to the intrigue is γ-TiAl, which machines better under the conventional anodic polarity. This research focused on clarifying the phenomena behind this interesting behavior by investigating removal mechanisms over a range of relevant process conditions. The anomaly is demonstrated to arise from the polarity-dependent nature and extent of TiC formation on the work surface, which significantly affects material removal.

Keywords: Electrical discharge machining (EDM), titanium, polarity

1. Introduction

In view of their uniquely favorable material properties, titanium alloys continue to be of significant importance in the manufacture of components in the turbomachinery and biomedical industries, among others. Precision machining of intricate geometric features in these components such as blind cavities with sharp corners and/or high aspect ratios demands the application of sink electrical discharge machining (EDM).

In EDM, material removal from the anode is generally higher than that from the cathode for discharge durations on the order of 20 μs or less, and vice versa for longer durations [1]. Accordingly, in sink EDM operations that typically operate at discharge durations higher than this threshold, an anodic tool is the preferred polarity to maximize the ratio of workpiece material removal rate to tool wear rate.

This polarity effect has for long been rationalized as being dictated by the time-dependent difference in the energy partition to the electrodes during dielectric breakdown. This has in turn been attributed to the difference in the relative mobilities of electrons and ions: the lighter electrons impinging on the anode surface well in advance of the comparatively massive ions reaching the cathode surface. There is however little evidence that such a delay could be on the order of nanoseconds or higher. Experiments have further indicated a consistently higher energy partition to the anode over the entire spectrum of practical discharge durations [1], which renders this school of thought obsolete.

The current understanding is that at longer discharge durations, there is less removal from the anode despite the higher energy partition, due to accretion of a protective pyrolytic carbon layer on the surface of the anode. This layer materializes from the breakdown-induced disintegration of the hydrocarbon oil dielectric that is commonly used in sink EDM. For the copper-steel system, spectroscopic investigation of the machining gap has demonstrated a decrease in the vapor density of copper, commensurate with an increase in the thickness of the carbon layer on the copper electrode, signifying its shielding effect [2]. Considering that a higher vapor pressure close to the tool surface would physically impede carbon deposition, a higher discharge duration was understood to favor the formation of the protective layer. This is due to the relatively low vapor pressure associated with the decrease in power density, brought about by the temporal expansion of the plasma channel. Deposition of the carbon layer on the anode was further thought to be related to negatively charged ions in the plasma.

In as much as this model is valuable in explaining the choice of the anodic tool polarity for sink EDM of most materials, it breaks down for pure titanium (Ti) and the Ti6Al4V alloy, both of which necessitate a cathodic tool polarity for productive machining. Rendering this furthermore intriguing is the case of the intermetallic gamma titanium aluminide (γ-TiAl) alloy, which does indeed machine better under the conventional anodic tool polarity. In this mystifying context, the objective of the research reported in this paper was to examine the pertinent mechanisms in fundamental scientific terms, with a view to enhancing our understanding of these atypical effects.

2. Experimental

To the end of accomplishing the objective above, sink EDM experiments were conducted on several materials using graphite tools with a square section of 225 mm² area in an oil dielectric, adopting interval flushing. Experiments primarily involved a systematic variation of discharge duration t_e and polarity, with the open circuit voltage, discharge current and duty factor fixed at 220 V, 30 A and 0.15, respectively; each process condition involved three repeat trials. Details of supplementary experiments conducted are presented in the next section as and where applicable. Responses measured include workpiece material removal rate (MRR), tool wear rate, surface roughness, subsurface microhardness and acoustic emission. Machined surfaces and subsurfaces were examined using light, confocal and scanning electron microscopy; further insights were obtained through electron back-scatter diffraction (EBSD), energy dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) techniques.

3. Results and discussion

Fig. 1 is a graphical summary of the influence of polarity on the sink EDM machinability of several materials, which clearly depicts the anomalous influence of polarity in the case of Ti and Ti6Al4V. The tool wear rate is similar across all materials for a given polarity, which implies that discharges occurred similarly in all cases, and that the process was unaffected by the workpiece material. Tool positive polarity further corresponded to a lower tool wear rate, which aligns with conventional practice [1]. While the workpiece removal rates were largely the same for the tool negative polarity, it dropped essentially to zero in the case of pure Ti and the Ti6Al4V alloy for the tool positive polarity.

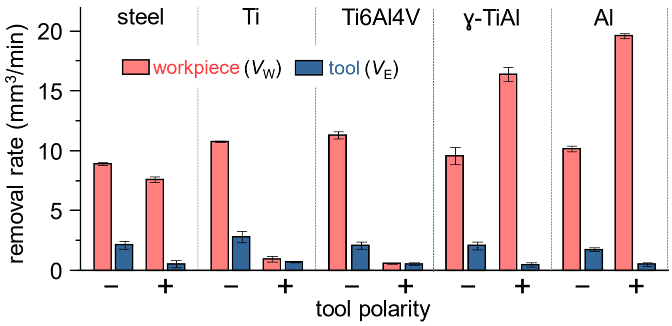

Fig. 1 A comparison of the machinability of several materials (t_e = 36 µs).

Given the interaction between polarity and discharge duration in sink EDM, the effect of discharge duration was investigated to verify that the ineffective material removal for Ti and Ti6Al4V was not an artefact of the discharge duration specific to that experiment. Results presented in Fig. 2 confirmed the tool positive polarity to be undoubtedly non-productive for Ti and Ti6Al4V, across the entire spectrum of discharge durations, while it is indeed to be preferred for machining γ-TiAl (Ti-45Al-5Nb-0.2B-0.2C) and Al for discharge durations over ~5 µs. For the latter two, the polarity effect can be understood in terms of the higher energy partition to the anode being offset by the deposition of the pyrolytic carbon layer on it at discharge durations longer than ~5 µs, which is consistent with the model [2] detailed in Sec. 1.

Such a rationale does not however apply to Ti and Ti6Al4V, since there is no crossover in their MRR characteristics, as there is for γ-TiAl and Al. The workpiece is further not the anode when the MRR of Ti and Ti6Al4V is inordinately low, for carbon deposition to have affected material removal. In this context, the following investigations focused on sink EDM of Ti6Al4V, the results of which may be extended to Ti, considering that the machinability of these two materials is essentially the same (Fig. 2).

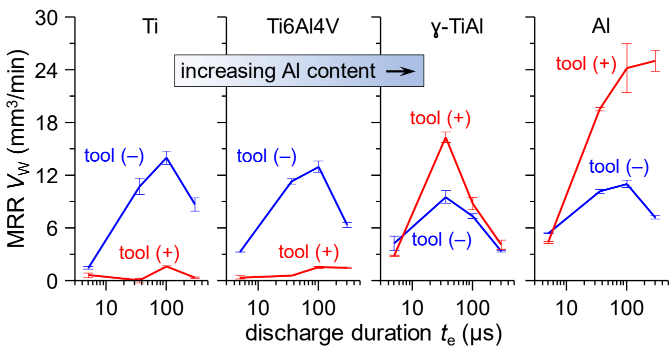

Fig. 2 Role of polarity on the MRR as a function of discharge duration.

The effects of discharge duration and polarity were investigated for the Ti6Al4V workpiece on another machine tool using the same dielectric fluid, which again confirmed the MRR to be an order of magnitude lower for the anodic tool polarity (Fig. 3a). It is remarkable that the roughly two-fold difference in discharge energy between the machine tools, ensuing from the difference in current pulse waveforms (Fig. 3b), is reflected on the MRR only under a cathodic tool polarity, with the anodic tool polarity registering no significant difference (Fig. 3a).

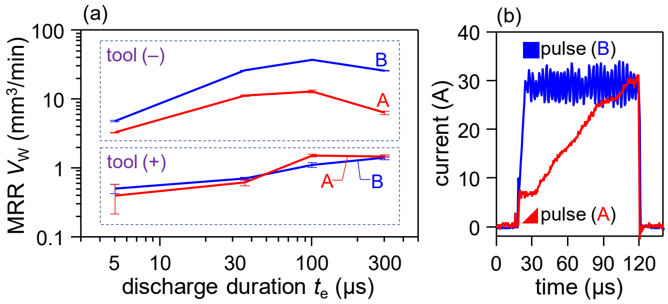

Fig. 3 Effect of discharge duration and polarity on the MRR of Ti6Al4V with respect to triangular (A) and rectangular (B) pulse shapes.

The rectangular pulse waveform (B) referred to a rougher machined surface due to the higher discharge energy, but the workpiece surfaces were qualitatively similar (Fig. 4). The difference due to polarity on the other hand was conspicuous in that the tool positive polarity resulted in smoother surfaces with a network of surface cracks but no perceptible craters, while the tool negative polarity generated surfaces with the characteristic concave craters but no apparent cracks. The cracks pointed to the likelihood of a hard/brittle material species on the machined surface for the anodic tool polarity, which was confirmed by microhardness measurements into the machined surface (Fig. 5).

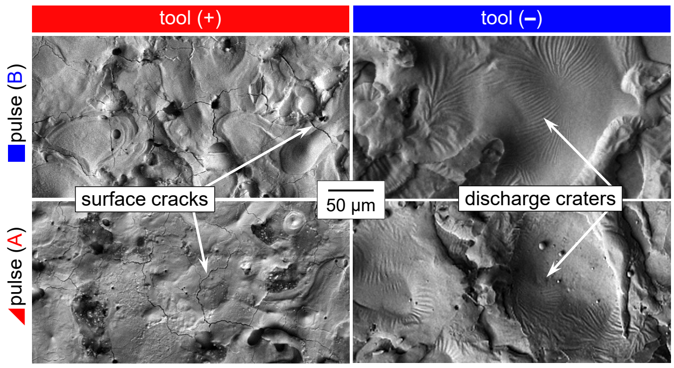

Fig. 4 Influence of polarity and pulse shape on the topography of Ti6Al4V.

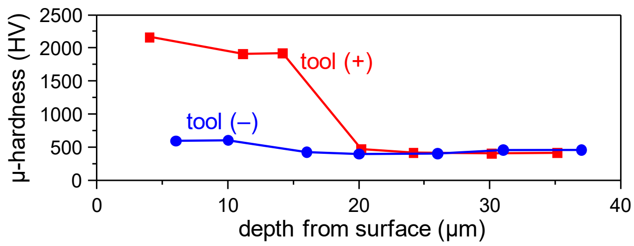

Fig. 5 Effect of polarity on the microhardness of Ti6Al4V subsurface.

For the tool positive polarity, the workpiece surface was further observed to exhibit a significant reduction in roughness during the initial stages of machining, and subsequently transition rather sharply to a constant value (Fig. 6a). Examination of the machined surfaces indicated this to relate to the gradual and sporadic accretion of a material layer, which in due course covered the entire area, as can be seen in the micrographs. On tracking the position of the tool advancing into the workpiece as machining progressed (Fig. 6b), it was further evident that the transition in the roughness value also corresponded to an abrupt reduction in tool speed (as indicated by the green line), when the tool was the anode. This signifies a distinct decrease in the MRR, discounting the minor confounding influence of tool wear. That such a decrease was not evident when the tool was the cathode (Fig. 6b) pointed to the material layer deposited on the work surface being likely responsible for the anomalous influence of polarity.

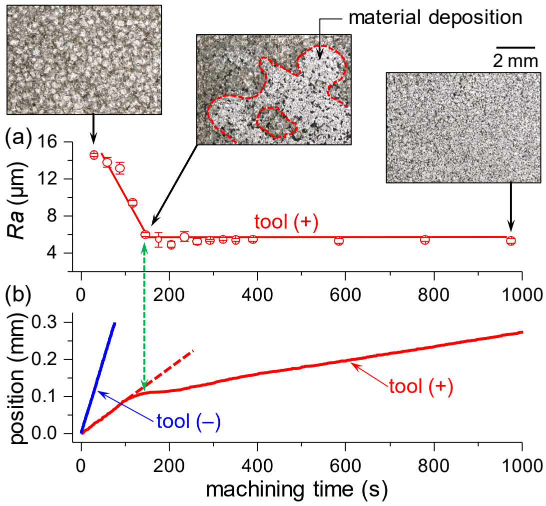

Fig. 6 Evolution of surface topography and machining speed of Ti6Al4V with respect to polarity.

The investigation hence focused on the cross-sections of machined surfaces. For the tool positive polarity, back scattered electron imaging showed a uniformly thick and continuous layer that appears dark in Fig. 7a, atop the heat affected zone. For the tool negative polarity (Fig. 7b), this layer was relatively lighter, thin and intermittent. EBSD and EDS analyses of domains shown as insets in Figs. 7a and 7b indicated this layer to comprise a face-centered cubic (fcc) structure rich in carbon (rendered yellow in Figs. 7c and 7d), suggesting the material layer to likely comprise TiC. The grain size in this layer was coarse for the anodic tool polarity (Fig. 7c) relative to that for the cathodic tool polarity (Fig. 7d).

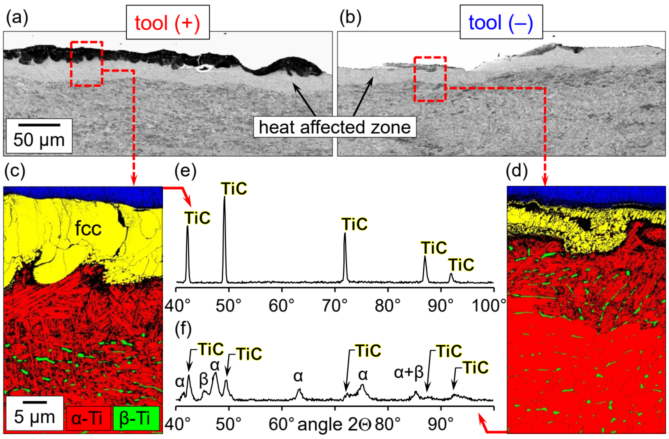

Fig. 7 Effect of polarity on Ti6Al4V subsurface (t_e = 36 μs).

XRD analysis confirmed the machined surface to be exclusively TiC for the tool positive polarity (Fig. 7e), and it to entail a mix of TiC, α-Ti and β-Ti for the tool negative polarity (Fig. 7f). This clearly indicates that for the tool positive polarity, the relatively thick and continuous layer of TiC deposited on the machined surface manifests a thermal barrier that severely hinders material removal.

An insight into the reason for the TiC layer being relatively thin and discontiguous (Fig. 7b and 7d), and therefore not much of a hindrance to material removal under the tool negative polarity, was gained through single discharge experiments using graphite pin electrodes (Fig. 8a). Measurement of individual craters on the workpiece using a confocal microscope indicated the anodic tool polarity to refer to an increasingly larger crater diameter with discharge duration, relative to when the tool is the cathode (Fig. 8b). Given that the energy partitioned to the anode is already higher at all discharge durations [1], it follows that the energy density incident on the workpiece is higher under a cathodic tool polarity, which is confirmed by the corresponding crater volumes being higher (Fig. 8c).

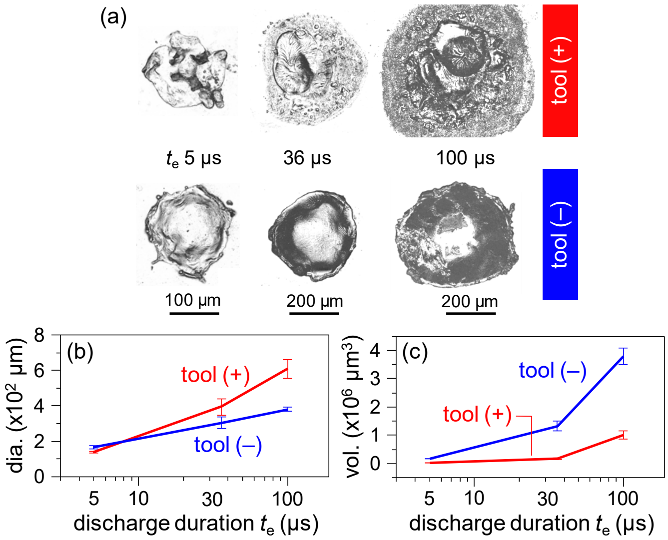

Fig. 8 Influence of discharge duration and polarity on the geometry of Ti6Al4V single discharge craters.

That the TiC layer is far less of an impediment to material removal under the tool negative polarity may hence be understood in terms of the higher energy density being responsible for the continuous and rapid removal of the incipient TiC layer, which renders it thin, intermittent and of a fine grain structure (Fig. 7b and 7d). This aligns with the observation in [3] wherein EDM was used for electro-spark deposition of TiC that the deposition process gave way to material removal at a higher discharge energy; it may be noted that the ~2000 HV hardness of the TiC layer (Fig. 5) is further similar to that obtained in [3].

Under the anodic tool polarity, on the other hand, with the lower energy density referring to its ineffective removal, TiC continues to accumulate into a thick, continuous layer comprising coarse grains (Fig. 7a and 7c). Such a preferential deposition of TiC brings up the interesting prospect of significantly reducing tool wear in sink EDM of Ti/Ti6Al4V by using negatively polarized Ti/Ti6Al4V tools. This was however tested to be impractical due to the corresponding removal rates being an order of magnitude lower, relative to when using graphite tools.

The development of the thermal barrier was reflected in the acoustic emission (AE) from the machining gap, which was shown in [4] to relate to the energy apportioned to the gas bubbles. The formation of a thermal barrier on either electrode should therefore increase the energy of the AE signal, on account of the decrease in the energy transmitted through that electrode. Validating this premise, the data in Fig. 8 does indeed show the tool positive polarity to refer to a stronger AE signal. It is further interesting to note the steady increase in AE over the first ~150 s of machining under the tool positive polarity, in contrast to it being essentially constant for the tool negative polarity, which indicates the gradual accretion of the TiC thermal barrier that was discussed previously (Fig. 6).

Having understood the detrimental influence of TiC in sink EDM of Ti6Al4V, it was of interest to determine the source of carbon that is required for its formation. Experiments comparing deionized water and oil dielectric fluids indicated the former to correspond to a higher MRR (Fig. 10), which points to the oil dielectric, rather than the graphite electrode material, to be the primary source of carbon.

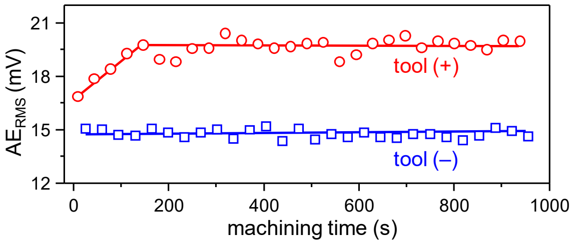

Fig. 9 Effect of polarity on acoustic emission when machining Ti6Al4V.

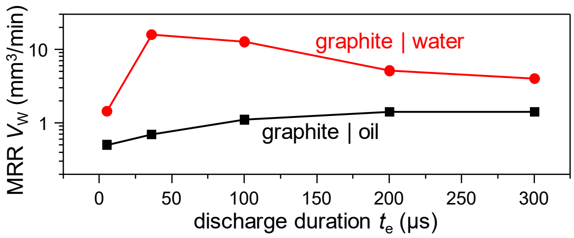

Fig. 10 Role of the dielectric fluid on the MRR of Ti6Al4V (+ tool polarity).

The adverse implication of TiC formation on the MRR when machining Ti6Al4V in an oil dielectric has been reported previously in [5]. To the best of our knowledge, the present work is however the first study that has highlighted and resolved the anomalous polarity effect. In fact, while the machining industry appears to be largely cognizant of this anomaly: albeit in empirical terms, the academic literature abounds with works such as [5] wherein the conventional but incorrect polarity has been applied, which our work hopefully helps address.

Referring back to Fig. 2, the machining behavior of γ-TiAl is conspicuously different from that of Ti6Al4V in that the conventional tool positive polarity corresponds to a higher MRR. As alluded to previously, the subtle crossover in the MRR characteristics of γ-TiAl that occurs at a discharge duration of ~5 µs (Fig. 2) is a tell-tale signature of the deposition of pyrolytic carbon on the anode at higher discharge durations [2] overwhelming the influence of the higher energy partition, which decreases the MRR. Visual inspection of the machined surface did indicate deposition of the carbonaceous layer for the tool negative polarity.

Further to this effect, the combination of the tool positive polarity and a discharge duration of 36 µs that maximized MRR for γ-TiAl (Fig. 2) referred to basically no deposition on the machined surface (Fig. 11a). XRD investigation further indicated the absence of TiC (Fig. 11b). This contrasts with Ti6Al4V that exhibited a thick layer of TiC at this condition (Fig. 7a, 7c and 7e). The tool negative polarity referring to a lower MRR for γ-TiAl at this discharge duration of 36 µs (Fig. 2) can be attributed in part to trace deposits on the work surface (highlighted by arrows in Fig. 11c), which were confirmed to comprise TiC (Fig. 11d). The formation of these TiC deposits was likely facilitated by the pyrolytic carbon layer deposited on the anodic workpiece.

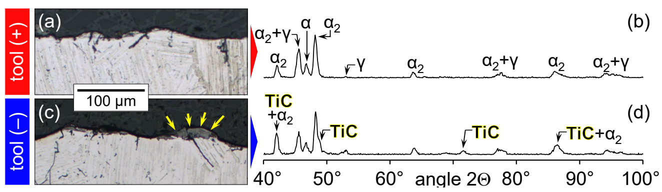

Fig. 11 Metallographic sections and XRD spectra of γ-TiAl surfaces machined at a discharge duration of 36 µs.

In the case of γ-TiAl, metallographic and XRD analyses indicated significant TiC formation only at discharge durations as high as 300 µs for either polarity (Fig. 12). Given that TiC formation in the Al–Ti–C system entails a temperature of at least 1150 K [6], this implies that a higher energy input was required to sustain a sufficient volume of the γ-TiAl subsurface at the requisite temperature and duration, for TiC to materialize. This is indeed logical considering that the thermal conductivity of γ-TiAl is about 1.5–3.0 times higher than that of Ti6Al4V at elevated temperatures [7].

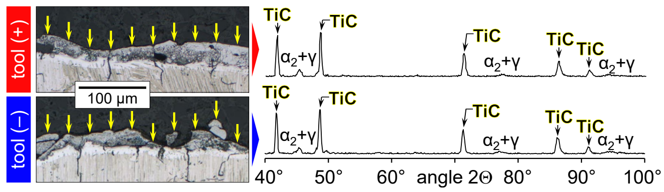

Fig. 12 Metallographic sections and XRD spectra of γ-TiAl surfaces machined at a discharge duration of 300 µs.

4. Conclusions

This research investigated the anomaly that the conventional tool positive polarity corresponded to essentially no material removal in sink EDM of Ti6Al4V alloy at all discharge durations. This was shown to be due to the formation of a TiC layer on the work surface, which by virtue of being a thermal barrier, manifests a significant impediment to material removal. In this instance, sink EDM largely ceases to be machining, and morphs into electro-spark deposition of TiC. Machining of Ti6Al4V under a tool negative polarity was however feasible, given that the TiC layer was rendered relatively thin and discontiguous, due to removal of the incipient TiC layers being facilitated by the higher power density incident on the workpiece. Appreciable formation of TiC on γ-TiAl was deferred to discharge durations as high as 300 µs, arguably due to the pertinent energy input being otherwise not high enough to form TiC, consequent to the significantly higher thermal conductivity of γ-TiAl.

Acknowledgements

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References

[1] Kunieda M, Lauwers B, Rajurkar KP, Schumacher BM (2005) Advancing EDM through Fundamental Insight into the Process. *CIRP Annals–Manufacturing Technology* 54(2):64–87.

[2] Kunieda M, Kobayashi T (2004) Clarifying Mechanism of Determining Tool Electrode Wear Ratio in EDM Using Spectroscopic Measurement of Vapor Density. *Journal of Materials Processing Technology* 149:284–288.

[3] Furutani K, Sato H, Suzuki M (2009) Influence of Electrical Conditions on Performance of EDM with Powder Suspended in Working Oil for TiC Deposition Process. *International Journal of Advanced Manufacturing Technology* 40: 1093–1101.

[4] Klink A, Holsten M, Schneider S, Koshy P (2016) Acoustic Emission Signatures of Electrical Discharge Machining. *CIRP Annals–Manufacturing Technology* 65:229–232.

[5] Chen SL, Yan BH, Huang FY (1999) Influence of Kerosene and Distilled Water as Dielectrics on the Electric Discharge Machining Characteristics of Ti6Al4V. *Journal of Materials Processing Technology* 87:107–111.

[6] Nukami T, Flemings MC (1995) In Situ Synthesis of TiC Particulate-Reinforced Aluminum Matrix Composites. *Metallurgical and Materials Transactions A* 26:1877–1884.

[7] Clemens H, Mayer S (2013) Design, Processing, Microstructure, Properties and Applications of Advanced Intermetallic TiAl Alloys. *Advanced Engineering Materials* 15:191–215.