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Original Research Article

Sustainable surface characterization and performance analysis of vibration-assisted EDM of Inconel 718

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ABSTRACT
Sustainable vibration-assisted electrical discharge machining (VA-EDM) has received much interest as a modern machining approach to nickel-based superalloys such as Inconel 718, due to its ability to address the inherent shortcomings of conventional EDM, such as low material removal rate (MRR) and poor surface integrity. The current work achieved the design of a new vibration-assisted EDM system with an improved flushing mechanism that will improve the debris removal rate and stabilize the discharge plasma channel. The influence of the main process parameters, i.e., the peak current and pulse-on time, on machining performance, were evaluated in a systematic manner. An extensive surface integrity evaluation was conducted, including white layer thickness, surface roughness, and microcrack density. Va-EDM process showed a high decrease in the thickness of recast layer and crack propagation due to better circulation of dielectric and even distribution of spark based on tool vibration. Moreover, the machined surfaces exhibited low roughness values in comparison to conventional EDM, which implies a higher quality of surfaces. The results confirm that thermal gradients and re-solidification behavior can be successfully controlled through vibration-assisted discharges, leading to better surface attributes and machining stability of Inconel 718.

1. Introduction

Inconel 718 is a precipitation-hardened nickel-chromium superalloy that is commonly used in aerospace, automotive and defence applications because of its superior high temperature strength, corrosion resistance and fatigue behavior. These high-quality features, however, make the alloy very hard to machine under normal methods due to its high strength at high temperature, extreme work hardening nature and low thermal conductivity. Consequently, traditional machining operations tend to result in high tool wear, low surface finish and low productivity. To address these issues, unconventional machining technologies like electrical discharge machining (EDM) have widely been used to machine Inconel 718 and other hard to cut alloys [1]. EDM is a thermoelectric process whereby material is removed by a series of controlled electrical discharges between the tool electrode and the workpiece in the presence of a dielectric medium. EMD is especially appropriate with hard and brittle materials due to the lack of mechanical contact. Nevertheless, even though it has its benefits, traditional EDM is commonly linked to the loss of surface integrity. The machined surface is normally composed of recast or white layer, microcracks and residual stresses and a relatively high surface roughness, all mainly brought about by the rapid melting and solidification under intense localized thermal cycles [2]. Such surface flaws have the potential to greatly undermine the service and life of vital parts in their value-added operation and, consequently, restrict the generalizability of EDM in high-precision sectors. To overcome these drawbacks, vibration-assisted electrical discharge machining (VA-EDM) has been proposed as an alternative promising hybrid method. In VA-EDM, vibration is controlled on either the tool electrode or the workpiece which boosts the circulation of dielectric and allows the effective removal of debris through the inter-electrode gap. Better flushing results in more consistent discharge generation, less arcing and evenly distributed energy during machining. Past research activities have shown that incorporation of vibration can greatly enhance the machining performance in terms of material removal rate, lessening of tool wear as well as the improvement of surface features [3]. Dynamic gap conditions brought about by vibration are vital in reducing abnormal discharges and enhancing stability in processes. Though these developments have been made, the impact of the vibration-assisted discharge parameters on the surface integrity parameters such as white layer thickness, surface roughness, and the density of cracks is not well understood, especially in Inconel 718. Furthermore, the overall impact of important electrical parameters, such as the peak current, and pulse-on time under the vibration-assisted conditions needs additional systematic research. Thus, the current research is supposed to come up with a better VA-EDM configuration, including a more efficient flushing system and to thoroughly analyze its influence on the machining results and surface quality. To investigate the efficacy of vibration assistance in improving the surface properties and maintaining process stability during the advanced engineering processes, a comparative study of the conventional EDM and VA-EDM is performed.

2. Materials and methods

Inconel 718 was considered as the workpiece machined for this work and was of dimensions (60×60×5) mm. Inconel is used as a super alloy and has remarkable characteristics against extreme heat. The use of super alloys like Inconel in industries is also legal. Nickel- chromium alloy that has excellent oxidation and creep-resistant properties at high temperature. This is because it is a high-temperature aluminum that is a complex oxide that can rapidly form a thick oxide film following heating that enables it to operate at high temperatures. Copper was selected as the material of the tools. This machining process was therefore carried out using a sugarcane tool that was 20 mm in diameter with step turning to hold it better (Fig. 2. c). It is a very high efficiency and cost-effective process, that produces reasonable material removal and finishes. Copper electrodes are popular for being cheap and easy to get hold of. Copper, too, is highly conductive, and may be readily machine-cut into shape. In this study, a flat copper electrode is used, which is a step rotated one. Electrical discharge machine (EDM) was used to machine workpiece (Fig. 2). Die sinking electrical discharge machining (EDM) was chosen for machining Inconel. The machine applied in this is found in the Advanced machine laboratory of production department of VSSUT, Burla. The silicon carbide (1g/lit) was utilized in the experiment. A dielectric was added to the powder to increase the machining ability. Fig. 1 shows the initial condition of the SiC powder, the scanning electron micrograph and X-ray diffraction pattern, respectively. A scanning electron micrograph (SEM) of the as-received SiC powder can be of great use to determine the size, shape and distribution of the powder. The micrograph in Fig. 2 shows the properties of the powder such as whether the powder is aggregated or there is a homogeneous distribution of the particles. In addition, the micrograph can provide information about the flaws or contaminants on the surface of the particles. The sample crystal structure and phase composition of the received SiC powder are investigated with the help of X-ray diffraction (XRD) analysis.

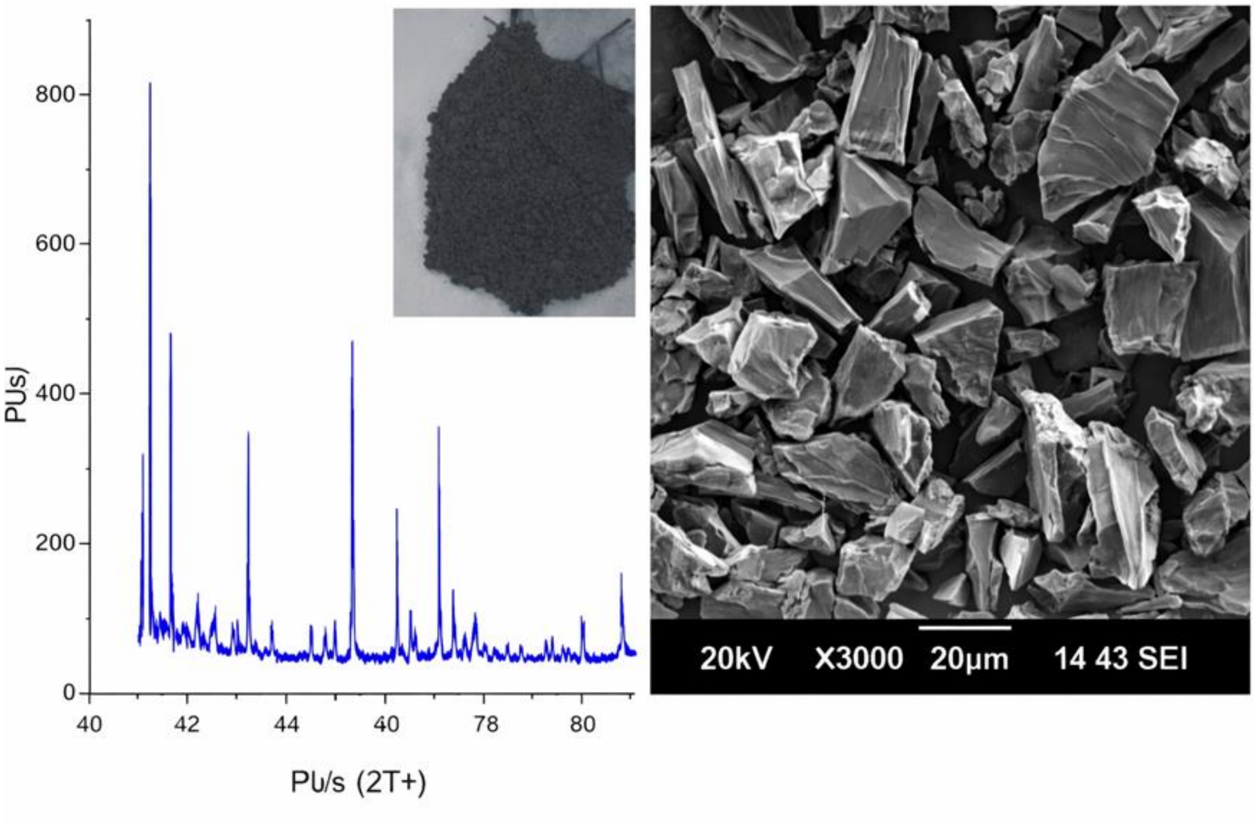

Figure 1: SEM micrograph and XRD spectra of 'as received' SiC powder.

The X-rays are focused on the sample and by scattering the X-rays off the atoms of the crystal lattice they create a diffraction pattern. The information about the crystal structure and phase composition can be extracted with the help of the diffraction pattern. The crystal structure and presence of impurities or flaws in the "as-received" SiC powder can be determined through examination of the XRD spectrum. Interactions of the X-rays with the atoms in the crystal lattice of sample give a pattern of diffraction. The study of the XRD spectra of the received SiC powder can help one learn more about its crystal structure and determine whether it contains some impurities or defects.

Figure 2: Electrical discharge machine (EDM).

Table 1: Domain of experiments and machining parameters.

Process Parameter	Level 1	Level 2
Peak current (IP)	25A	35A
Pulse-on time (Ton)	1000 µs	2000 µs

Also, Figure 1 shows the SEM micrograph and X-ray diffraction (XRD) spectrums of the as-received SiC powder that was used in the course of the experimentation and indicates its morphology and phase composition. The machining experiments were conducted through the variation of two key process parameters, i.e. peak current and pulse-on time, at two levels each. These parameters have been chosen due to their considerable impact on discharge energy and surface properties. Table 1 presents the process parameters and the levels of the same.

3. Results and discussion

Surface morphology and integrity of Inconel 718 machined in conditions of vibration assisted EDM (VA-EDM) and conventional EDM were systematically examined under conditions of SEM, as demonstrated in Figure 3. The experiments were carried out with a peak current of 35 A (Table 1), which is a fairly high discharge energy condition. The identified variations in the recast layer properties, crack density, and morphology of the debris are valuable clues to the effect of the vibration assistance on the EDM process. 3.1 Characteristics of Surface Morphology and Recast Layer. Figure 3(a) (VA-EDM) and Figure 3(b) (conventional EDM) clearly show the differences in surface features using the SEM micrographs. In the typical conditions of EDM, the surface is more dominated by the larger globules, thickened solidified debris, and deep microcracks, which are the common features of the unstable discharge conditions, and inefficient flushing of the debris. They are caused by repeated melting and rapid solidification of the material as a result of which a thick and brittle recast (white) layer is formed. Higher discharge energy has been found to cause severe thermal damage and surface irregularities with the same report as Guu [2] and Ho and Newman [1]. Conversely, the VA-EDM surface (Figure 3(a)) has finer globular structures, low adhesion of debris, and much less density of cracks. The introduced vibration increases dielectric circulation, which facilitates efficient removal of molten material across inter-electrode gap. As a result, the recast layer formed is thinner and more uniform. This can be explained by the fact that the tool and the workpiece are intermittently separated when vibrating and thus no long channels of plasma are formed and the localized overheating is minimized [3]. The effect of Vibration on Crack Formation and Propagation, 3.2. The formation of crack in EDM is mainly influenced by thermal stresses that occur when the molten substance is subjected to rapid cooling. Figure 3(b) indicates that the traditional EDM surface has long and joined microcracks, which means that the residual tensile stresses in the recast layer are high. These cracks are harmful to the performance of the components and in particular aerospace where fatigue life is a key issue. The VA-EDM surface (Figure 3(a)) on the other hand has less interconnected cracks with shorter cracks, as indicated in the shaded areas. The decreasing crack density can be attributed to the fact that the flushing conditions are improved and the distribution of energy within them is more uniform due to vibration. Repeat interruption in the discharge channel minimizes the peak thermal gradients, and hence less stress residue accumulation. The same has been observed in recent research, in which vibration-assisted EDM had a significant impact on reducing crack density and enhancing surface integrity [4].

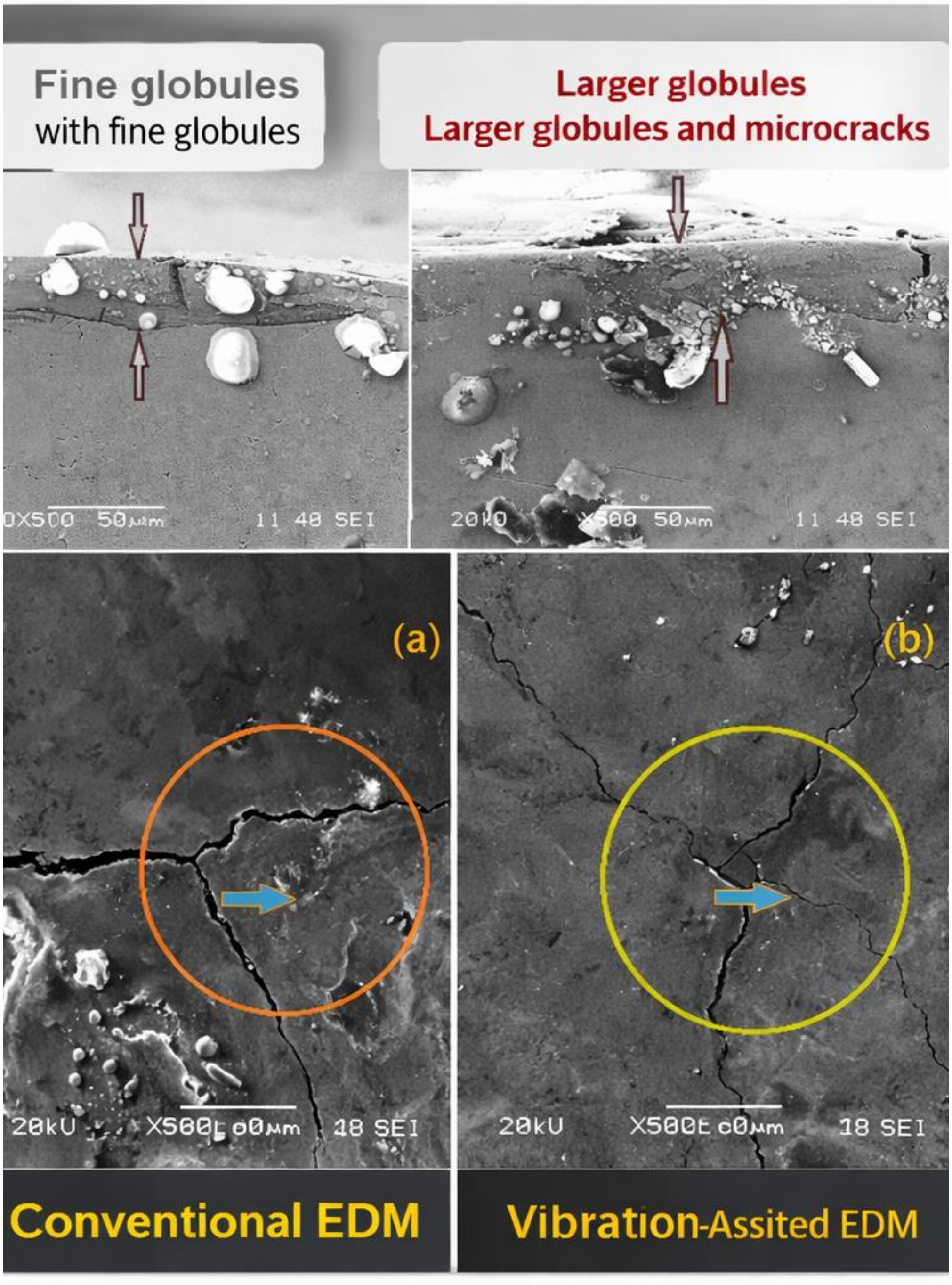

Figure 3: SEM micrographs recast layer of the EDMed work surfaces of Inconel 718 obtained in (a) Vibration Assisted Powder mixed EDM; (b) Conventional EDM at IP=35A.

3.1 Process parameters influence

The parameters of the process that are provided in Table 1, especially peak current (IP) and pulse-on time (Ton), are critical to the discharge energy and, therefore, surface characteristics. There is a significant increase in the discharge energy with an increase in the peak current (35 A), which results in increased material melting and deeper crater formation. This is the cause of the extreme surface damage that is seen in conventional EDM at this state. Nevertheless, with VA-EDM conditions, the adverse effects are alleviated, even at large current levels, because of the increased flushing efficiency. Continuous renewal of the dielectric fluid in the spark gap is promoted by the vibration which dilutes the concentration of debris particles. This avoids secondary discharges and arcing which causes a more stable machining process. Pulse-on time also has an important effect, with longer pulse durations (2000 μs) permitting greater heat input, thus increasing the thickness of the recast layer. However, the vibration is useful in regulating the excessive heat build-up by encouraging quick removal of debris [5].

3.2 Powder characteristics role

Figure 1 presents the SEM micrograph and XRD spectra of the as-received SiC powder, which indicates that it has an angular morphology and is crystalline. The sharp-edged particles increase the dispersion of sparks and better the gap conditions in machining. The existence of these particles in the dielectric media helps in evenly distributing the energy and decreasing concentration of sparks which eventually lead to better surface finishes and minimized cracks. Past research has demonstrated that powder mixed EDM results in better surface integrity since bridging effects and better distribution of plasma channels occurs [6,7].

3.3 Effect of experimental setup

The experimental system as shown in Figure 2 demonstrates the combination of a vibration unit with the EDM system. A controlled vibration source adds greatly to the efficiency of flushing as compared to traditional EDM. The enhanced arrangement guarantees the constant elimination of molten waste, thus avoiding its re-solidification on the work surface. This is directly related to the reduction in recast layer thickness and surface defects as seen in VA-EDM. Moreover, vibration introduces dynamic motion resulting in periodic change of spark gap thus avoiding abnormal discharge conditions like short-circuiting and arcing. This causes a more uniform crater formation and higher surface morphology. Similar improvements in machining performance due to enhanced flushing and spark stability have been reported in recent EDM studies [8, 9]. Comparative analysis of vibration-assisted EDM (VA-EDM) and traditional EDM shows clearly that integration of controlled vibration plays a key role in improving surface integrity in machining Inconel 718. The VA-EDM process leads to the creation of thinner and smoother recast layers with a significant decrease in the density of microcracks. Also, the morphology of the surface is also significantly fined with finer globular structures and lower deposition of irregularly shaped debris. These are mainly explained by the better dielectric circulation and improved removal of debris between electrodes that reduce secondary discharges and re-solidification of molten material. Moreover, the conditions of dynamic gap that are brought about by vibration contribute to the minimization of local thermal gradients and stabilization of the discharge process. Consequently, VA-EDM appears as an extremely viable method of enhancing surface properties and guaranteeing high-quality functional performance of machined Inconel 718 parts in the harsh engineering environment.

4. Conclusion

The current paper systematically examined the effect of vibration-aided electrical discharge machining (VA-EDM) on surface integrity of Inconel 718 against traditional EDM. The findings have clearly shown that the use of a controlled vibration as well as an enhanced flushing mechanism have a significant effect in the performance of machining and the surface properties. VA-EDM is very effective in minimizing the recast (white) layer thickness, inhibiting microcracks formation, and giving a more uniform and refined surface morphology with smaller globular features. This increase in surface integrity is mainly due to an increase in dielectric circulation and effective removal of debris out of the inter-electrode gap to reduce secondary discharges and stabilize the plasma channel. Moreover, vibration-induced dynamic spark gap results in a smoother energy distribution and, thus, lowers the local thermal stresses and avoids overre-solidification of materials. VA-EDM is also superior to conventional EDM in terms of surface quality, even in high discharge energy (increased peak current and pulse-on time) conditions. In general, the results of the study prove that VA-EDM is a good and feasible machining method to work with hard-to-cut materials like Inconel 718, where the integrity of the surface bears paramount significance. The system that has been developed has the potential of industrial use where better functional performance and reliability is needed. To better understand the behaviour of microstructural evolution and residual stress there is future work where the vibration parameters can be optimized and the use of advanced methods of characterization to better understand microstructural evolution.

Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

The author declares no conflict of interest.

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Data availability

No new data were created.

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