Evaluation of surface integrity of WEDM processed inconel 718 for jet engine application

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Abstract. A unique superalloy, Inconel 718 has been serving for aerospace industries since last two decades. Due to its attractive properties such as high strength at elevated temperature, improved corrosion and oxidation resistance, it is widely employed in the manufacturing of jet engine components. These components require complex shape without affecting the parent material properties. Traditional machining methods seem to be ineffective to fulfil the demand of aircraft industries. Therefore, an advanced feature of wire electrical discharge machining (WEDM) has been utilized to improve the surface features of the jet engine components. With the help of trim-offset technology, it became possible to achieve considerable amount of residual stresses, lower peak to valley height, reduced density of craters and micro globules, minimum hardness alteration and negligible recast layer formation.

1. Introduction
Since past few years, aircraft manufacturing industries are continuously demanding complex shaped components for their utilization in jet engines in order to improve their efficiency and service life. Turbine section is amongst the most critical part in jet engine as it is exposed to a high temperature and high pressure gas stream [1]. Nickel based superalloys are an exceptional class of structural materials as they exhibit outstanding properties such as high mechanical strength at elevated temperature, excellent oxidation/corrosion resistance, hot hardness and high fatigue endurance limit [2]. For an example, Inconel 718 alloy comprises of about 34% of the total weight of aircraft engine [3] as shown in figure 1. An improved thermal, mechanical and chemical properties of Inconel 718 make it difficult to machine using traditional machine tool as it offers poor surface quality on the machined component and exhibits low process capability [4]. To overcome the issues of traditional machine tool, some advanced machine tools are successfully implemented, which uses energy particles such as laser (photon), electron and ions for removal of material. Wire electrical discharge machining (WEDM) is most widely accepted advanced machine tool due its capability in manufacturing of complex shape component with the help of CNC programming. Moreover, WEDM process offers minimum surface damage to the workpiece as it utilizes the ultrafine electrical discharge and produces the surface features within the tolerance band of 1–0.1 μm. Previous literature [5-8] indicates that a significant research was conducted on the machinability enhancement of Inconel 718 superalloy for various engineering applications. Some researchers [9, 10] have utilized the statistical tool and evolutionary
algorithm to determine the feasible range of WEDM control parameters for improved machining performance.

Despite the abundant literature available in the field of WEDM process, very few studies have been reported on evaluation of surface integrity of aircraft components madeup of Inconel 718 using WEDM process. In the current study, special features of WEDM process such as trim-offset technology was utilized to achieve the feasibility in manufacturing of jet engine components. The adopted technology also offers less surface damage to the machine components and helps to obtain the better surface integrity in terms of minimum hardness alteration, negligible recast layer formation, low density of craters, micro globules creation and, also produces minimum residual stresses.

![Material distribution in GE CF6 aircraft engine](image)

**Figure 1.** Material distribution in GE CF6 aircraft engine [2].

2. Materials and Methods

2.1 Material selection and preparation

Inconel 718 plate (250 mm and 100 mm × 10 mm) was used as experimental workpiece. The alloy was procured from ‘Special Metal’ (India). The chemical composition of Inconel 718 has been shown in table 1. Further, the workpiece was heat treated in a tubular furnace at a temperature of 800 °C to avoid the chances of distortion during manufacturing of aircraft component. Before actual experimentation, it was confirmed that workpiece is free from dust and rust to ensure the proper functioning of WEDM during edge finding.

| Alloy (%) | Ni+Co | Cr | Fe | Nb+Ta | Mo | Ti | Al | Co | Cu | C | Mg | Si |
|-----------|-------|----|----|-------|----|----|----|----|----|---|----|----|
| Inconel   |       |    |    |       |    |    |    |    |    |   |    |    |
| 706 Min.  | 50    | 17 | Bal| 4.75  | 2.8| 0.65| 0.2|    |    |   |    |    |
| 706 Max.  | 55    | 21 |    | 5.50  | 3.3| 1.15| 0.8| 1  | 0.3| 0.08| 0.35| 0.35|

2.2. Experimental details

The experimental work was performed on WED machine (Model: ECOCUT from Electronica Machine Tools, Pune, India). Zinc coated wire was selected as tool electrode whereas de-ionized water was used as dielectric fluid. An optimum value of wire feed (6 m/min) and flushing pressure (1.96 bar) was selected based on preliminary investigation [11]. In the current study, rough cut technology was used for basic cutting of complex shape profile through aircraft components, however trim-offset technology was employed to obtain the high dimensional accuracy and better surface integrity on the aircraft component. Six control parameters were selected for manufacturing of aircraft components as shown in table 2. The feasible range of control parameters was estimated based on the several trial experiments. Within the range of parameters selected, no gap short and wire breakage was reported. CNC programming of complex aircraft components was carried out using ‘ELCAM’ software. The mechanism of WEDM operation has been shown in figure 2. Initially, a high potential difference was applied between the wire electrode and workpiece using a pulse generator which produces a strong electric field. If the bonding strength of electrons is less than the electric field strength, then electrons are cold emitted from wire electrode and, attracted towards the workpiece material. Thus, electrons gain some kinetic energy and collide with the molecules of dielectric fluid resulting in ionization. Due to ionization of dielectric fluid, plasma channel forms which has very low electrical resistance. Therefore, more number of electrons and ions are formed between wire electrode and workpiece due
to ionization. All of a sudden, a large density of electron starts flowing from wire electrode to the workpiece and ions from workpiece to wire electrode. These avalanche motion of electrons and ions are visually seen as spark. Thus, electrical energy is converted into thermal energy of the spark. Generally, electrical discharge has a temperature of around 10,000°C which is more than enough to melt and vaporize the any conductive material.

### Table 2. Technology table for manufacturing of jet engine components.

| WEDM Technology | Pulse current (A) | Pulse on Time (µs) | Pulse off Time (µs) | Servo Voltage (V) | Servo Feed (µm) | Wire offset (µm) |
|-----------------|-------------------|--------------------|--------------------|-------------------|----------------|-----------------|
| Rough-cut       | 12                | 112                | 36                 | 20                | 2150           | 0               |
| Trim-offset     | 2                 | 105                | 20                 | 10                | 200            | 50              |

3. Result and Discussion

3.1 Surface Topography Analysis

For surface topography analysis, 3D laser microscope was utilized which is capable enough to measure the micro/nano level surface texture due to its low spot diameter of 0.4 µm. A scan area of 106 µm × 106 µm was selected for topographic investigation. The surface topography result was shown in figure 3 which shows that rough cut surface has higher peak to valley height (Rz) whereas trim cut surface exhibits the lower Rz value. The behavior could be explained by the fact that in the rough cut mode, pulse on time is too high which increases the spark intensity. Therefore, consequently, more amount of material is melted from the machined surface. A part of the molten material was flushed away by pressurized wave generated in the absence of plasma channel. When remaining molten metal re-solidify, forms a large crater on the machined surface. Therefore, machined surface shows the high Rz value of 23 µm as shown in figure 3(a). However, in trim cut mode, ultrafine electrical discharges are produced which melts only a small amount of material from the machined surface which can be easily flushed away by pressurized wave. Thus, forms micro/nano craters on the machined surface and shows the low Rz value of 11 µm as shown in figure 3(b).

![Figure 2. Principle of WEDM operation [10].](image)

![Figure 3. Surface topography analysis of WED machined surface, (a) Rough cut surface; (b) Trim cut surface.](image)
3.2. Microstructure Analysis
For microscopic investigation, machined surface was exposed to scanning electron microscope (SEM). The SEM analysis revealed that under rough cut mode, there is a high density of micro globules, micro holes, craters and melted debris on the machined surface as shown in figure 4(a). This is because, under rough cut, discharge pulse has a high pulse on time which increases the spark intensity. This, in turn, melts more amount of material and forms larger crater on the machined surface. A part of molten material is flushed away by pressurized waves, however some air bubbles get entrapped in it. When remaining molten material re-solidify, these air bubbles collapse and generate micro holes on the machined surface. On the other hand, the propensity of micro globule and crater formation are considerably reduced in trim cut mode due to ultrafine electrical discharge except few micro holes and melted debris. These ultrafine discharge pulses melt only a small amount of material from the machined surface which can be easily flushed away by pressurized wave and allow the formation of micro/nano cavities on the machined surface as shown in figure 4(b).

![Figure 4](image1.png)

**Figure 4.** Micrograph of WED machined surface, (a) Rough cut surface; (b) Trim cut surface.

3.3. Recast Layer Analysis
Recast layer is a layer which is commonly observed on the machined surface due to melting and resolidification of material. To measure the recast layer thickness, sample are cross-sectionally polished at a rotational speed of 300 rpm using a progressive grade of silicon carbide (SiC) papers and diamond paste. The recast layer formed on the machined components has been shown in figure 5 which indicates significant thermal damage in case of rough cut mode however minimum surface damage was detected under trim cut mode. The behavior could be explained by the fact that under rough cut mode, more thermal energy has been transferred to the workpiece material which melts consequently more amounts of material from the workpiece. A part of the molten material was flushed away by pressurized waves when remaining molten material re-solidify and form a thick recast layer on the machined component as shown in figure 5(a). But, recast layer formation has a detrimental effect on aircraft component. With the use of ultrafine discharge pulse in trim-offset technology, it became possible to reduce the recast layer thickness significantly. These ultrafine discharge pulses melt only a small amount of material which can be easily flushed away by pressurized waves generated in the absence of plasma channel. Hence, recast layer formation significantly reduced in trim cut mode.

![Figure 5](image2.png)

**Figure 5.** Recast layer formed on WED machined surface, (a) Rough cut surface; (b) Trim cut surface.
3.4. Microhardness Analysis

To measure the subsurface microhardness, sample are cross-sectionally cold mounted using acrylic resin. Then, mechanical polishing was done using sequential grade of SiC papers and diamond paste in order to obtain the mirror finish structure. Microhardness profile of WEDM processed Inconel 718 has been shown in figure 6 which indicates that microhardness of WED machined surface has been decreased to a depth of 80 µm below the machined surface under rough cut. However, no significant change in microhardness was detected under trim cut mode. The behavior could be explained by the fact that Inconel 718 has very low carbon content which won’t make the surface harder even quench by dielectric fluid.

![Figure 6. Microhardness analysis of WED machined surface.](image)

3.5. Residual Stress Analysis

The residual stresses induced in WED machined Inconel 718 was measured using ‘PROTO-iXRD’ stress measuring system. Due to sudden heating and cooling during WEDM process, high temperature gradient is acting on the machined component. When, workpiece material was melted due to the thermal energy of the spark. A part of the molten material was flushed away by pressurized wave when remaining molten material re-solidify then its shrinkage was opposed by the bulk material. Hence, recast material exhibits the tensile residual stresses whereas bulk material exhibits the compressive residual stresses as shown in figure 7. For jet engine application, tensile residual stress should not exceed beyond 850 MPa as it produces harmful effect on aircraft component and significantly reduces the service life. In the current study, residual stresses were significantly reduced under the trim cut due to negligible recast layer formation and make the WEDM process highly suitable for manufacturing of jet engine components.

![Figure 7. Residual stresses generated in aircraft component during WEDM process.](image)

4. Conclusion

Based on the experimental investigation, following conclusion were derived:

- The surface topography analysis exposes that WEDM trim-offset technology offers lower Rz value of 11 µm and significantly improve the profile accuracy.
- Microstructure analysis reveals that trim-offset technology offers no micro globules and no crater formation on machined components except few micro holes and melted debris.
The recast layer analysis exposes that trim-offset technology offers almost negligible recast layer thickness due to ultrafine discharge pulse and make it highly suitable for manufacturing of jet engine components.

Microhardness analysis reveals that subsurface microhardness has been decreased to a depth of 80 µm below the machined surface under rough cut mode. However, no significant change in subsurface microhardness was detected under trim cut mode.

Residual stress analysis discloses that machined surface exhibit tensile residual stresses due to sudden heating and cooling during WEDM process. However, trim-offset technology offers very low level of tensile residual stresses on the machine component.

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