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# Surface integrity comparison of wire electric discharge machined Inconel 718 surfaces at different machining stabilities

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## Abstract

Current study aims to investigate the effect of machining stability on the surface integrity of the wire electric discharge machined Inconel 718 superalloy. The wire electrode material used for machining is hard zinc coated brass. Experiments were conducted at various levels of machining stabilities, defined with respect to discharge energies and machining gap conditions. The topographical characteristics were analysed by contact surface profilometer and non-contact 3D profilometer. Scanning electron microscope (SEM) images were analyzed to observe and compare the surface defects like microvoids, micro-cracks, micro globules, micro-craters on the samples machined at different stability levels. The least stable machining condition, with highest discharge energy, lowest inter electrode gap and least pulse off time, produced the most uneven topography. Recast layer (RCL) thickness was analyzed by observing the polished cross-sectional view of machined specimens under SEM. The conditions that provided the least RCL thickness were the most stable machining conditions. Furthermore, the surface layer characteristics like elemental contamination and thermal softening effects were analyzed using EDS and micro hardness tester respectively. All these characteristics have close relationship with the degree of machining stability.

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*Keywords:* Wire electric discharge machining; machining stability; surface integrity

## 1. Introduction

Wire electric discharge machining (WEDM) is a non-traditional machining technique which uses controlled repetitive electric sparks for material removal. The process is superior to conventional processes due to its non-contact nature of material removal. [1] The process is thus suitable for machining superalloys which are difficult to machine otherwise using conventional techniques [2]. However, since the mechanism of material removal is by melting and vaporization, analyzing the surface integrity is crucial, especially if the machined component has high temperature application [1].

Even though WEDMed parts were used in aerospace components for decades, the surface integrity and thus safety of WEDMed parts was a concern throughout the history. Anurag [3] has observed that even though WEDM possesses many advantages over the conventional machining methods, poorer surface integrity in terms of recast layers and residual

stresses are restricting its usage for high temperature applications. Klocke et al. [4] observed that the discontinues and porous recast layer is considered to have a detrimental effect on high temperature performance on Wire EDMed components. The suitability of the process to machine fir tree slots in gas turbine discs in terms of geometry and surface integrity was studied.

Li et al. [5] studied the effect of WEDM discharge energies on surface integrity of Inconel 718. They found discharge energy has high influence on the surface topography, white layer thickness and surface roughness. Sharma et al. [6] have studied the effect of wire material and discharge energy on the surface integrity of Inconel 706. Discharge energy was found to have an influence on subsurface hardness, residual stresses, elemental contamination and surface topography. Jadam et al. [7] studied the effects of trim cuts in improving the surface integrity. Coated wires and trim cuts are observed to reduce the recast layer thickness. Reolon et al. [8] compared the effect of

wire coatings on WEDM performance during the machining of IN718 and found the traces of zinc and copper on the recast layer during elemental analysis. The effect of wire coatings on the surface integrity was also compared by Antar et al., [9]. The work materials considered were Udimet 720 and 6246 Ti alloy (Ti-6Al-2Sn-4Zr-6Mo). Coated wires were found to increase productivity and reduce recast layer thickness. Sharma et al. [10] explored the effect of wire diameters on machining performance for IN706. Smaller diameter wires were found to improve the surface integrity in terms of recast layer thickness and subsurface hardness. Goswami and Kumar [11] studied the surface integrity of WEDMed Nimonic 80A using Gray relational analysis (GRA) and Taguchi methods. They observed that higher discharge energy is produced thicker recast layers and deeper and larger surface craters.

WEDM is considered as a stochastic process due to its complex material removal mechanism and many uncontrollable factors. Also, the process is having various instantaneous instabilities due to the continuously varying inter electrode gap (IEG) state. Accurate modeling of the process taking all these variables into account is very difficult [12]. However, the surface integrity of the part has to be understood in the stability point, in a view to make it suitable for high temperature applications. Williams and Rajurkar defined the stability of the WEDM process as the machining conditions that results in least surface damages [13]. Short circuit pulses, caused by high discharge energies and poor flushing conditions are considered as the chief contributors for surface damages and poor surface integrity [14].

As evident from the literature survey, surface integrity of the wire EDMed components is of utmost importance for its industrial applications. Researchers have found that surface integrity is most affected by discharge energies and arc/short circuit pulses. However, these two are actually related to one single phenomenon called machining stability, which is the least focused area when dealing with surface integrity. The relationship trends between machining stability and various surface integrity aspects will remain same for any material, even though the effect can change quantitatively from material to material. The objective of the study is to explore the effects of machining stabilities on the machined surface.

## 2. Experimental procedure

The current study explores the surface integrity of Inconel 718 at various machining stabilities. Inconel 718 is a nickel based super alloy known to retain its strength at elevated temperatures. The alloy is also resistant to corrosion and oxidation and has high fatigue strength. The superalloy is thus used in the aerospace applications specially to make gas turbine components. Aerospace industries demand its components to be made with best accuracy and excellent surface integrity. WEDM is a potential machining method to achieve that level of part quality. Table 1 shows the properties of Inconel 718.

The machining is said to be stable when the following conditions are satisfied

- (1) The discharge energy of spark raises the temperature of the workpiece locally to allow melting and vaporization.

- (2) The pulse off time should be equal to or greater than the time required for completely clearing the debris produced from the previous spark.
- (3) The inter electrode gap (IEG) distance is set in such a way that the passage can enable the debris to clear through easily which flushed with dielectric fluid.

Table 1. Properties of Inconel 718

Property	Value
Density	8.19 g/cm <sup>3</sup>
Melting Point	1260 – 1336° C
Specific Heat	435 J/kg K
Average Coefficient of thermal expansion	13 $\mu$ m /m K
Thermal Conductivity	11.4 W/m K
Ultimate Tensile strength	1240 MPa

If discharge energy is high, the relative amount of debris is high and there are higher chances of spark gap bridging. Similar is the case when pulse off time or spark gap is less. Then also the chances of debris agglomeration in IEG is more. Such a condition is called machining instability and it causes short circuit sparks causing poor surface integrity for machined components. Based on this knowledge, five machining stability levels are considered in terms of input parameters for the analysis, as shown in Table 2. The parameter ranges were chosen based on the pilot experiments and literature in such a way that the wire breakages do not occur in the selected range. The aim is not to consider all the parameters to optimize the performance, but to artificially create unstable conditions to study its effects. The process parameters considered are Pulse on time ( $T_{on}$ ), pulse off time ( $T_{off}$ ) and servo voltage. Discharge energy is the product of spark voltage (V), discharge current (I) and discharge duration. In this study, V and I are kept constant at 12 V and 11A and  $T_{on}$  is the only factor that effects the discharge energy. Also, servo voltage is chosen since it effects the spark gap.

Table 2. Process parameter combinations based on machining stability

Machining Stability	Symbol	$T_{on}$ ( $\mu$ s)	$T_{off}$ ( $\mu$ s)	Servo Voltage (V)
Level 1 (Least Stable)	Lv_1	116	42	40
Level 2	Lv_2	113	44	45
Level 3	Lv_3	110	46	50
Level 4	Lv_4	107	48	55
Level 5 (Most Stable)	Lv_5	104	50	60

The research aims to highlight the potential of achieving better surface integrity during the roughing operation itself. Even though the similar part quality could be achieved by a high energy rough pass (aimed at high cutting speed) followed by multiple trim passes, the material (consumable) utilisation and overall material removal rate gets affected negatively. In the current strategy, the aim is in eliminating or at least reducing the subsequent trim passes and post processing requirements.

Machining was done by Electronica Ecocut wire-EDM machine. Wire electrode used was zinc coated hard brass wire of 0.25 mm diameter. Zeiss GeminiSEM 300 field emission scanning electron microscope was used for microstructural

analysis. Energy dispersive X-Ray spectroscopy (EDS) was used to conduct elemental analysis. AEP Nanomap1000 Non-contact 3D surface profilometer was used for imaging 3D surface morphology. Wilson VH1102 microhardness tester is used to measure subsurface hardness. Wire ED machine and workpiece profile is shown in Fig. 1.



Fig. 1 Wire ED machine and workpiece

The workpiece machined is of constant thickness of 10mm. The profile machined is 10 mm x 10 mm square with one semicircular side as shown in Fig. 1. The experiments were repeated thrice to avoid errors.

### 3. Results and discussion

The surface topography was compared by non-contact 3D profilometer images and the results are shown in Fig. 2 and Fig. 3.

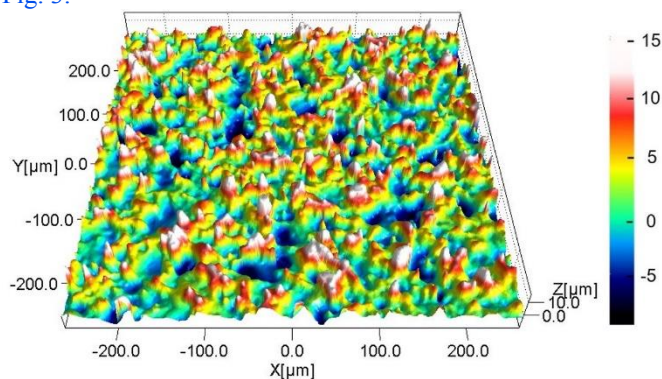


Fig. 2. 3D surface morphology image at least stable condition (Lv\_1)

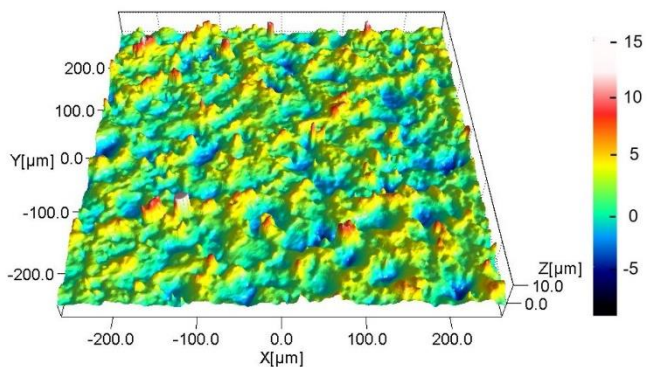


Fig. 3. 3D surface morphology image at most stable condition (Lv\_5)

The surface irregularities are observed to be more at lesser stability. The surface roughness is also observed to increase with instability as shown in the Fig. 4. The reason is due to increased crater size when machined with higher discharge

energy at lesser machining stabilities. Also, the relative amount of short circuit sparks are more at least stable conditions. Arc/short circuit sparks are said to cause surface damages due to spontaneous increase in instantaneous energy [12].

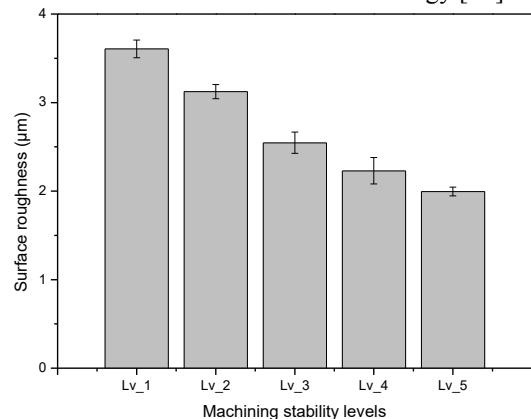


Fig. 4. Effect of machining stability on surface roughness

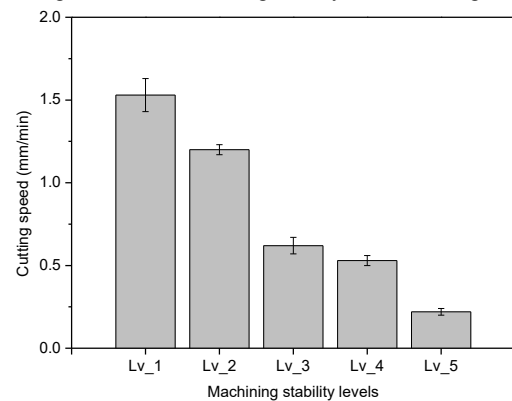


Fig. 5. Effect of machining stability on cutting speed

The term instability is observed to be used in both extremities of the machining. First case is when the spark gap condition is unsuitable to sustain continuous repeated sparks. Then open circuit or false discharges predominates and the machining speed is the lowest. In such cases, if the condition worsens, the machining stops due to spark absence. Such kinds of instabilities are not reported to cause surface integrity related issues. However, in the current context, the instabilities considered are the ones related to excessive discharge energy and the inability of the process conditions to prepare the spark gap for the subsequent sparks. Since the discharge energy is proportional to the material removal per spark, greater the instability, higher will be the cutting speed. Such a trend is shown in Fig. 5. The cutting speed is observed to increase at lesser stability levels due to the said reasons. If such instabilities worsen, the wire breakage can occur, due to the incapacity of the wire to sustain the discharge energy of that high magnitude.

The SEM images of machined surfaces at all five stability levels are shown in Fig. 6. The surface morphology shows a number of micro cracks, globules and micro pits at lower machining stability levels.



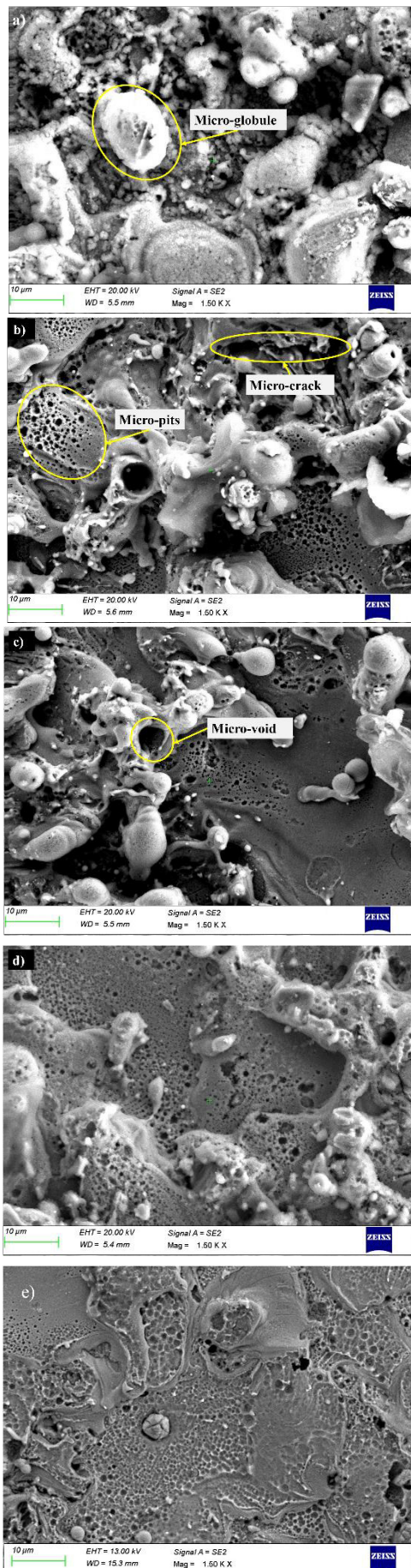


Fig. 6. SEM images of machined surface at machining stability (a) Level 1; (b) Level 2; (c) Level 3; (d) Level 4 (e) Level 5

The surface features like micro globules (debris in spherical form) and other irregularities are formed by re-solidification of molten material at machined surface. The amount of re-solidification and thus the irregularities caused by it, is a factor of discharge energy. The irregularities reduced as the discharge energy comes down at more stable levels. In addition to this, better flushing of debris prevented the spark gap bridging and resulted in smoother surfaces in stability level 4 and 5.

The recast layer is formed by the redeposition of molten material on workpiece surface. The quenched recast layer could contain micro cracks which is the primary reason for EDMed component stress failures. Below the recast layer, there is a heat affected zone (HAZ) which is annealed due to the process heat generation.

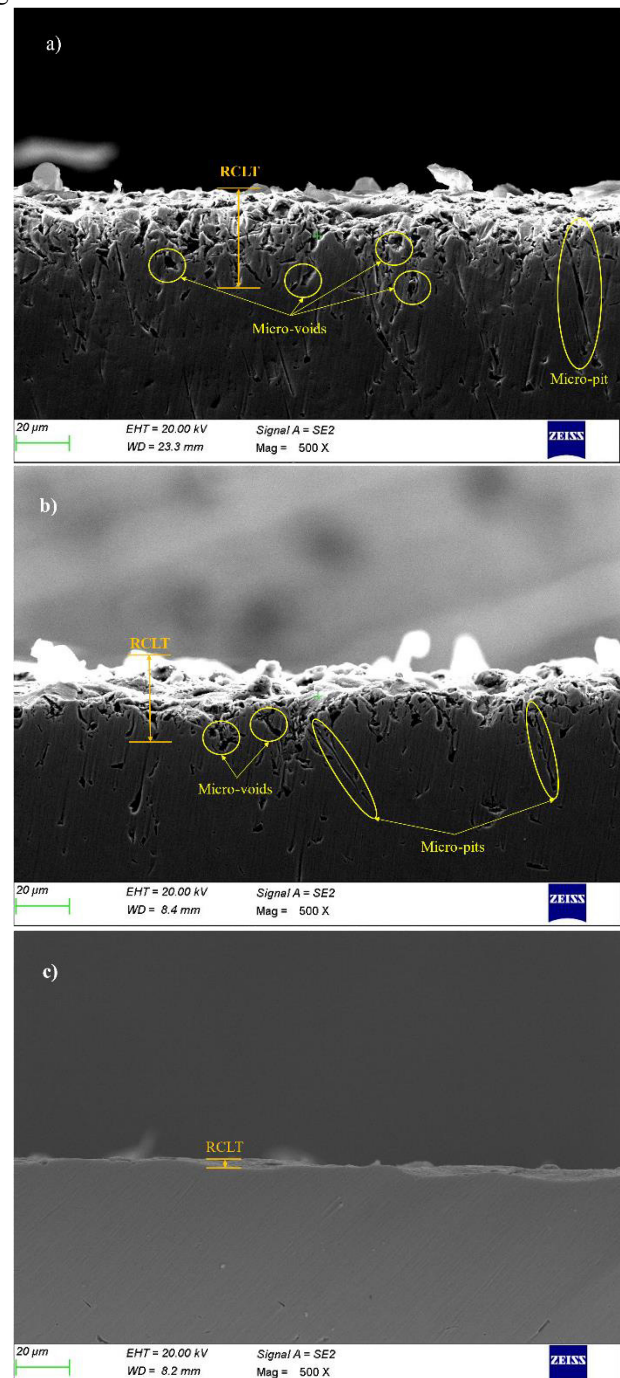


Fig. 7. Recast layer on WED machined surface at machining stability (a) Level 1; (b) Level 3; (c) Level 5

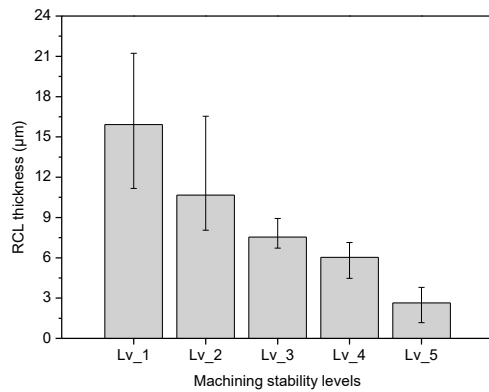


Fig. 8. Variation of RCL thickness with machining stability levels

The recast layer (RCL) thickness was analysed by taking SEM images of polished cross-sectional images of machined surface. The surfaces were polished into a mirror finish by diamond paste polishing and imaging was done on the edges to reveal the RCL. The RCL thickness at least stability (Lv\_1) is observed to have a number of micro voids and pits as evident from Fig. 7 (a). This is due to the entrapment of the vapour bubbles in the layer during solidification. Also, the thickness of RCL is maximum at this level. This is because of the greater amount of material removal (due to higher discharge energy) coupled with improper flushing conditions (due to lower spark gap and pulse off time). The resultant effect is a thicker RCL on the machined surface. As the stability improves in the subsequent levels, the RCL was observed to get thinner as shown in Fig. 7 (a) to Fig. 7 (c). This is due to the combined effects of lesser discharge energy and better flushability.

Near zero recast layer could be possible at maximum stability condition (Lv\_5) as shown in Fig. 7 (c). Such stability levels would reduce the mechanical or chemical post processing requirements in the case of EDMed components for aerospace applications. Fig. 8 shows the decrease in RCL from 15.91 µm to 2.64 µm. The RCL thickness was measured at four different places and the average value is taken. Even at roughing condition, 83.41% reduction is observed by varying the stability conditions. This highlights the significance of considering machining stability while studying the surface integrity.

Table 3 shows the chemical composition of Inconel 718. Energy-dispersive X-ray spectroscopy (EDS) analysis was conducted to check for elemental composition of machined surface. The aim of the analysis is to check for zinc and copper migration from the wire electrode to the workpiece. Traces of copper and zinc elements were found in the recast layer at all stability levels. However, the relative amount of zinc and copper was found to decrease from machining stability Lv\_1 to Lv\_5. Fig. 9 and Fig. 10 shows these extreme cases corresponding to least stable and most stable machining conditions respectively. The weight % of zinc reduced from 6.58 to 2.4 and copper from 2.38 to 1.81 respectively. During the WEDM process, the material removal happens not only to the workpiece but also to the wire. Similar to work material removal rate, wire erosion rate also increases from Lv\_1 to Lv\_5 which explains higher deposition of wire electrode elements to the recast layer at lesser stability levels. Increased wire wear at least machining stability was observed when the wire surfaces was observed under SEM as shown in Fig. 11.

Table 3. Chemical composition of Inconel 718 [5]

Element	Ni	Fe	Cr	Nb	Mn	C
Weight (%)	51.05	19.43	18.70	5.7	0.07	0.04
Element	Co	Al	Si	Ti	Mo	Other
Weight (%)	0.2	0.56	0.08	1.01	3.1	0.06

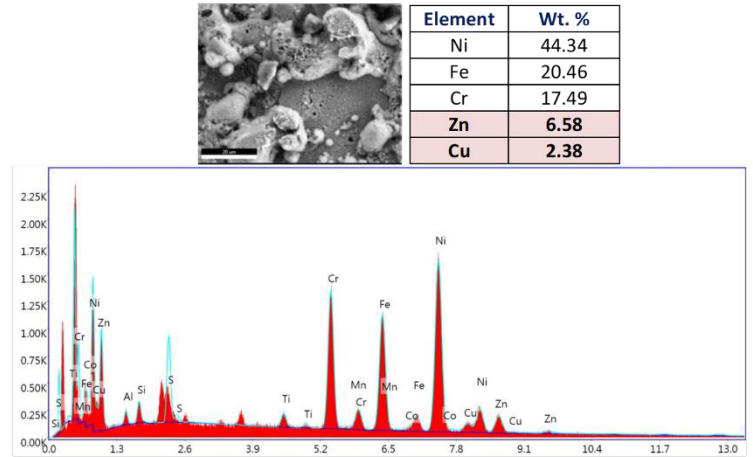


Fig. 9. EDS analysis of IN718 at least stable machining condition

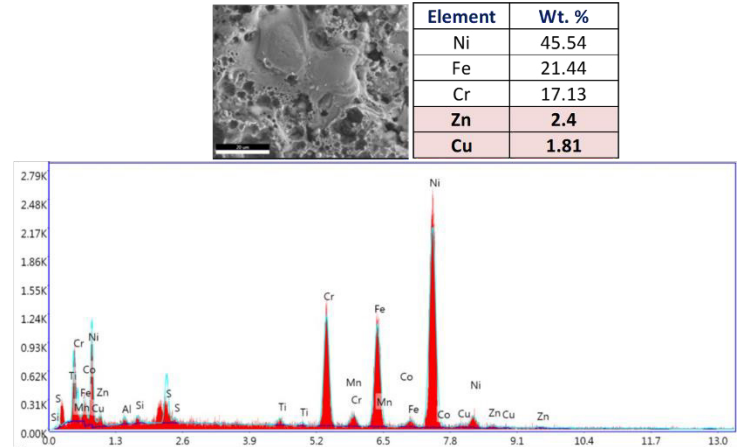


Fig. 10. EDS analysis of IN718 at most stable machining condition

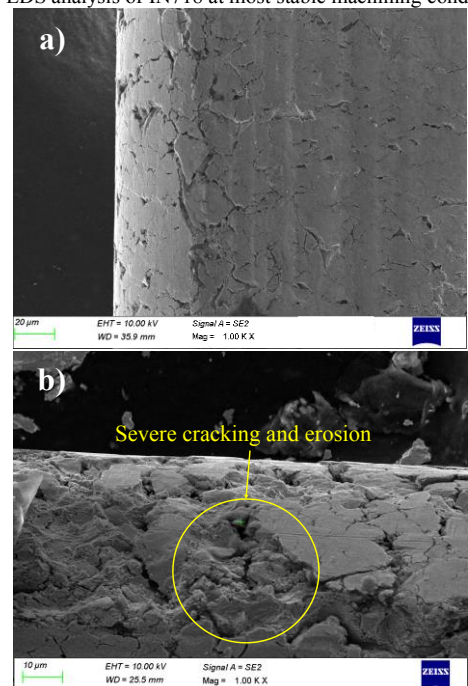


Fig. 11. SEM images of wire surface at machining stability (a) Level 5; (b) Level 1



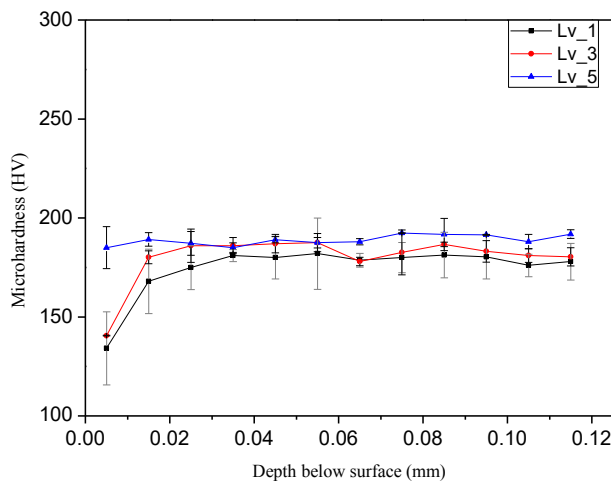


Fig. 12. Subsurface microhardness of the machined specimens at various stability levels

Fig. 12 shows the subsurface microhardness of the machined surface at various levels of machining stability. The quenched recast layer, annealed heat affected zone (HAZ), and unaltered parent material offered different levels of subsurface hardness. The least stable machining condition (Lv\_1) is observed to have a higher thermal impact on the subsurface, since the subsurface hardness is comparatively lesser compared to other stability levels. The region adjacent to the surface (up to 60  $\mu\text{m}$ ) is observed to have softened the most with a minimum hardness of around 130 HV in case of Lv\_1 and Lv\_3 machining stability. The hardness away from the machined surface (> 60  $\mu\text{m}$ ) is observed to be constant with around 180 HV as the thermal effects are lesser away from the surface. However, most stable machining condition (Lv\_5) does not have any observable impact on the subsurface. This is evident from the relatively flat subsurface hardness curve with minimal variations for this condition.

#### 4. Conclusions

The aim of the study is to understand the surface integrity of components machined at various machining stability levels. The study revealed that by controlling the machining stability, there is a huge scope to improve the surface integrity of machined components. The salient conclusions are as follows.

1. The specimens machined with higher stabilities have significantly better surface integrities compared to the ones machined at less stable conditions. Surface morphology studies revealed that irregularities and surface roughness was lesser when machined at higher stability.
2. SEM images showed lesser number of micro globules, voids, cracks and craters at higher machining stabilities. Also, by improving the machining stability, the recast layer thickness got reduced by 83.41%.
3. EDS analysis revealed that the elemental contamination is lesser for stable machining conditions compared to unstable machining conditions. Higher elemental contamination by migration of zinc and copper from wire electrode to machined surface was observed when machining with lesser stability.

4. Subsurface microhardness was found unaltered when machined under stable conditions. The unstable conditions showed varying subsurface hardness due to the thermal effects on the surface.
5. Even though the cutting speed showed improvement at lesser stability levels, the surface damages were too high to recommend it as an advantage.

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