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An experimental study on trim cutting operation using metal powder mixed dielectric in WEDM of Nimonic-90

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A B S T R A C T

This paper presents an experimental study on rough cut, trim cut using distilled water as a dielectric fluid and Al & Si metal powders in dielectric fluid for WEDM of Nimonic-90. First, the influence of discharge energy (DE) in rough cut is evaluated for machining rate (MR) and surface roughness (SR) and compared with trim cut without any metal powder additives in dielectric fluid. The effect of Al and Si metal powders (varying concentration of 1g/L, 2g/L and 3g/L) in dielectric fluid is studied separately and comparison is also made for MR, SR, recast layer and micro hardness of machined Nimonic-90. From the results it is observed that using trim cut, a fine and uniform surface texture is obtained irrespective of the high discharge energy of rough cut. Al and Si powders additives show a significant reduction in MR for trim cutting operation whereas a remarkable modification is obtained in surface textures after trim cut using metals powder mixed dielectric. SR improves with a concentration of 1g/L and shows a little increase with high concentration of both metals powder. Using metals powder in dielectric fluid, the recast layer becomes smooth and denser and thus, micro hardness increases.

1. Introduction

In wire electrical discharge machining (WEDM), material removal takes place due to melting and evaporation of work material through the localized heat generation by the repetitive electrical sparking between wire electrode and material. Through WEDM, all conductive materials can be processed irrespective of their hardness but an optimized process parameters setting is always required in WEDM to avoid wire breakage and to obtain high surface finish, and dimensional precision with high material removal rate. WEDM parameters may be categorized into three major categories namely discharge parameters (pulse-on time (Ton), pulse-off time (Toff), Peak current (Ip), servo voltage (SV)), wire electrode (wire material, wire diameter, wire coating, wire tension, wire feed rate etc.) and dielectric conditions (dielectric conductivity, flow rate). Since the material removal takes place because of the high

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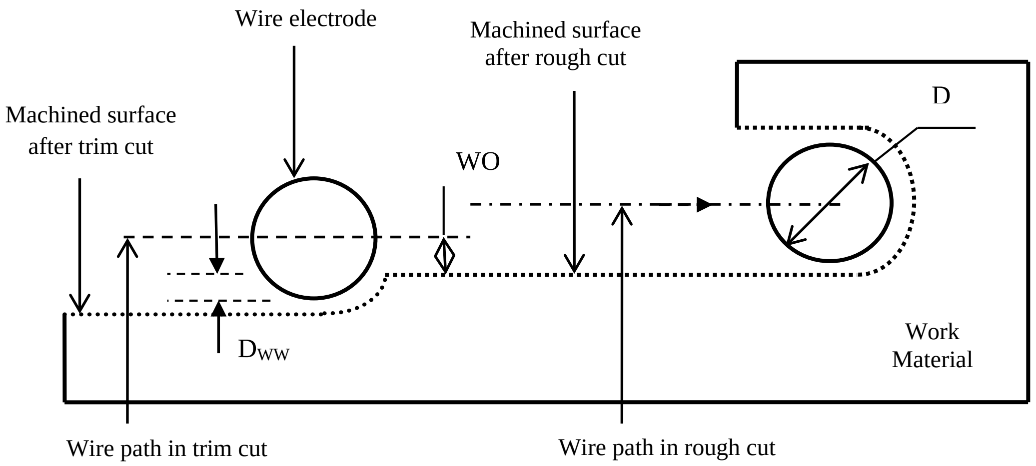
localized heating and the repetitive electrical sparks, top machined surface consists of poor surface integrity having hollow cavities and several micro-cracks (Lee & Li, 2003; Wang et al., 2009). Top machined layer consists of recast layer or white layer which is a re-solidified melted material on work surface, which is not completely flushed during the process. Jangra et al. (2011) utilized the grey based Taguchi method to optimize the MRR and SR for WEDM of WC-Co composite. Results revealed that taper angle, Ton and Toff are the most significant process parameters.

In WEDM, trim cut is the best option to improve the surface characteristics and dimensional accuracies of the machined surface. In trim cut, wire electrode traces back the rough cut path with certain value of wire offset (WO) to remove a very small layer of work surface (Jangra, 2015; Sarkar et al., 2008) as shown in Fig. 1. In rough cut; spark zone is quite large as compared with trim cut operation. As a result, a volume of molten metal is very high in rough cut, which generates large pressure energy in spark zone. It causes large size craters and cracks on work surface. In trim cutting operation, spark zone is influenced by wire offset value and discharge parameters. Therefore, using low discharge energy (DE) parameters and accurate value of WO in trim cutting operation, damaged surface layer may be minimized or eliminated.



D : wire diameter; WO: wire offset; D_{WW} : gap between wire periphery and work surface before trim cut

Fig. 1. Terminology used for rough and trim cut in WEDM

With the availability of micro fabrication facilities and latest pulse generators for micro machining (Yeo et al., 2009), present WEDM tools are becoming more precise. Therefore, WEDM are being commercialized in various manufacturing industries (Jangra et al., 2014) and research institutes.

2. Literature and motivation for present work

In the past, significant research works are carried out on WEDM to evaluate the influence of process variables viz., discharge parameters, work height, wire electrode materials, dielectric conditions, etc. on machining performance like cutting speed (CS), metal removal rate (MRR), surface roughness (SR), geometrical accuracy, recast layer etc. in processing of different work materials ranging from simple alloy steel, aluminium MMC high strength-heat resisting alloys and composite materials (Bhuyan & Yadava, 2014; Bobbili et al., 2014; Delgado et al., 2011; Gupta & Jain, 2014; Hascalyk et al., 2004; Hewidy et al., 2005; Huang et al., 1999; Jangra & Grover, 2012; Kumar et al., 2013; Kumar et al., 2014; Prohaszka et al., 1997; Shandilya et al., 2013; Yu et al., 2011). The majority of the research works conducted on WEDM deal with rough cut and very limited research works are conducted for trim cutting operation (Jangra, 2012). Huang et al. (1999) unveiled the influence of various WEDM parameters on the performance characteristics of WEDM of alloy steel for trim or finish cutting operations. Authors considered the performance characteristics namely gap width, SR and thickness of recast layer (TRL) on the machined surface. Using Taguchi method and numerical analysis; Ton and gap between wire periphery and work surface are found significant parameters affecting the performance characteristics. Experimental results show that a medium value of D_{ww} (about 30μm) may produce better surface finish. Feasible direction algorithm is proposed to determine the numbers of finish cut and parameters setting to obtain optimal machining performance. Sarkar et al. (2010) optimized the machining parameters of WEDM for γ-titanium aluminide using ANN modelling. Machining parameters namely Ton, Ip, dielectric flow rate (DFR) and effective wire offset are investigated on CS, SR and dimensional shift for multi pass cutting. Klink et al. (2011) compared the surface finish, microstructure, micro hardness and residual stresses after rough and trim cuts in WEDM. Using trim cuts, very fine surface finish and minimum recast layer thickness may be achieved.

Jangra et al. (2014) compared the machinability of Tungsten Carbide (WC-Co) composite, high carbon high chrome steel alloy, Nimonic-90 and Monel-400, for rough and trim cutting operation of WEDM using zinc coated brass wire electrode. Results indicate that surface characteristics are improved using single trim cut with optimal machining parameters and correct wire offset, irrespective the high DE of rough cut. Jangra (2015) investigated multi trim cutting operation after a rough cut in WEDM for WC-5.3% Co composite. Using Taguchi' design of experiment method, influence of Ip, Ton, wire offset (WO) value and number of trim cuts are evaluated on two performance measures namely SR and depth of material removed in trim cutting operation. A technological data is obtained for rough and trim cut on WEDM for efficient machining of WC-5.3%Co composite. In the field of die sinking EDM, many investigations have been carried out using metal powder additives in dielectric medium to improve the MRR and surface characteristics. Conductive metal powder reduces the dielectric strength of the fluid and thereby increases the spark energy across the two electrodes, thus, enhances the stability of the process and improves the performance measures (Kansal et al., 2005; Sidhu et al., 2014). As per the literature available, no research work found on powder mixed dielectric in WEDM. Therefore, the concept of metal powder mixed dielectric is attempted for WEDM in present work. The complete experimental plan is discussed in section 3. A comparative experimental analysis of rough and trim cut using distilled water and trim cut with metal powder mixed distilled water is presented. The influence of two metals powder namely Al and Si (varying concentration of 1g/L, 2g/L and 3g/L) is an evaluated on machining rate (MR) and surface characteristics of Nimonic-90; a nickel based high strength-high heat resisting super alloy.

3. Experimentation

3.1 Setup for Supplying of Powder Mixed Dielectric Fluid

In rough cut operation of WEDM, the area covered by the spark zone around the wire electrode is large and the spark gap between wire electrode and work surface in the direction of cutting is very small and therefore, the dielectric fluid is used at high pressure to expel the eroded particles from the spark zone. If the metal powder mixed dielectric fluid is used at high pressure, the effect of powder additives on machining performance will not be justified. Also, due to the recirculation of dielectric fluid in WEDM setup, mixing of metal powder directly in dielectric tank (having large size ≥ 400 liters) is not economical. Therefore, the use of metal powder in dielectric fluid for rough cut of WEDM is quite challenging as compared with die sinking EDM where dielectric fluid (kerosene or distilled water) mixed with metal powder is easily pumped under the electrode facing the work material. However, in trim cutting operation, work surface in contact with wire electrode periphery is small which requires a laminar dielectric flow for effective sparking. Therefore, the idea of metal powder mixed dielectric is attempted in trim cutting operation only.

In present work, a separate tank of size 40 liters is used to mix the additives in dielectric water and to pump the metal powder mixed dielectric fluid in trim cutting operation. Fig. 2 shows the experimental setup. To supply the metal powder mixed distilled water in trim cut operation, a small capacity water pump is connected to the upper nozzle through a connector pipe and the upper nozzle is disconnected from main dielectric tank.

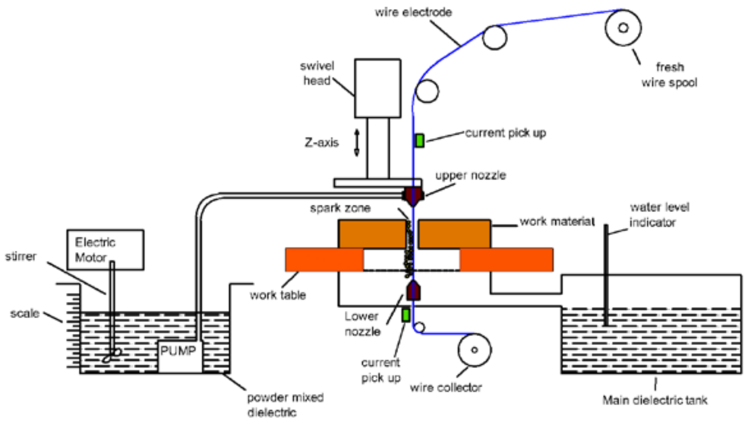


Fig. 2. Experimental setup for Powder Mixed WEDM in present work

3.2 Work Material and Machined Geometry

Nimonic-90 (nickel-chromium-cobalt alloy) seems suitable for high temperature applications (600^{0}C to 900^{0}C). High rupture strength and creep resistance at elevated temperature (up to 950 ^{o}C) allow us to use in turbine blades and combustion chamber. The machining of nickel based super alloys using conventional processes like turning, milling, drilling, etc., is very difficult because of the formation of built up layer on cutting tool face resulting large crater wear and poor surface integrity. It is involving several surface defects such as surface drag, material pull-out/cracking, tearing surface, etc., (Herbert et al., 2012; Kortabarri et al., 2011; Ulutan & Ozel, 2011). WEDM may yield better finish and accuracy while machining to generate intricate and complex parts in this hard and high heat resisting material. Table 1 shows the composition and mechanical properties of Nimonic-90.

Table 1
Composition and Mechanical Properties of Nimonic-90

Composition	Density (g/cm^3)	Melting point (^{0}C)	Elastic modulus (GPa)	Co-efficient of thermal expansion (µmĊ)	Thermal Conductivity (W/m Ċ)
Ni: 60%, Cr: 19.3%, Co: 15%, Ti: 3.1%, and Al: 1.4%	8.18	1370	220	12.7	11.47

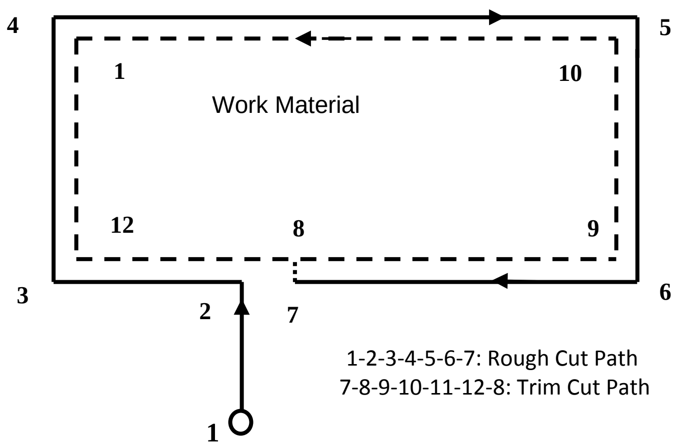


Fig. 3. Geometry of wire path for rough and trim cut

Work material is available in the form of rolled sheet of thickness 12.5 mm and the work samples are obtained in the form of rectangular punch of size 8 mm × 6 mm × 12.5 mm. Fig. 3 shows the geometry of the wire path that is followed for rough and trim cut.

3.3 Machining Conditions

5 axis sprint cut WEDM (ELPUSE-40) is used for the experimentation made of Electronic M/C Tool LTD India. The entire work is divided into three categories: (a) rough cutting operations are performed at three different level of DE; (b) rough cut at high DE followed by a single trim cut using distilled water and (c) metal power (Al/Si) mixed distilled water as dielectric fluid.
Distilled water having conductivity of 20 mho is used as a dielectric fluid. To control the spark energy across the work material, values of discharge parameters namely Ton, Toff, Ip and SV are varied. High DFR is desirable in rough cutting operation to expel the melted debris quickly and completely out of the spark gap. Therefore, for rough cutting operation, DFR is kept at high value of 12 liters per minute (LM^{-1}). To minimize the wire consumption, wire feed rate is kept at low value of 5m/min. Jangra (2015) reported that low DE along with a laminar dielectric flow is required for trim cutting operation to obtain effective spark generation for fine surface finish. Therefore, for trim cutting operation, a low dielectric supply is allowed through upper nozzle while bottom nozzle is closed. Table 2 shows the process parameters for rough and trim cutting operation.

4. Results and discussions

Experiments are conducted for rough and trim cutting operation corresponds to the parameters settings mentioned in Table 2. The influence of these parameter settings for rough and trim cutting operation is compared for MR, SR and surface morphology. Also the influence of Al and Si metal powders (mesh size of 400 for both) is evaluated (with a concentration of 1g/L, 2g/L and 3g/L) and compared on these characteristics.

Table 2
Parameters setting for rough and trim cutting operation

<table>
<tr><th>Type of operation</th><th>Dielectric Used</th><th>Dielectric conditions</th><th>Wire offset (μm)</th><th colspan="2">Discharge parameters (machine unit)</th><th>Wire Electrode Parameters</th><th>Other Fixed parameters</th></tr>
<tr><td rowspan="3">Rough Cutting Operation</td><td rowspan="3">Distilled water</td><td rowspan="3">Dielectric Pressure: High
Flow rate:
Upper nozzle: 12L/Min
Lower nozzle: 12L/Min</td><td rowspan="3">Zero</td><td>Low DE</td><td>Ton:106; Toff:40, Ip:90; SV:30</td><td rowspan="3">WT: 8
WF: 5
Servo Feed: 0200</td><td rowspan="5">Work piece height: 12.5mm;
Wire diameter: 250 μm;
Wire material: copper coated brass</td></tr>
<tr><td>Medium DE</td><td>Ton:112; Toff:40, Ip:120; SV:30</td></tr>
<tr><td>High DE</td><td>Ton:118; Toff:43, Ip:120; SV:25</td></tr>
<tr><td rowspan="2">Trim Cutting Operation</td><td>Distilled water</td><td>Dielectric Pressure: Low
Flow rate:
Upper nozzle: 4L/Min
Lower nozzle: closed</td><td>105</td><td colspan="2" rowspan="2">Ton:105; Ip:100; Toff:30, SV:30</td><td rowspan="2">WT: 10;
WF: 2
Servo Feed: 0150</td></tr>
<tr><td>Metal powder mixed distilled water</td><td>Dielectric Pressure: Low
Flow rate:
Upper nozzle: 4L/Min
Lower nozzle: closed</td><td>105</td></tr>
</table>

***4.1** Effect on Machining Rate (MR)*

MR represents the average speed of machining (mm/min.) of work material in linear direction which is observed from the monitor of the machine tool. Fig. 4(a) shows a comparative chart of the MR for experiments performed under two categories (a) and (b); that is rough cutting operation corresponding to low, medium and high level of DE and a trim cutting operation followed after rough cut. High values of Ton, Ip and low values of SV and Toff results into high DE per unit time and vice versa.

It is also observed that MR increases with increasing DE across two electrodes for rough cutting operation. High DE causes high heat generation across two electrodes, thereby facilitating large melting and evaporation of work material (Li et al., 2013; Yu et al., 2011). MR increases with increase in DE for rough cut. MR corresponds to high DE is 2.54 mm/min as compared with MR of 1.02 mm/min correspond to low DE for rough cut. But in trim cutting operation, MR reaches to 11.6 mm/min even at low values of discharge parameters. It is due to the fact that in trim cut, sparking occurs between a small fraction of wire electrode and work surface; thus, a small amount of work material is removed as compared to rough cutting operation. This contact area is mainly affected by wire offset value for trim cutting operation. Therefore, by selecting the accurate wire offset, spark frequency across the electrodes may be controlled.

Fig. 4(b) compares MR for the experiments for trim cutting operation using distilled water and Al and Si metals powder mixed distilled water. Increasing the concentration of metal powder in dielectric fluid decreases the MR remarkably. It is apropos that addition of both types of metal powder in distilled water resulted in improved and continuous sparking across the electrodes. In powder mixed EDM (PMEDM), material removal rate (MRR) increases due to the addition of metal powder in dielectric (Kansal et al., 2005; Singh et al., 2014) but in the presented work MR decreases.

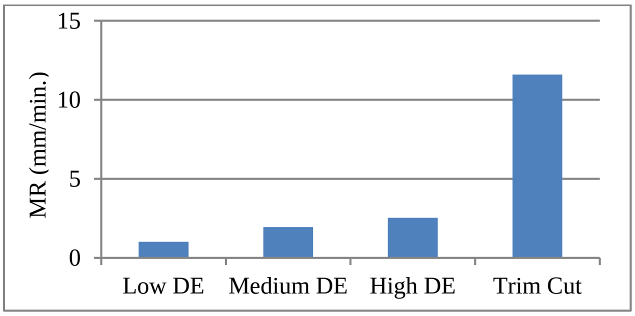


Fig. 4(a) Comparison of different WEDM operations for MR

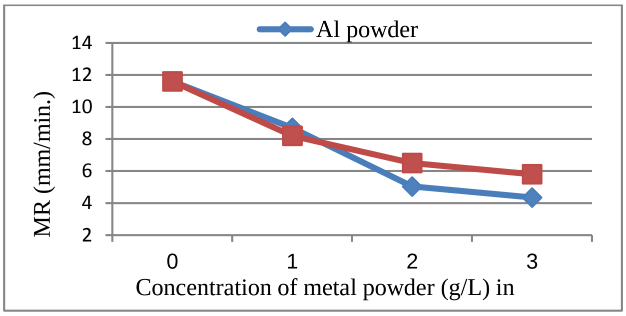


Fig. 4(b) Influence of concentration of metal powder on MR for trim cut

In both, EDM and WEDM, addition of conductive metallic powders in dielectric fluid reduces the insulating strength of the dielectric fluid and increases the discharge channel for a given value of discharge parameters (Kansal et al., 2005). This process increases the melting and erosion of work material in PMEDM and increases the material removal rate. In case of trim cutting operation of WEDM, due to increase in spark radius and spark frequency, discharge area between wire periphery and work surface increases. This increase in discharge area reduces the servo feed as compared with trim cutting without metal powder. Thus, MR decreases in trim cut using metal powder mixed dielectric. The addition of metals powder up to the concentration of 2g/L shows a remarkable reduction in MR but beyond 2g/L, the reduction is very low. Because the addition of more metals powder did not participate in lower down the insulating strength of dielectric. As compared with Al, Si powder exhibits less discharging and hence the reduction in MR is low for Si powder.

4.2 Effect on Surface Roughness (SR)

Fig. 5(a) compares the surface roughness (R_a, values) for the experiments performed under categories (a) and (b); that is rough cutting operations corresponding to low, medium and high level of DE and a trim cut followed after rough cut. The value of SR increases from 1.42 µm corresponding to the parameters of low DE and 3.1 µm corresponding to the parameters of high DE for rough cut. SR is characterized by the size and depth of the craters that are developed after the melting and expulsion of work material.

Increasing DE increases the diameter and depth of surface craters resulting in high SR (Hewidy et al., 2005).

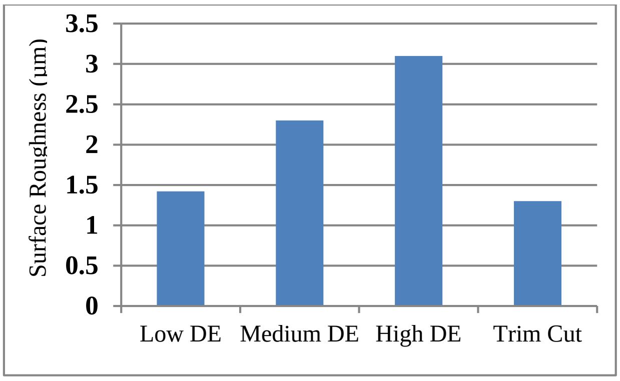


Fig. 5(a) Comparison of different WEDM operations for SR

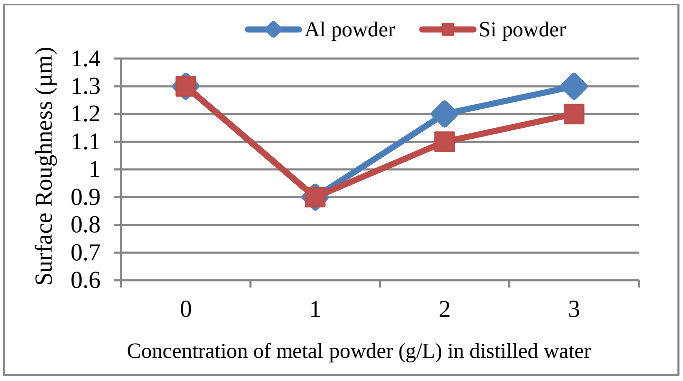


Fig. 5(b) Influence of concentration of metals powder in dielectric fluid for trim cut on SR

This graph also shows that the SR may be improved significantly using trim cutting operation irrespective of high DE in rough cut operation. In trim cutting operation, a very thin layer of surface material is removed at appropriate wire offset value and thereby surface irregularities (peaks) are minimized to improve the SR. Wire offset (WO) has a significant impact on SR for trim cut (Jangra, 2015; Sarkar et al., 2008). By decreasing WO value beyond 125µm (radius of wire), the area of contact between wire electrode and work surface increases. This increases the spark frequency and which in turn increases melting and erosion of work material increases. Increasing WO beyond 125 µm will not be useful in generating the effective sparking because of large gap between wire electrode and work surface. Therefore, in present work, an effective wire offset of 105 µm is selected, which is D_{ww} of 20 µm.

Fig. 5(b) illustrates the influence of Al and Si powders on SR for trim cutting operation. The addition of metal powder in a concentration of 1 g/L yields the best surface finish of 0.90 µm. Further addition of 1g/L of metal powder in distilled water causes better spark generation and distribution on work surface, which produces shallow craters on machined surface. The minimum achievable SR in WEDM is limited by the wire electrode diameter. The smaller the wire diameter, the smaller the spark radius, and thus, smaller surface craters. By increasing the concentration of metal powders beyond 1g/L, the spark frequency and spark zone increase because of the reduction in insulating strength of dielectric and SR increases.

The melting point and resistivity for Si is high as compared with Al powder and sparking is low in case of Si powder mixed dielectric. Therefore, SR is low for Si powder. SR corresponds to 3g/L of Al powder is 1.3 µm, which is equal to SR value obtained in trim cut without metal powder. But the surface morphology for two different conditions are very different and discussed in subsequent section.

4.3 Surface Morphology and Recast layer

Fig. 6 (a-d) and 7 (a-d) show the Scanning Electron Microscopic (SEM) images of the machined and transverse surface of work samples after (a) rough cut at high DE, (b) trim cut without metal powder in dielectric fluid, (c) trim cut using 3g/L Al powder, and (d) trim cut using 3 g/L Si powder in dielectric fluid. It is obtained from SEM image (Fig. 6a) that the machined surface after rough cut at high DE consists of deep and large size craters. The high DE causes overheating and evaporation of molten metal forming high pressure energy that creates large size craters (Li et al., 2013).

Using trim cut at low discharge parameters, a thin layer of work surface is removed that completely eliminates the surface layer produced in rough cut. A fine and uniform surface texture obtained after trim cut as shown in Fig. 6(b). Fig. 6(c) and 6(d) show a remarkable modification in surface textures after trim cut using metal powder mixed dielectric fluid. SEM image shows that the sparking on these surfaces is highly stable and uniformly distributed. Absence of carbon in Nimonic-90 and a stable sparking, gives a micro cracks free machined surface. Some nm sized impingements are observed on these surfaces as encircled in Fig. 6(c-d). These impingements may be due to the Al and Si powders that are not completely evaporated while sparking and thus, impinge at high pressure to the molten surface.

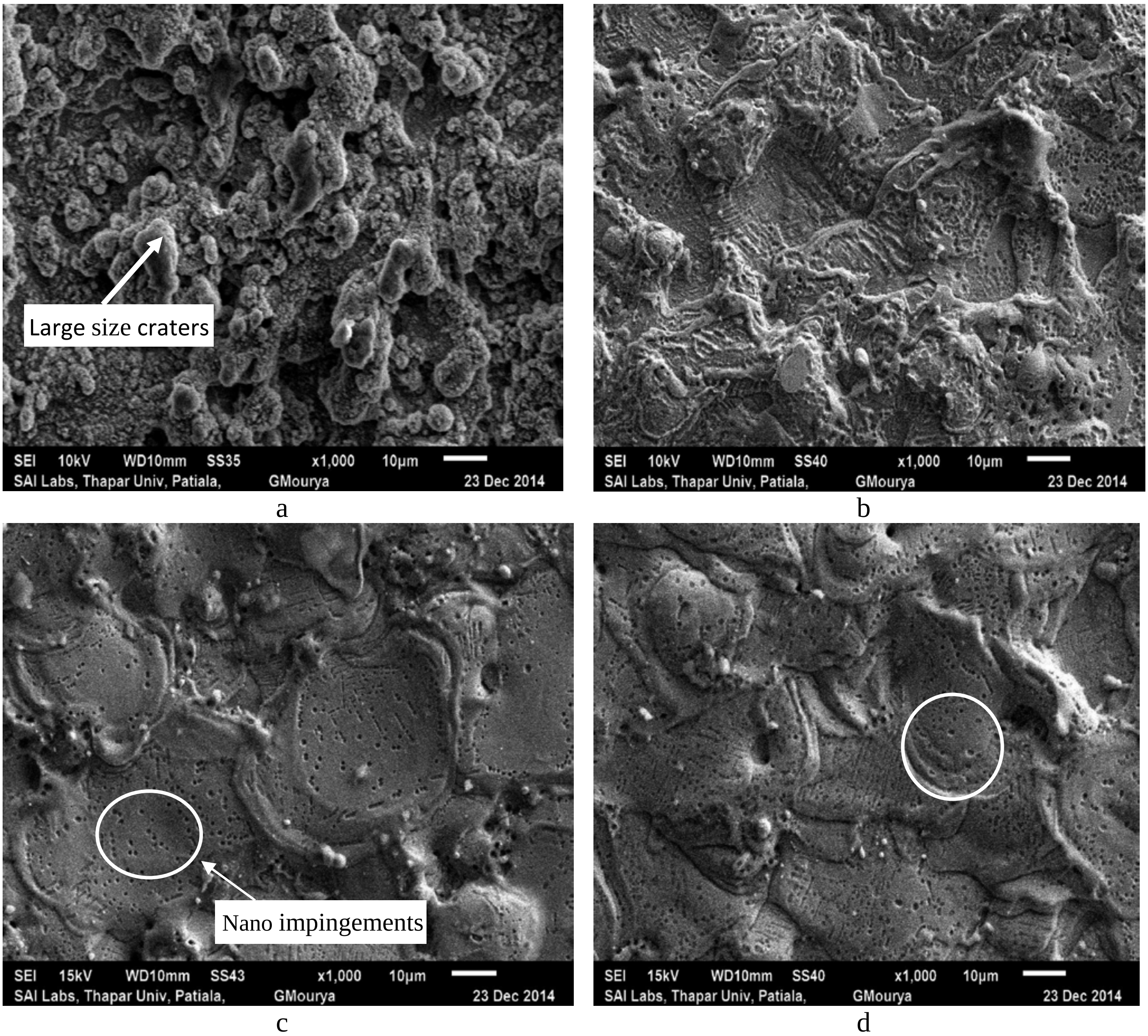


Fig. 6 SEM images of machined surface after (a) rough cut at high DE (b) trim cut (without metal powder) (c) trim cut using 3g/L Al powder in dielectric (d) trim cut using 3 g/L Si powder in dielectric

Fig. 7(a-d) show the recast layer on machined surface after rough and trim cutting operations. Fig. 8 presents thickness of recast layer (TRL) corresponding to the different machining conditions. The average TRL (in µm) for high DE for rough cut is found nearly 15 µm which is quite low as compared with steel alloys and WC-Co composites (Jangra, 2015). Trim cutting operation makes a remarkable reduction in TRL and is noticed from Fig. 7(b) and Fig. 8.

Fig. 7(c) and 7(d) show the TRL for metal powder mixed dielectric having the powder concentration of 3g/L for Al and Si powders, respectively. Al powder results in little increase in TRL while Si powder results in a small reduction in TRL. An addition of Al powder beyond 1g/L increases discharge frequency and spark radius, thus, more melting and heating results in little increase in TRL. Due to high melting point and electrical resistivity of Si powder, less sparking occurs using Si powder in comparison to Al powder mixed dielectric fluid. As a result, TRL is low in case of Si powder mixed dielectric fluid.

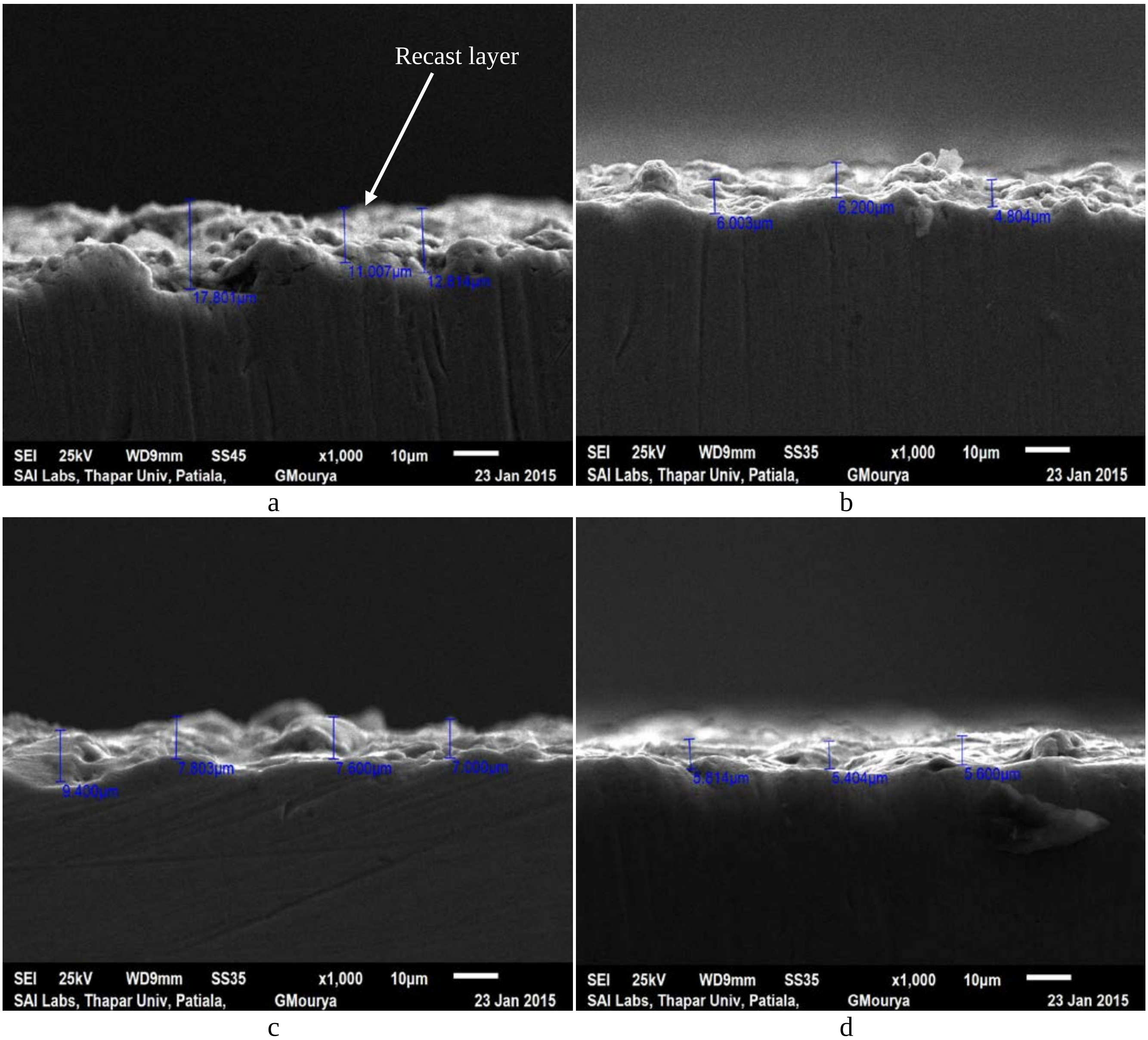


Fig. 7. SEM images of transverse surface after (a) rough cut at high DE (b) trim cut (without metal powder) (c) trim cut using 3g/L Al powder in dielectric fluid (d) trim cut using 3 g/L Si powder in dielectric fluid

4.4 Micro Hardness

Micro hardness test is used to measure the extent of surface damage caused by thermal energy of WEDM process. Micro-hardness is measured on transverse section of the machined surface. Micro-hardness profiles underneath the machined surface is shown in Fig. 9 for the samples under rough cut (high DE), trim cut without metal powder and trim cuts using Al and Si powder in dielectric fluid.

Profiles show that the micro hardness is low at the machined top layer as compared with bulk material. This reduction in hardness because of the thermal damage of machined surface which is predominately due to the pressure energy generated inside the plasma channel and transfer of heat energy to the work material underneath the machined surface causing large heat affected zone (Li et al., 2013). The top damaged layer consists of recast layer while heat affected zone having longer grain size as compared with the bulk of the work material.

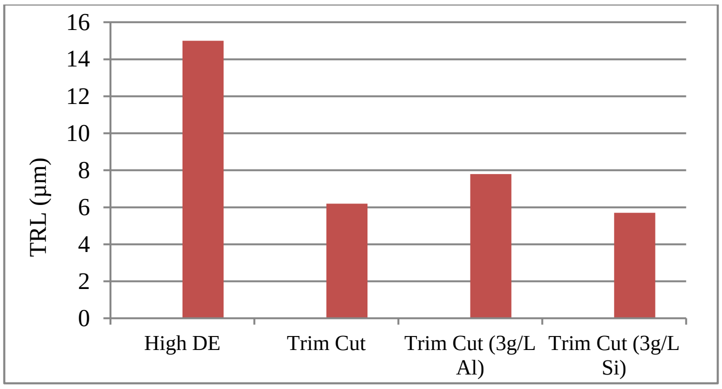


Fig. 8. Comparison of different WEDM operations for TRL

Using trim cut, this surface damage may be reduced as shown by the improved micro hardness profiles for trim cutting operation. It is worth to mention that measurement of micro hardness value corresponding to top machined layer is difficult because of the large surface damage at top surface that causes inaccurate impression of micro indent on this region. Therefore, the reading for micro hardness is missing up to 20 µm underneath the top layer in case of rough cutting operation at high DE.

Using metal powder in dielectric fluid, the recast layer becomes smooth and dense as noticed from Fig. 7(c-d). Therefore, the micro hardness improves using metal powder mixed dielectric fluid in trim cutting operation. In comparison to Al powder, Si powder results in denser machined surface and yields better machined surface.

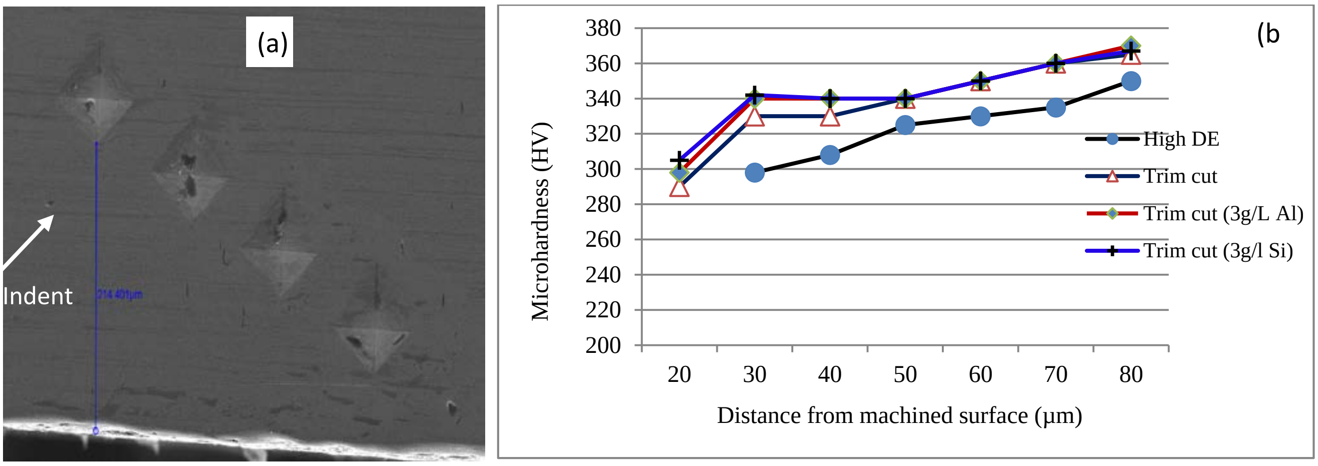


Fig. 9 (a) Micro indent on transverse surface (b) Comparison of micro-hardness underneath the machined surface under different process conditions

5. Conclusions

This article has presented a comparative experimental study on WEDM of Nimonic-90, for rough cut and trim cut without any metal powder additives and using Al and Si metal powders in dielectric fluid. The influence of DE for rough cut has been evaluated for MR and SR and compared with trim cut without any metals powder additives in dielectric fluid. In succeeding experiments, influence of Al and Si metals powder in dielectric fluid has been evaluated separately and a comparative analysis is made for MR, SR, recast layer and micro-hardness. The important findings of this work are summarized as follows:

- MR increases from low DE to high DE in rough cut. MR corresponding to high DE is 2.54 mm/min as compared with MR of 1.02 mm/min corresponding to low DE in rough cutting operation. It reaches to 11.6 mm/min, in trim cut performed at low values of discharge parameters without using metal powder additives. Increasing the concentration of metal powder in distilled water decreases the MR remarkably. The addition of metal powders up to the concentration of 2g/L yields more than 50% reduction in MR but beyond 2g/L, the reduction is low.
- The value of SR increases from 1.42 µm corresponding to the parameters of low DE to 3.1 µm for the parameters of high DE for rough cut. SR is improved significantly using trim cut irrespective of high DE for rough cut. An addition of metal powder in a concentration of 1 g/L yields best surface finish of 0.90 µm because of the better spark generation and distribution on work surface. Si powder yields better SR as compared to Al powder.
- SEM images show that the machined surface after rough cut at high DE consists of deep and large size craters whereas a fine and uniform surface texture is obtained after a trim cut. Micro hardness profiles show that the top machined layer is under high thermal damages in rough cut and the extent of this damage is low for trim cut operation. Al powder with a concentration of 3g/L results in little increase in TRL while Si powder with a concentration 3g/L in a smaller TRL.
- Using Al and Si metals powder in dielectric fluid, a remarkable modification is obtained for surface textures after trim cut. Using metal powder in dielectric fluid, the recast layer becomes smooth and dense which increases the micro hardness. Some nm sized impingement is observed on machined surfaces after trim cut using metal powder additives.
- This work is added an opportunity for future research on powder mixed WEDM. The WEDM parameters namely Ton, Ip, Toff, SV and WO using different concentration of metal powders may be investigated more precisely. Further investigation using high concentration of different metal powders may be carried out to modify the morphology of machined surface.

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