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RESEARCH ARTICLE - MECHANICAL ENGINEERING

AFM Nano Analysis of Inconel 825 with Single Wall Carbon Nano Tube in Die Sinking EDM Process Using Taguchi Analysis

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Abstract A carbon nanotube has high mechanical and electrical properties, and specifically, high electrical conductivity. By using these properties in Electrical Discharge Machining, the single-wall carbon nanotube is mixed with dielectric fluid to analyse the surface characteristics of Inconel 825, which is very much used in moulds and dies. Carbon nanotube will absorb the heat from electrically discharged material and also minimize the white layer formation in the work piece. Experimental results indicate that the surface texture after electrical discharge machining (EDM) is increased very much due to discharge energy. An excellent machined nanolevel surface finish can be obtained by setting the machine parameters at low pulse energy. The surface roughness and the depth of the microcracks were proportional to the power input, especially the input current. Furthermore, the AFM tests yielded information about the surface morphology which is particularly important in the post treatment of Inconel 825 machined by EDM. Analysis of variance and *F* test were used to determine the significant parameter affecting the surface roughness.

Keywords Single wall carbon nanotube · Electric discharge machining process · Surface roughness · Taguchi method · ANOVA analysis · Atomic force microscope · MRR

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الخلاصـة

يمتلك أنبوب النانو كاربون خواص ميكانيكية وكهربائية عالية ، وبخاصة قدرة توصيل كهربائية عالية . ويتم - باستخدام هذه الخواص في آلات التفريغ الكهربائي - خلط أنبوب النانو كاربون مع الموائع الكهربائيه ، وذلك لتحليل خصائص السطح Inconel 825 الذي يستخدم بشكل كبير في القوالب والـ dies. وسوف يمتص أنبوب النانو كاربون الحرارة من مواد التفريغ الكهربائية ويقلل من تشكل الطبقة البيضاء في قطعة العمل . وتدل نتائج الاختبارات أن نسيج السطح بعد الـ EDM يزداد بشكل كبير نتيجة لتفريغ الطاقة . ويمكن الحصول على مستوى سطح ممتاز للنانو عن طريق ضبط معاملات الآلة عند أقل مستوى نبض للطاقة . إن خشونة السطح وعمق الشقوق الصغيرة كانت تتناسب ومدخلات الطاقة ، وبخاصة التيار الداخل. وقد أسفرت - إلى جانب ذلك - اختبارات AFM على معلومات حول مورفولو جيا السطح التي لها أهمية خاصة في المعالجة المتقدمة لـ Inconel 825 المصنعة بوساطة EDM.وقد تم استخدام تحليل الثباين (ANOVA) واختبار F لتحديد المعاملات المهمة التي تؤثر في خشونه السطح.

1 Introduction

EDM machining is widely used in industries for machining of heat treated tool and die steels. Heat treated tool steels have proved to be extremely difficult-to-machine using traditional processes, due to rapid tool wear, low machining rates, inability to generate complex shapes and imparting better surface finish. Guu et al. [1] proposed the electrical discharge machining (EDM) of AISI D2 tool steel was investigated. The surface characteristics and machining damage caused by EDM were studied in terms of machining parameters. Based on the experimental data, an empirical model of the tool steel was also proposed. Surface roughness was determined with a surface profilometer. Prabhu et al. [2] proposed the nanosurface finish of AISI D2 tool steel material using multiwall carbon nanotube (MWCNT) in electrical discharge machining process (EDM). The surface morphology, surface roughness and microcracks are determined using an atomic force microscope (AFM). Puertas et al. [3] carried out on the influence of the factors of intensity (*I*), pulse time (ti) and duty cycle (η) over the listed technological characteristics. The ceramic used in this study was a cemented carbide or hard metal such as 94WC–6Co. Guu [4] proposed the surface morphology, surface roughness and microcrack of AISI D2 tool steel machined by the electrical discharge machining (EDM) process were analyzed by means of the atomic force microscopy (AFM) technique. Mamalis et al. [5] has given a consolidated view of the synthesis, properties and applications of carbon nanotubes with the aim of drawing attention to useful available information and to enhancing interest in this new highly advanced technological field. Pecas et al. [6] presented electrical discharge machining using simple and powder-mixed dielectric: The effect of the electrode area in the surface roughness and topography. (PMD-EDM) EDM technology with powder-mixed dielectric and to compare its performance to the conventional EDM when dealing with the generation of high-quality surfaces. Wong et al. [7] presented near-mirror-finish phenomenon in EDM using powder-mixed dielectric. A study of the near-mirror-finish phenomenon in electrical discharge machining (EDM) when fine powder is introduced into the dielectric fluid as a suspension at the tool–work piece or inter-electrode gap during machining. Ho [8] proposed to improve performance measures, optimizing the process variables, monitoring and control the sparking process, simplifying the electrode design and manufacture. Singh et al. [9] proposed an experimental investigation carried out to study the effects of machining parameters such as pulsed current on material removal rate, diametral overcut, electrode wear, and surface roughness in electric discharge machining of En-31 tool steel. Luis [10] investigate a material removal rate (MRR) and electrode wear (EW) study on the die-sinking electrical discharge machining (EDM) of siliconised or reaction-bonded silicon carbide (Sic) has been carried out. Chow et al. [11] proposed the development of Powder Mixed Electrical Discharge Machining (PMEDM) and the result shows that by applying PMEDM, the material removal rate is increasing and the surface roughness is decreasing. In this paper, carbon nanotube mixed dielectric fluids are used in the EDM process to analyze the surface characteristics of Inconel 825 material. Till now no work has been carried out by using carbon nanotube mixed EDM machining. Carbon nanotube blended dielectric fluids are used to improve the surface finish from microlevel to nanolevel which improves the accuracy of surface characteristics of the work piece. AFM is used to analyze the surface roughness, microcrack and surface topography of the machined surface.

Most of the single-walled nanotubes (SWCNT) have a diameter of close to 1 nm, with a tube length that can be many thousands of times longer. The 3D structure of a SWCNT can be conceptualized by wrapping a one-atom-thick layer of graphite called graphene into a seamless cylinder. CNTs have been of great interest, both from a fundamental point of view and for future application. The most eye catching features of these structures are their mechanical, optical and chemical characteristics, which open a way to the machining application. CNTs have a tremendously high surface area, good electrical conductivity and very importantly, their linear geometry makes their surface highly accessible to the electrolyte. This CNT is 100 times stronger than steel and weight is 1/6th weight of steel. CNT having high strength to weight ratio is used in aerospace industry. Young's modulus of CNTs is over 1 TPa, 70 GPa for aluminium, steel 210 and 700 GPa for C-fibre. The strength to weight ratio is 500 times greater than aluminium. Maximum strain will be 10 % much higher than any material. The thermal properties of nanotubes are also very impressive.

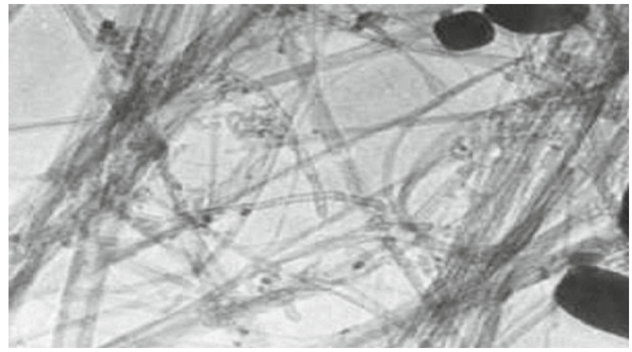

Fig. 1 A TEM image of our single walled nanotubes—SWCNT's 60 wt% 1–2 nm OD

Nanotubes are stable in vacuum up to 2,800 °C, and in air up to 750 °C. The heat transmission is predicted to be as high as 6,000 W/mK at room temperature. This can be compared with nearly pure diamond, which is a very good heat conductor and transmits 3,320 W/mK [5]. The density of bundled nanotubes is 1.33–1.40 g/cm^3. This is very low, as compared with aluminium, possessing a density of 2.7 g/cm^3 [12]. CNTs have very high current carrying capacity, excellent field emitter and high aspect ratio. There is a considerable change in the mixture of abrasive particles with Carbon nanotube when compared to the normal one. These results indicate that CNTs can be used as an additive in the lubricant. The flash point is increased when carbon nanotube is mixed with cutting fluid uniformly, so that cutting fluid can withstand more heat which is generated during EDM process. The source of single wall carbon nanotube shown in Fig. 1 is received from Cheap tubes Inc, USA (http://www.cheptubes.com).

From the Table 1 shows the specification for single wall carbon nanotubes which having graphite purification is 60 wt% and Table 2 shows the 96.3 wt% carbon content and remaining aluminum and sulphur.

Table 1 Specifications of SWCNT's (http://www.cheptubes.com)

Outer diameter	1–2 nm
Length	5–30 μm
Purity	>60 wt%
Ash	<3.0 wt%
Specific surface area	>407 m^2/g
Electrical conductivity	>100 s/cm
Bulk density	0.14 g/cm^3

Table 2 Chemical composition of single wall carbon nanotubes (http://www.cheptubes.com)

Elements	C	Al	Cl	Co	S
wt %	96.3	0.08	0.41	2.91	0.29

Inconel 825 is a high performance alloys, mainly Nickel Alloy and also Cobalt and Titanium. Inconel 825 might be used in any environment that requires resistance to heat and corrosion. They have good resistance to oxidation and corrosion at high temperatures. Inconel 825 typically finds application in Furnace components, chemical processing, Food processing industry and Nuclear engineering. The chemical composition of Inconel-825 material was tested by using optical emission spectrometer of shimadzu/PDA7000 model instrument and and Mechanical properties are tested by using Vickers & Brinell hardness tester VEB-HP0250 model according to CML/WP/036 & IS:1056 standards in Mettex Lab, Chennai, India.

From the Tables 3, 4 chemical composition of Inconel 825 has high nickel content, sufficient to resist chloride ion stress corrosion cracking, and a very stable austenite structure. The levels of molybdenum and copper enable the alloy to resist reducing agents and acids. Chromium gives resistance to oxidizing conditions, such as nitric acid solutions, nitrates and oxidizing salts. The alloy is titanium stabilized to resist pitting and inter granular attack after fabrication, particularly welding, which includes heating in the critical sensitization temperature range (650–760 °C). Inconel 825 is classed as a 'C' alloy and is reasonably easy to machine. From the Table 4 high hardness 83–85 HRB materials are machined by using carbon nanotube based dielectric EDM machining process.

The cryogenic process typically involves slowly cooling a mass of parts to −196 °C, holding them at this temperature for 30 h or more, and then slowly heating them back to ambient temperature. In case of steels, the benefits are usually attributed to the reduction or elimination of retained austenite from hardened steel and accompanied by the precipitation of small finely dispersed carbides in the martensite.

Table 4 Mechanical properties of Inconel-825

Tensile strength	655 MPa
Hardness [HRB]	83–85

The temperatures well below room temperature, i.e. 0–269 °C, are called cryogenic temperatures. Normally these temperatures can be generated using solid carbon dioxide or mechanical refrigeration or liquefied gas system. The solid carbon dioxide method is the oldest method and is capable of cooling components down to −80 °C. The mechanical refrigeration method may be capable of cooling to about −100 °C using Freon as a convection fluid. The last and very important method in cryogenic technology is the liquefied gas system which is capable of cooling to around −250 °C. The gases that are used for generating the cryogenic temperatures are oxygen, nitrogen, neon, hydrogen and helium. Cryogenic treatment just transforms brittle austenite into martensite and as such there is no noticeable increase in core hardness (58–59 HRC). Liquefied gas system using liquid nitrogen as the cooling medium. Components can be cooled to around −196 °C. The liquid nitrogen system compared to other systems is more advantageous where it can be used for applications with a wider temperature range. The system is capable of cooling the components to desired temperatures at controlled rate.

From the Fig. 2 the hardening process for a work piece can be divided into three technical process steps. First, the work piece is heated to its hardening temperature, typically 750–1,300 °C, which is material composition dependent. Then the piece is maintained at its hardening temperature in order to dissolve the alloying elements, including carbon, to promote an even composition within the austenite. The last stage is quenching at a suitable cooling rate in order to achieve a uniform, hardened structure, known as martensite. Steel is having high level of brittleness after hardening which often makes them unsuitable for practical applications. Subsequent heating (tempering) not only reduces this brittleness but, depending on the temperature selected, modifies the properties to meet the relevant technical requirements. In most cases, tempering is carried out after hardening as part of the same process. On some occasions hardening is followed by a subzero process to maximize the transformation to martensite prior to the tempering process. This approach may be appropriate in certain specific applications. It has been found and proved that cryogenic treatment improves wear resistance of Inconel 825 to a great extent. The temperature is increased over a period of time the hardness is increased.

Table 3 The chemical composition of Inconel 825

Elements	C	Si	Cu	Mn	Mo	Cr	Ni	Al	S	Ti	Fe
wt %	0.05	0.5	1.5–3	1.0	2.5–3.5	19.5–23.5	38–46	0.2	0.03	0.–1.2	22

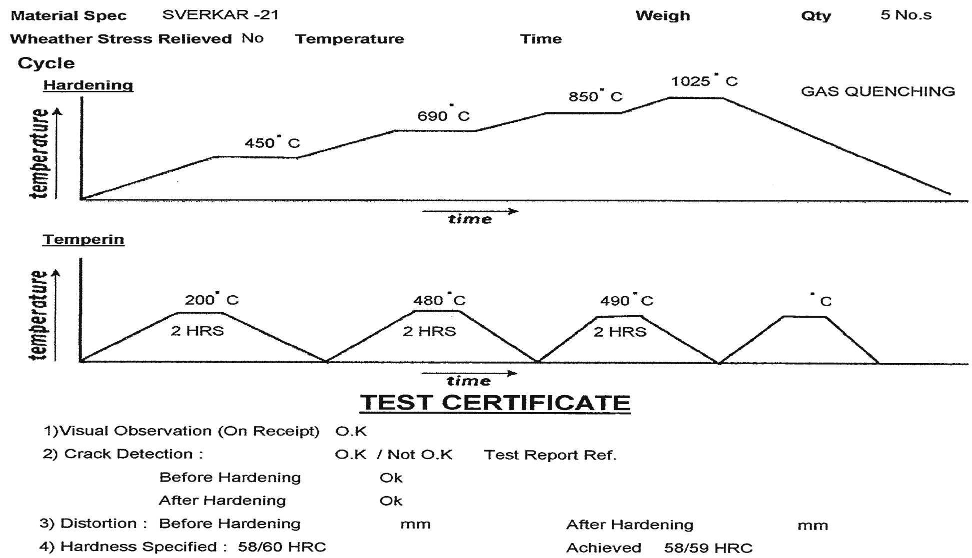

Fig. 2 The process involved in cryogenic treatment and subsequent tempering

Fig. 3 Electric discharge machining (SD35-5030)

2 Experimental Details

Electrical discharge machining (EDM) is one of the important non-traditional machining processes shown in Fig. 3 with ISO 5030 standards. It is one of the most successful, practical and profitable non-conventional machining processes for machining newly developed high strength alloys with high degree of dimensional accuracy and economical cost of production. Machining of electrically conductive material irrespective of its hardness, by the application of thermal energy, is one of the prime advantages of electrical discharge machining process.

Table 5 Electrical discharge machining conditions

Work material	Inconel 825
Dielectric	Kerosene
Electrode material	Copper
Pulsed current	2, 5, 8 A
Pulse-on duration	1, 3, 5 μs
Pulse voltage	60, 80,100 V

The specimen of INCONEL 825 material is machined using several conventional methods. The specimens were made to a size of diameter 20 mm and length 15 mm. Both the faces of the raw material are to be ground to get a smooth surface. The cryogenic treatment was carried out on Inconel 825 to improve the Hardness. The hardness obtained for the specimen is 83-85 HRB. Table 3 lists the chemical composition (wt%) of the material. The EDM specimens were sparked on a model type SD35-5030. The experiment was carried out in kerosene dielectric covering the work piece by 20 mm. A cylindrical copper rod machined was used as the electrode for sparking the work piece. The copper electrode was the negative polarity and the specimen was the positive polarity during the EDM process. During EDM, the primary parameters are pulsed current, pulse-on duration, and pulse-off duration. Table 5 shows the electrical discharge machining conditions.

During the EDM process, the varying pulse-off duration setting from 1 to 7 μs could effectively control the flushing of the debris from the gap, giving machining stability. Hence, the effect of the pulse-off duration on the machined characteristics was not considered in the present work. After each experiment, the machined surface of the EDM specimen was studied like surface roughness, microcrack and morphology

Fig. 4 EDM set up using SWCNT

Table 6 Identifying control factors and their levels

Item	Control factor	Units	Level 1	Level 2	Level 3
A	Pulse current (I)	Amp	2	5	8
B	Pulse duration (τ)	Microsecond	1	3	5
C	Pulse voltage (V)	Voltage	60	80	100

by means of an Atomic force microscope. The dielectric fluid was mixed in a proportion of 2 g of SWCNT for 1Lit of kerosene. A separate tank was made to hold the dielectric fluid containing SWCNT in which the specimen was placed. The sparking was carried out in this setting Fig. 4. Different samples were examined.

The process parameters in EDM process to influence the objective function like surface finish and metal removal rate was analyzed. The parameters control factors and their levels are identified Table 6.

Here three levels and three parameters are taken so based on Taguchi design of experiments L9 orthogonal array was taken Table 7. So totally nine experiments were conducted. The surface roughness of INCONEL 825 with and without single wall carbon nanotubes and S/N ratio values are tabulated in Table 8.

3 Analysis and Methodology

To determine the effect of the carbon nanotube on the surface roughness of the INCONEL 825, the surface profiles of the EDM machining work piece were measured by Surface roughness tester (Hommel Tester TR500).

Table 7 L9 orthogonal array

Exp. no	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	3
5	2	2	2
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

From the Table 8 shows that three levels and three parameters are chosen to machine the EDM using carbon nanotube based dielectric fluid and compared without using CNT. The surface roughness results are decreased by using CNT and Signal to noise ratio is calculated by using the formula 1.

By using carbon nanotube the Inconel 825 material has been improved to nanolevel surface finish. S/N ratio calculated based on quality of the characteristics. The objective function of this method is to improve the surface finish of EDM machining process using carbon nanotubes. The Smaller the best S/N ratio is calculated. The formula used for calculating the S/N ratio is given below: Smaller the best

$$\text{S/N ratio}(\eta) = -10 \log 10 \sum_{i=1}^{n} y^2 \tag{1}$$

where n is the no. of experiments and y is the no. of response value

From the Table 9 determines the factor effects of S/N ratio by using without CNT mixed dielectric fluid in EDM process. The high delta values of pulse current are obtained by using MINITAB 15 software which is ranked as 1 is most influenced parameters in EDM.

From the Fig. 5, Level 1 of A and Level 1 of B and Level 2 of C which gives the maximum effect of improving Surface roughness. Naturally A1, B1 and C2 is the best combination i.e. a Pulse current 2 Amp, Pulse duration of 1 µs and pulse voltage 80 V will give the minimum of Surface roughness. From the factor effect graph shows that pulse current giving more impact to improve the surface finish.

The based on Taguchi analysis the optimum level setting of EDM parameters is **A1B1C2**.

The predicted S/N ratio η' using the optimal levels of the machining parameters can be calculated as:

$$\eta' = \eta_{\text{m}} + \sum_{i=1}^{p} (\eta_i - \eta_{\text{m}}) \tag{2}$$

where η_{m} is the total mean of S/N ratio, η_i is the mean of S/N ratio at the optimum level and p is the number of

Table 8 Surface roughness and S/N ratio value

Exp. no	Coded values			Actual values			Without carbon nanotubes surface roughness R_a (y1)	Without carbon nanotubes surface roughness R_a (y2)	With carbon nanotubes surface roughness R_a (y1)	S/N ratio with CNTη	S/N ratio without CNTη
	A	B	C	A	B	C					
1	1	1	1	1	1	60	2.078	2.19	2.009	−6.0596	−7.74024
2	1	2	2	1	3	80	3.25	3.19	2.896	−6.83265	−8.17036
3	1	3	3	1	5	100	5.89	5.78	3.788	−4.07154	−14.2169
4	2	1	3	5	1	100	6.98	2.567	3.674	−9.46974	−13.9638
5	2	2	2	5	3	80	5.678	6.789	4.762	−11.2101	−16.0396
6	2	3	1	5	5	60	7.984	5.842	3.436	−9.15158	−15.4779
7	3	1	3	8	1	100	7.981	6.075	3.828	−15.2955	−17.1816
8	3	2	1	8	3	60	8.286	6.834	3.225	−11.6594	−15.5367
9	3	3	2	8	5	80	7.892	5.982	4.786	−10.1706	−15.0164
Mean (μ)										−9.32452	−13.70

Table 9 Determining the factor effects of S/N ratio without nanotube

Factor	Level 1	Level 2	Level 3	Delta	Rank
A. Pulse current	−10.04	−15.16	−15.91	5.87	1
B. Pulse duration	−12.96	−13.25	−14.90	1.94	3
C. Pulse voltage	−12.92	−12.38	−15.81	3.43	2

Table 10 Determining the factor effects of S/N ratio with nanotube

Factor	Level 1	Level 2	Level 3	Delta	Rank
A. Pulse current	−5.655	-9.944	−12.375	6.721	1
B. Pulse duration	−10.275	-9.901	−7.798	2.477	2
C. Pulse voltage	−8.957	-8.824	−10.192	1.368	3

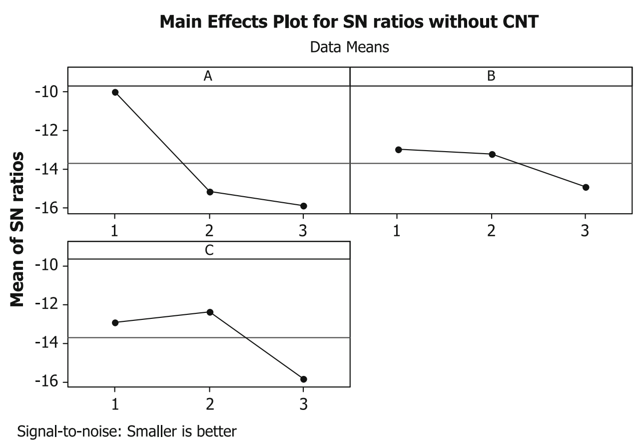

Fig. 5 Factor effect diagram for S/N ratio without nanotubes

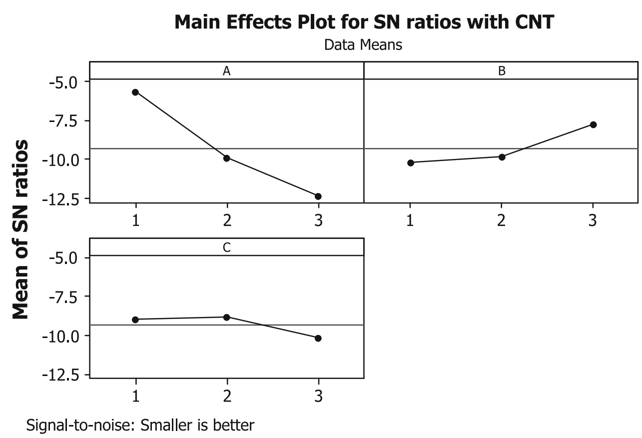

Fig. 6 Factor effect diagram for S/N ratio with nanotubes

main machining parameters that significantly affect the performance.

From the definition without carbon nanotubes

$$\text{S/N ratio } (\eta) = -10 \log 10/n \sum_{i=1}^{n} y^2 = -7.97824$$

So predicted surface roughness without carbon nanotubes R_a (y) = 2.55 μm.

Therefore, actual surface roughness without carbon nanotubes R_a (y) = 2.50 μm.

From the Table 10 determines the factor effects of S/N ratio by using with CNT mixed dielectric fluid in EDM process. The high delta values of pulse current are obtained by using MINITAB 15 software which is ranked as 1 is most influenced parameters in EDM.

From the Fig. 6 Level 1 of A and Level 3 of B and Level 2 of C which gives the maximum effect of improving surface roughness. Naturally A1, B3 and C2 is the best combination i.e. a Pulse current 2 Amp, Pulse duration of 5 μs and pulse voltage 80 v will give the minimum of Surface roughness. From the factor effect graph shows that pulse current giving more impact to improve the surface finish.

The based on Taguchi analysis the optimum level setting of EDM parameters is **A1B3 C2.**

So predicted surface roughness with carbon nanotubes R_a (y) = 1.516 μm.

Table 11 Shows the results of ANOVA for the surface roughness without carbon nanotubes

Machining parameters	Degree of freedom	Sum of squares (SSA)	Variance (VA)	FAo	*P*	Contribution (%)
A	2	1.320	0.660	0.16	0.862	9.13
B	2	4.222	2.386	0.58	0.633	29.22
C	2	0.659	0.329	0.08	0.926	4.57
Error	2	8.247	4.124			57.08
Total	8	14.448				100

Significant $S = 2.03067$
R-Sq = 42.92 %
R-Sq (adj) = 10.00 %

Table 12 Shows the results of ANOVA for the surface roughness with carbon nanotubes

Machining parameters	Degree of freedom	Sum of squares (SSA)	Variance (VA)	FAo	*P*	Contribution (%)
A	2	8.331	4.165	3.73	0.212*	66.40
B	2	1.651	0.726	0.65	0.606	13.17
C	2	0.329	0.165	0.15	0.872	2.62
Error	2	2.235	1.117			17.81
Total	8	12.545				100

*$S = 1.05708$ R-Sq = 82.19 %
R-Sq (adj) = 28.74 %

Actual surface roughness with carbon nanotubes
$R_a = 1.59$ µm
Predicted surface roughness without carbon nanotubes
$R_a = 2.55$ µm
Actual surface roughness without carbon nanotubes
$R_a = 2.50$ µm.

3.1 Confirmation Test

The confirmation experiment is the final step in the first iteration of the design of experiment process. The purpose of the confirmation experiment is to validate the conclusions drawn during the analysis phase. The confirmation experiments were conducted by setting the process parameters at optimum level. Pulse current 2 Amp, pulse duration of 1 µs and voltage as 80 V as optimum parameters and the actual surface roughness was obtained without carbon nanotubes is 2.50 µm compared to predicted surface roughness 2.55 µm. Similar way with carbon nanotubes the confirmation test is carried out with Pulse current 2 Amp, pulse duration of 5 µs and voltage as 80 V as optimum parameters and the actual surface roughness was obtained with carbon nanotubes 1.59 µm compared to predicted surface roughness 1.516 µm.

3.2 ANOVA Analysis

The purpose of analysis of variance is to find the significant factors affecting the machining process to improve the surface characteristics of INCONEL 825 material in EDM machining process. ANOVA gives clearly how the process parameters affect the response and the level of significance of the factor considered. The ANOVA table for surface roughness of with and without carbon nanotubes is calculated.

The R^2 value of developed empirical model for surface roughness with nanotube is 82.19 %. The high R^2 value indicates that better the model fits your data. Here 0.212 p value of pulse current factor is significant. The main output from an analysis of variance study ANOVA arranged in a Tables 11, 12, list the sources of variation, their degrees of freedom, the total sum of squares, and the mean squares. The analysis of variance table also includes the F-statistics and p values. Use these to determine whether the predictors or factors are significantly related to the response. Larger FAo value indicates that the variation of the process parameter makes a big change on the surface roughness.

3.3 Metal Removal Rate

The calculation of MRR was done by measuring the weights before and after machining and dividing the answer with time taken for machining

$$\text{MRR} = \text{wt before machining} - \text{wt after machining/time taken} \quad (3)$$

From the Table 13 Metal removal rate are determined by using carbon nanotube based machining. In that MRR is increased by using CNT because it will absorb the heat from material and flushed with dielectric fluid. By using CNT signal to nose ratio is decreased.

From the Fig. 7 it is clearly note that D1E1F3 is the best combination that can be used without CNT.

Larger the better

$$\text{S/N ratio } (\eta) = -10 \log 10\ 1/\text{n} \sum_{i=1}^{n} (1/y^2) = -27.8949$$

Table 13 MRR and S/N ratio value

Exp. no	Coded Values			Actual values			Without carbon nanotubes MRR (g/min)(y1)	With carbon nanotubes MRR (g/min)(y2)	S/N ratio without CNTη	S/N ratio with CNTη
	A	B	C	A	B	C				
1	1	1	1	1	1	60	0.01047	0.00152	−39.6011	−56.3631
2	1	2	2	1	3	80	0.007086	0.0023	−42.992	−52.7654
3	1	3	3	1	5	100	0.01747	0.0089	−35.1541	−41.0122
4	2	1	3	5	1	100	0.004473	0.082	−46.988	−21.7237
5	2	2	2	5	3	80	0.002893	0.0058	−50.773	−44.7314
6	2	3	1	5	5	60	0.00002	0.0089	−93.9794	−41.0122
7	3	1	3	8	1	100	0.000267	0.0116	−91.4698	−38.7108
8	3	2	1	8	3	60	0.000033	0.0055	−89.6297	−45.1927
9	3	3	2	8	5	80	0.00004	0.0097	−87.9588	−40.2646
Mean (μ)									−64.2829	−42.4196

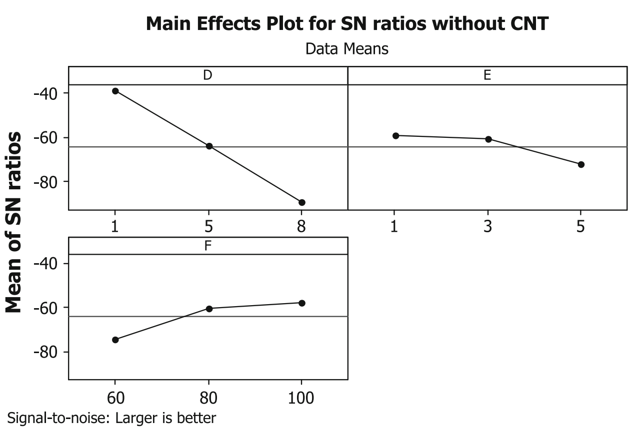

Fig. 7 Factor effect diagram for S/N ratio without nanotubes

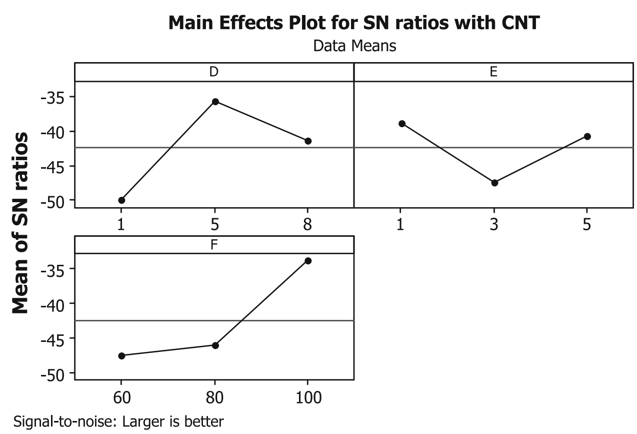

Fig. 8 Factor effect diagram for S/N ratio with carbon nanotubes

So predicted MRR without carbon nanotubes R_a (y) = 0.0404 g/min.

So actual MRR without carbon nanotubes R_a (y) = 0.0398 g/min.

From the Fig. 8 it is clearly note that D2E1F3 is the best combination that can be used with CNT. From the definition with carbon nanotubes larger the better

$$\text{S/N ratio } (\eta) = -10 \log 10\ 1/\text{n} \sum_{i=1}^{n} (1/y^2) = -23.73$$

So predicted MRR with carbon nanotubes R_a (y) = 0.065 g/min.

So actual MRR with carbon nanotubes R_a (y) = 0.059 g/min.

The R^2 value of developed empirical model for surface roughness with nanotube is 90.61 %. The high R^2 value indicates that better the model fits your data. Here 0.212 p value of pulse current factor is significant. The main output from an analysis of variance study ANOVA arranged in a Tables 14 and 15, list the sources of variation, their degrees of freedom, the total sum of squares, and the mean squares. The analysis of variance table also includes the F-statistics and p values. Use these to determine whether the predictors or factors are significantly related to the response. Larger FAo value (8.24) indicates that the variation of the process parameter makes a big change on the surface roughness

4 Results and Discussions

4.1 Surface Morphology

During the EDM process, the primary parameters were pulsed current and pulse-on duration, both of which are settings of the power supply. In order to assess the surface measurement results, an AFM study of the surface morphology of the EDM machined surface was conducted. The three-dimensional

Table 14 Shows the results of ANOVA for the MRR with carbon nanotubes

Machining parameters	Degree of freedom (f)	Sum of squares (SSA)	Variance (VA)	FAo	P	Contribution (%)
A	2	0.0002263	0.0001132	8.24	0.108*	77.34
B	2	0.0000097	0.0000042	0.30	0.767	3.31
C	2	0.0000291	0.0000145	1.06	0.486	9.94
Error	2	0.0000275	0.0000137			9.38
Total	8	0.0002926				100

* Significant
$S = 0.00370613$ R-Sq = 90.61 %
R-Sq (adj) = 62.45 %

Table 15 Shows the results of ANOVA for the MRR without carbon nanotubes

Machining parameters	Degree of freedom (f)	Sum of squares (SSA)	Variance (VA)	FAo	P	Contribution (%)
A	2	0.0013485	0.0006743	0.75	0.571*	26.3
B	2	0.0012679	0.0001743	0.19	0.837	24.7
C	2	0.0007111	0.0003556	0.40	0.716	13.8
Error	2	0.0017932	0.0008966			35.01
Total	8	0.0051208				100

* Significant
$S = 0.0299434$ R-Sq = 64.98 %
R-Sq (adj) = 20.00 %

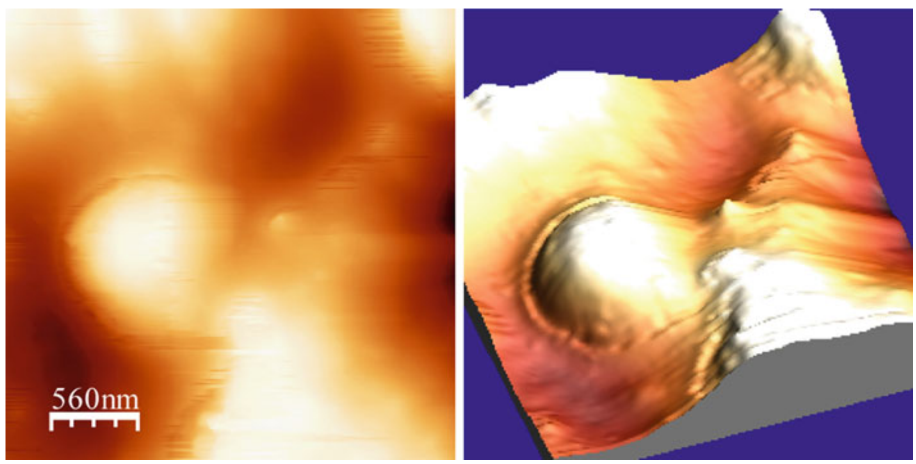

Fig. 9 Work piece 1 side without carbon nanotubes

AFM images of the machined surface obtained from the EDM specimens, where Ip is the pulsed current, and ton denotes the pulse-on duration. The darker contrast corresponds to the lower areas of the surface, and the brighter corresponds to the higher.

The Fig. 9 shows the 2D and 3D image of the work piece 1 without carbon nanotubes. The input parameters were 2 amperes of current, 5 microseconds of pulse on time, and voltage 100 volts. This means that the energy must be minimum, the machining was performed with carbon nanotubes with the same parameters and the following results were obtained.

From the Figs. 10, 11 and 12 the same reading was observed for the second work piece which was carried out at 2 amps, 3 microseconds and 80 V, with and without carbon nanotubes. It is clear that the surface microgeometry characteristics include machining damages such as ridge-rich surfaces, microvoids, and microcracks. The ridge-rich surface was formed by material melted during EDM, and blasted out of the surface by the discharge pressure. However, the surface immediately reached the solidification temperature being cooled by the surrounding working fluid. The microvoids can be attributed to the gas bubbles expelled from the molten material during solidification. The microcracks were the result of the thermal stresses. The primary causes of the residual stress in the machined surface were the drastic heating and cooling rate and the non-uniform temperature distribution. In addition, the morphology of the EDM surface was dependent on the applied discharge energy. When applying the smaller pulsed current the surface characteristics have

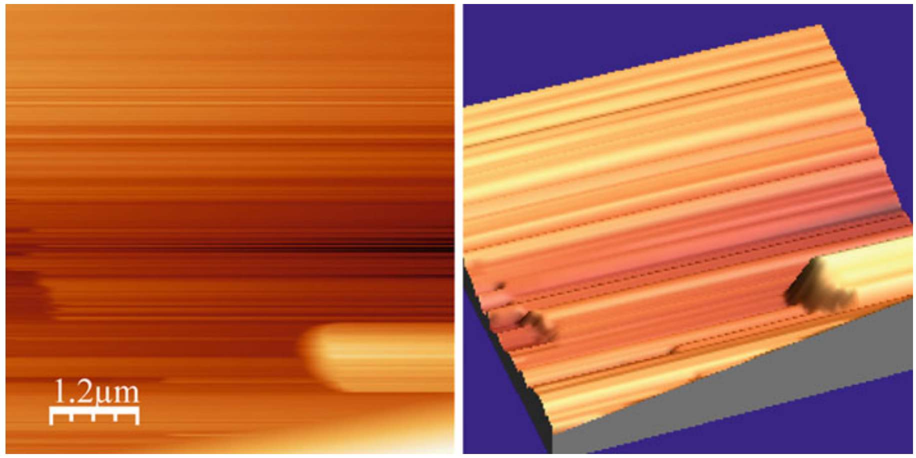

Fig. 10 Work piece 1 side with carbon nanotubes

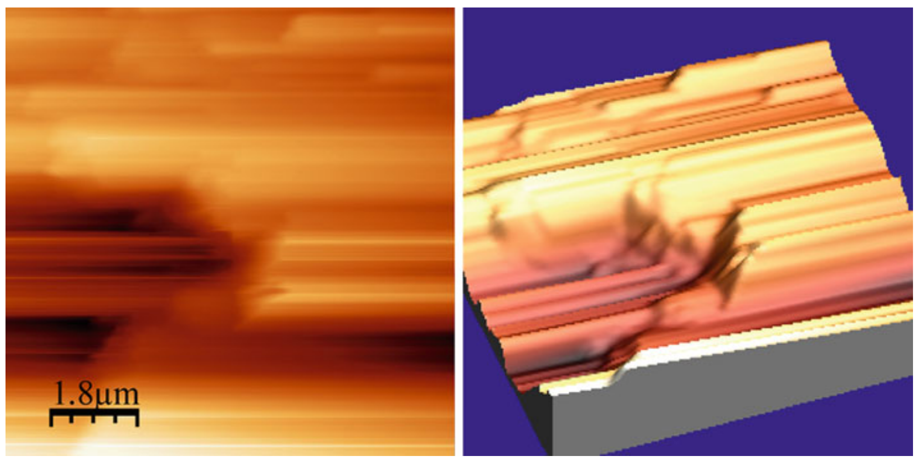

Fig. 11 Work piece 2 side without carbon nanotubes

minor hillocks and valleys. When the pulsed current and pulse-on duration increased the machined surface exhibited a deeper crack or void and more pronounced defects.

4.2 Surface Roughness

By using AFM, surface roughness of the machined work piece can be calculated from the following formulas:

$$R_a = \sum_{n=1}^{n} ((Z_n - Z)/N) \quad (4)$$

$$R_{\mathrm{Rms}} = \sqrt{\sum_{n=1}^{n} ((Z_n - Z)^2/N - 1)} \quad (5)$$

where Z_n is the height of the data points, R_a is the surface roughness, Z is the mean height, N is the number of data points, R_{Rms} is the Rms method of surface roughness.

R_a is used to find out the surface finish of rough surface when R_{Rms} is used to find the surface finish of smooth surface.

Mean height can be calculated from

$$Z = 1/N \sum_{n=1}^{n} Z_n \quad (6)$$

EDM erodes surfaces randomly, to determine the effect of the EDM process on the surface roughness of the Inconel 825, the surface profiles of the EDM specimens were measured by AFM. The average surface roughness, R_a, of the machined specimen was calculated from the AFM surface topographic data. The Fig. 13 shows the measurement results. The surface roughness on the machined surface varied from 0.1 to 0.2 µm for a scanning area of 1.7 µm ×1.7 µm.

From these results it is clear that the specimens machined using CNT exhibit better surface finish as compared to specimens sparked without using CNT (Table 16). Moreover a higher pulsed current and longer pulse-on duration cause a poorer surface finish. Comparing with the results of Figs. 13, 14, 15 and 16, find that an excellent machined finish can be obtained by adding CNTs to dielectric fluid and setting the machine parameters at an optimum pulsed current and pulse-on duration.

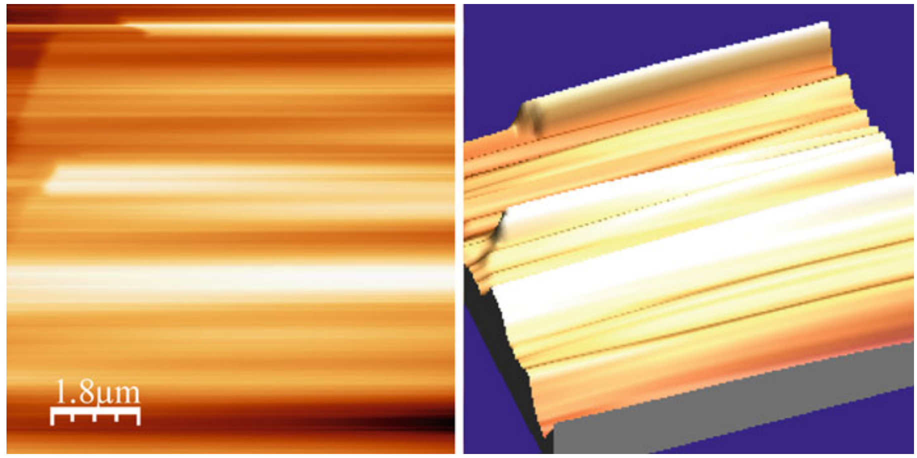

Fig. 12 Work piece 2 side with carbon nanotubes

Table 16 Comparison results of AFM surface roughness and microcracks

Samples	Surface roughness (µm)	Micro cracks (nm)
w/p 1 without CNT	0.1757	259
w/p 2 without CNT	0.48974	294
w/p 1 with CNT	0.13431	202
w/p 2 with CNT	0.12903	79.2

4.3 Micro Cracks

In order to measure the maximum depth of the microcracks of the EDM specimen, the AFM was used to measure the object generating the line diagram of the cross section shown in the figures shown below.

From the Figs. 17, 18, 19 and 20, the microcracks are increased without using carbon nanotubes as dielectric fluids when compared with using CNT. The reasons for getting smooth surface is that the carbon nanotubes are having high mechanical and electrical properties specifically high electrical conductivity of 6,000 w/mk compared to copper having 3,000 w/mk. The darker contrast corresponds to the lower areas of the surface, and the brighter corresponds to the higher areas of the surface. It is clear that the surface microgeometry characteristics include machining damages such as ridge-rich surfaces, microvoids, and microcracks. The ridge rich surface was formed by the material melted during the EDM process and an unwanted white layer was formed. This layer would be removed by applying more contact pressure to the work piece and due to which more deflection and chattering occurs. However, the surface immediately reaches the solidification temperature since its being cooled by the cutting fluid. The

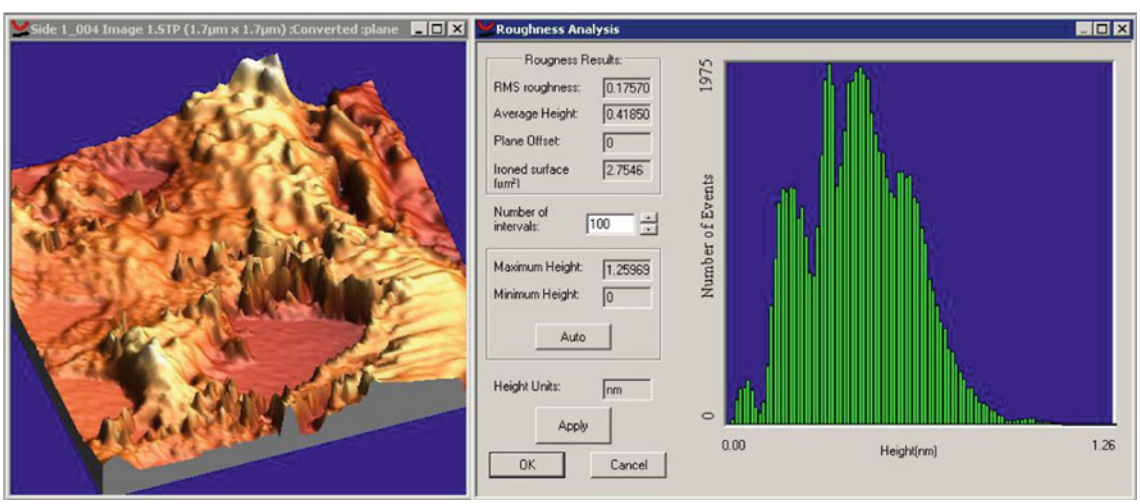

Fig. 13 Surface roughness of work piece 1 without carbon nanotube

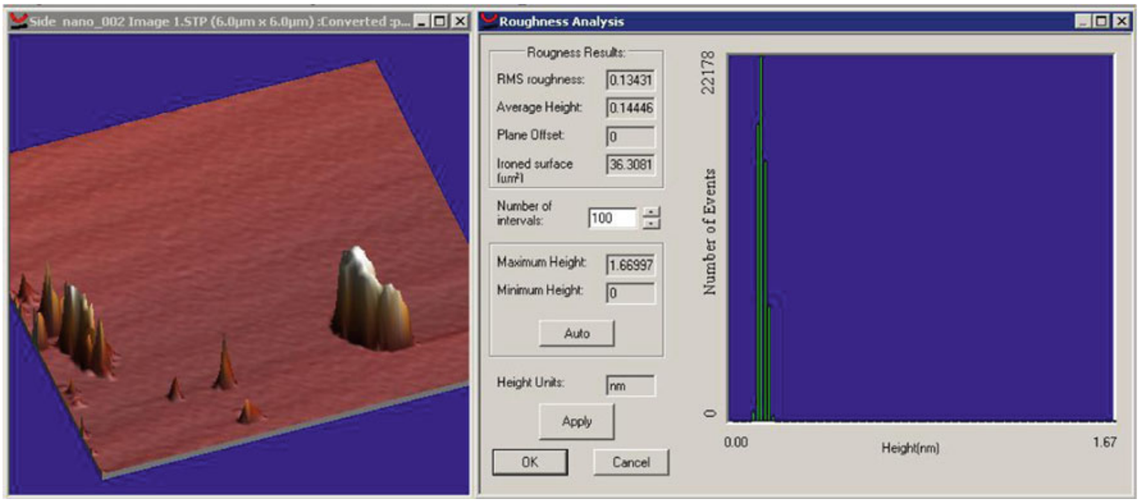

Fig. 14 Surface roughness of work piece 1 with carbon nanotube

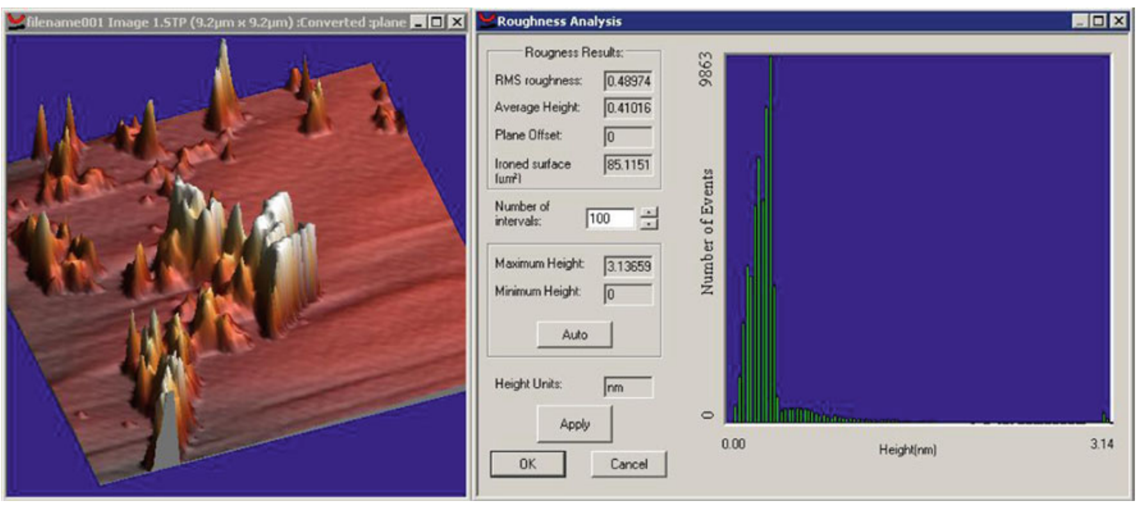

Fig. 15 Surface roughness of work piece 2 without carbon nanotube

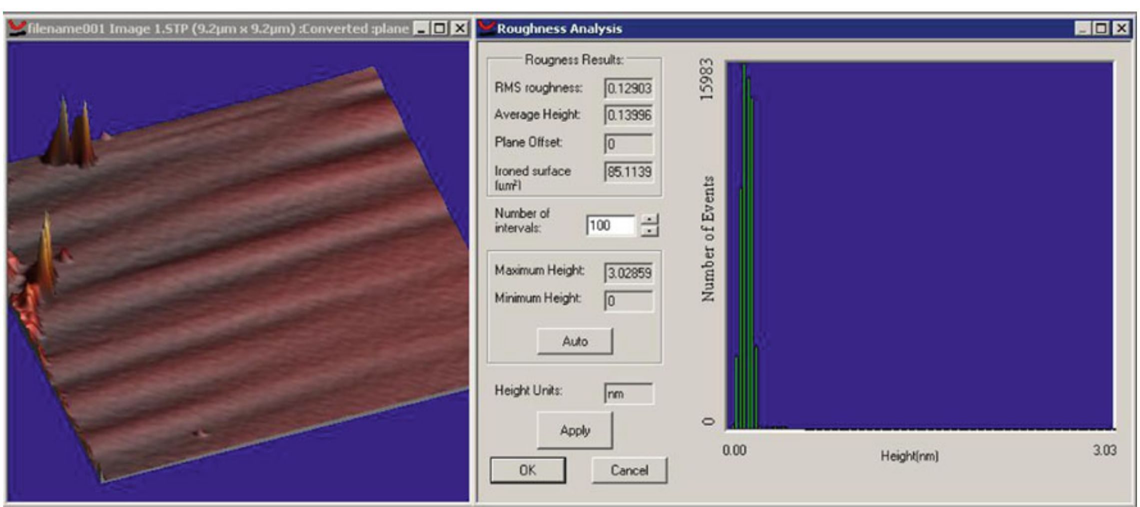

Fig. 16 Surface roughness of work piece 2 with carbon nanotube

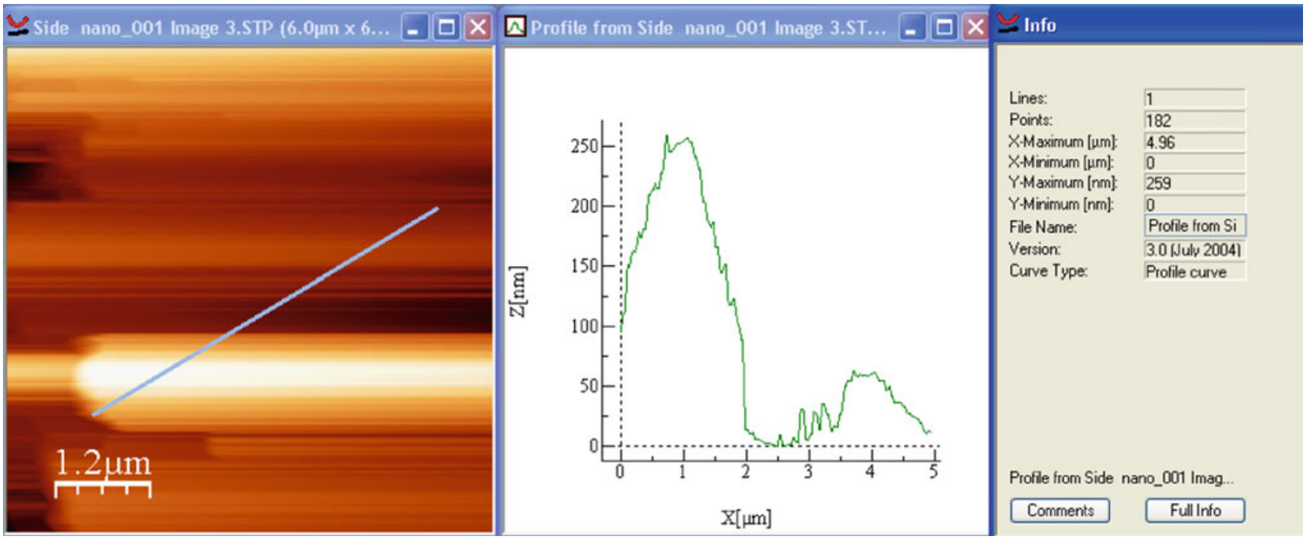

Fig. 17 The microcracks observed in work piece 1 without carbon nanotubes

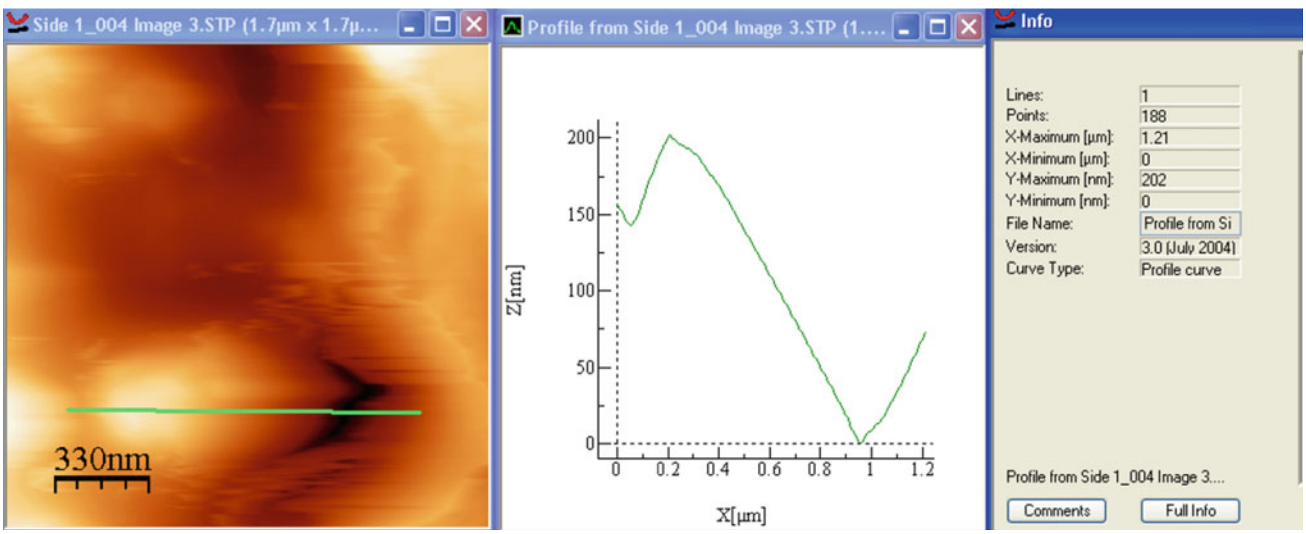

Fig. 18 The microcracks observed in work piece 1 with carbon nanotubes

formation of microvoids could be due to the gas bubbles expelled from the molten material during solidification and these can be minimized by using nanofluids. The presence of microcracks leads to thermal stress. The primary causes of the residual stress in the machined surface were the drastic heating and cooling rate and the non-uniform temperature distribution. The main reason for getting smoothness is carbon nanotube is because it is having excellent thermal and mechanical property.

5 Conclusions

The experimental results indicate that the surface roughness of Inconel 825 material are improved by using single wall CNT as dielectric fluid in EDM machining process. An excellent nanolevel surface finish is obtained by setting the machine parameters at optimum pulse current. The surface roughness, metal removal rate and the depth of the microcracks are compared with and without CNTs. The speci-

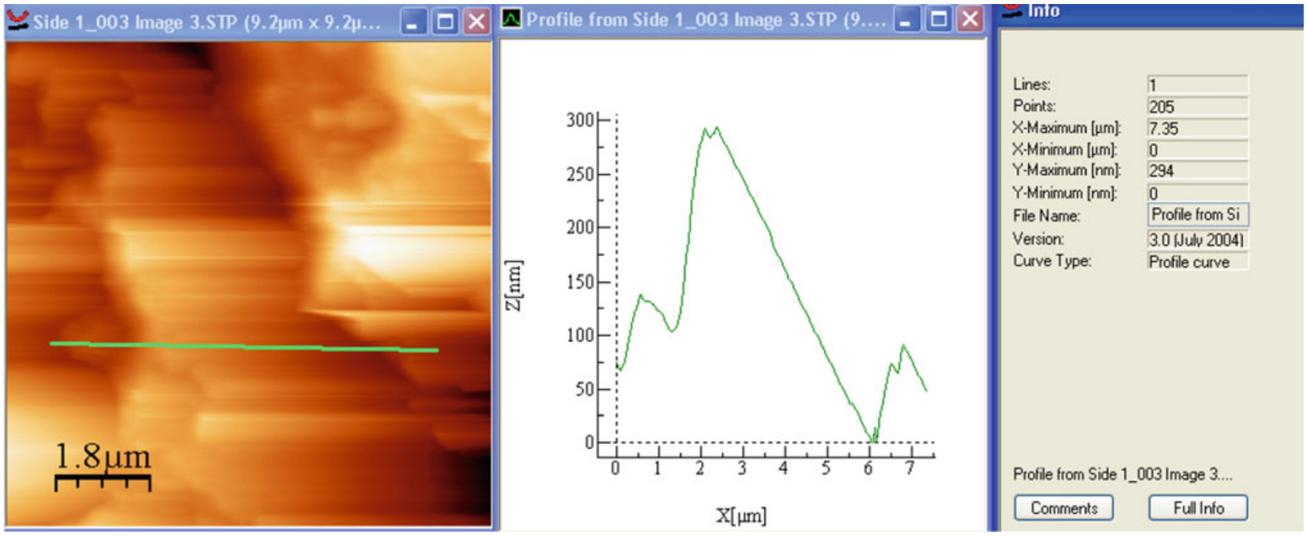

Fig. 19 The microcracks observed in work piece 2 without carbon nanotubes

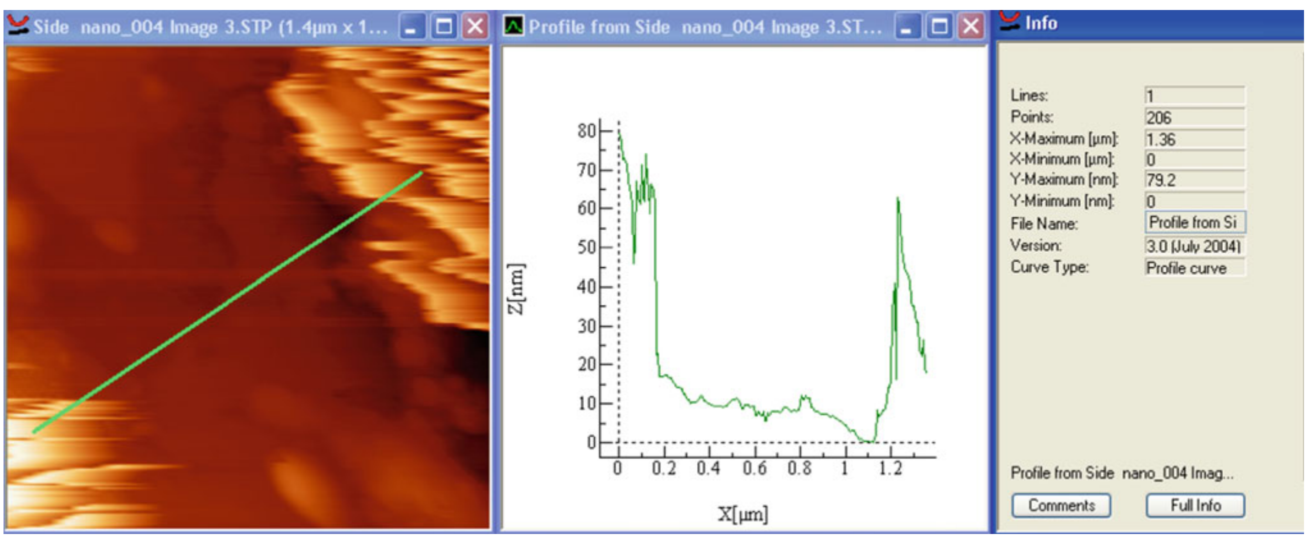

Fig. 20 The microcracks observed in work piece 2 with carbon nanotubes

mens sparked using CNTs have better surface finish, reduced microcracks and better surface morphology as compared without CNTs. Furthermore, the AFM applications yielded information about the depth of the microcracks are particularly important in the post treatment of Inconel 825 material machined by EDM and also significant improvement in metal removal rate.

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