Fractal Dimensional Surface Analysis of AISI D2 Tool Steel Material with Nanofluids in Grinding Process Using Atomic Force Microscopy

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The surface analysis of nanomachined AISI D2 tool steel materials is measured using atomic force microscopy. The surface roughness and fractal dimensional analysis are the important factors in nano tribology and evaluating the quality of nanomachined surface. Carbon nanotube increases the heat carrying capacity, thermal conductivity of the lubricating oil and thus prevents any damage to the work piece. The surface morphology of different machined surface was studied by Fractal Dimension analysis and roughness characterization was carried out. The results indicate that the fractal dimension changed according to the smoothness of the machined surface. The Power Spectrum Density (PSD) method based Root mean square (Rms) surface roughness was calculated for carbon nano tube based nanofluids in grinding process. The fractal dimension and roughness are decreased due to single wall carbon nano tube based nanofluids and smooth surface finish has been obtained.
Keywords: *carbon nanotube, nanofluids, atomic force microscopy, fractal dimension, roughness, power spectrum density*

Introduction

Demand for better surface finish and accuracy has been increasing rapidly in recent years. To improve the surface characteristics from micro level to nano level, nanofluids are used in the machining process. The fractal concept has been applied to determine the surface irregularities of the machined surface. This study presents a fractal analysis of nanofluids based grinding surface, and uses the Powder Spectrum Density methods to determine the Fractal Dimension (D) of atomic force microscopy (AFM) image for different machining conditions. The formation of fractals has been extremely useful in describing the behavior of nanofluids surfaces that result from imperfection such as scratches, roughness, or partial passivation. We describe herein atomic force microscopy (AFM) fractal analysis of AISI D2 tool steel material surface using nanofluids. Our results indicate that the Fractal Dimension (D) decreases by using nanofluids while machining, heat is generated between the tool and the work piece, from which an oxide layer is formed since the heat carrying capacity of nanofluids is more than conventional fluids. Carbon nano tube has excellent thermal conductivity and heat carrying capacity. By using these properties a uniform surface morphology image was obtained at nano level, getting smooth. Fractal analysis has become a new and powerful tool to describe the geometric and structural properties of AISI D2 tool steel surfaces. The fractal dimension is the number used to quantify these properties.

Nomenclature

D	= *dimension of fractal*
$L(r)$	= *length of the corresponding curve, mm*
N	= *number of data points*
$N(r)$	= *number of measurements taken*
r	= *length of the measurement scale, mm*
Ra	= *surface roughness, µm*
R_{Rms}	= *root mean square method of surface roughness, µm*
Z	= *mean height, mm*
Zn	= *height of the data points, mm*

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Literature Review

Te-Hua Fang et al. (2005) proposed Surface analyses of nanomachined films are performed using atomic force Microscopy. Both surface roughness and fractal dimension are the important factors in all areas of nano tribology and in evaluating the quality of a nanomachining operation. Yeau-Ren Jeng et al. (2003) proposed the radio frequency (RF) magnetron sputtering process is used to generate a lead zirconate titanate (PZT) ferroelectric thin film on a silicon substrate. The surface characteristics of this lead zirconate titanate film are then investigated by means of an atomic force microscopy (AFM) method. Asvestas et al. (1998) defined a modified version to estimate the Fractal Dimension (FD) of a two variable Fractional Brownian Motion (FBM) functions from its average power spectrum. The method is called Power Differentiation method. Kwasny et al. (2005) presented structure, texture, thickness, micro-hardness and fractal dimension of surface topography of the two-layer TiC coatings onto the ASP 30 sintered high speed steel. The fractal dimension value of surface topography of analyzed coatings was determined using the projective covering method basing on investigation results in the atomic force microscope. Su-Il Pyun et al. (2004) investigated the fractal characteristics of meso porous carbon electrodes with various pore structures using the N2 gas adsorption method and the transmission electron microscopy (TEM) image analysis method. Bigerelle et al. (2005) proposed to create a fractal function defined by an infinite series to model worn surfaces obtained by a grinding process. In these series, each elementary term characterizes a wear process at a given scale. These series are only defined by two parameters: an amplitude parameter and the fractal dimension. Y.H. Guu (2005) proposed the surface morphology, surface roughness and micro-crack of AISI D2 tool steel machined by the electrical discharge machining (EDM) process by means of the atomic force microscopy (AFM) technique. Mamalis et al. (2004) has written to give a consolidated view of the synthesis, the properties and applications of carbon nano tubes in mechanical, automotive and space industries. Prabhu et al. (2008) proposed nanosurface generation in grinding process using multi wall carbon nanotube mixed with SAE20w40 coolant oil to improve the surface finish of grinding process. Contact mode of AFM is used to trace the surface of D2 tool steel using nano Si tip. Thus the surface roughness of nanofluids based machining is studied at micro level of 9 x 9 µm size of the object.

Paik et al. (2008) developed the nano sphere of polypropylene synthesized under controlled growth condition. Its molecular weight is equivalent to the commercial grade polypropylene. The SEM is conducted in order to inspect the surface morphology. The surface roughness, i.e. surface roughness amplitude parameters Ra (arithmetic average roughness) and root mean square roughness (RMS) at nanoscale, was calculated for nanoparticles by AFM. It is found that the surface profiles depend on particle size and it increases with increasing particle size. In Raeissi et al. (2007), atomic force microscopy was employed successfully to evaluate the morphological development of zinc electrodeposited onto steel substrate. Atomic force microscopy study of deposits proposed different mechanism of zinc development. Tanaka et al. (2008) proposed the particle outline image analyzed using fractal dimension. In the fractal dimensional analyses, when the scaling was not less than or equal to 1/20th of the particle diameter, the fractal dimension was very large. In this study, the scaling was adjusted to less than or equal to 1/20th of the particle diameter. Sayyad Amin et al. (2009) aimed to investigate the topography alteration of a glass surface as a result of asphaltene precipitation and its growth at various pressures using a bi-fractal approach. The fractal plots were indicative of bi-fractal behavior and for each surface type one fractal dimension was calculated. The topography information of the surfaces was obtained by two image analyses, AFM and SEM imaging techniques. Risovic et al. (2008) proposed that there are many methods for analysis and description of surface topographies that rely on analysis of surface images obtained by various methods such as SEM or AFM. However, they can seldom provide quantitative topographical information. Such information can be obtained by fractal analysis of the images resulting in a characteristic fractal dimensions. The advantage of fractal approach to surface characterization is that it is insensitive to the structural details, and the structure is characterized by single descriptor, the fractal dimension D. Here it is discussed the results of comparison of two methods for the determination of topological fractal properties of porous/rough surfaces: electrochemical impedance spectroscopy and SEM gray-scale image analysis. Jen-Fin Lin et al. (2010) proposed the frictional and indented behavior of a diamond asperity on a diamond plate carried out using a molecular dynamics (MD) and experiments. The micro contact and frictional behavior can be evaluated between a rigid smooth hemisphere to a deformable rough flat plane by combining the deformed behavior of the asperity obtained from MD results with the fractal and statistic parameters. Dash et al. (2009) proposed the Quantitative roughness and microstructural analysis of as-deposited and swift heavy ion (SHI) irradiated 10 and 20 nm thick Au films were performed by atomic force microscopy (AFM). Power spectral density (PSD) analysis was done from the AFM images. The Rms roughness estimated from the AFM data did not show either monotonic increase or decrease with ion influences. Grzesik et al. (2009) used the surface profiles generated in longitudinal turning operations characterized using continuous wavelet transform (CWT) and normalized fractal dimension *D*n. The wavelet transform together with fractal dimension can be capable of the detection of local self-similarity in the surface profile.

In this paper, carbon nano tube based nanofluids are used in the grinding process to analyze the surface characteristics of D2 tool steel material. Till now no work has been carried out by using carbon nano tube based machining. Carbon nano tube based nano fluid is used to improve the surface finish from micro level to nano level which improves the surface finish of the work piece. Electrolysis In-process Dressing (ELID) technique is adapted in grinding process to enhance the protrusion of the grinding wheel by nanofluids (CNT with SAE20w40 oil) based machining process. Nanofluids having low Reynolds number and transport by diffusion can be very effective means of mixing in the low Reynolds number regime, further, conventionally fluids have poor thermal conductivity compared to nanofluids. The major challenge is the rapid settling of these particles in fluids. Nanoparticles stay suspended much longer than micro-particles and, if below a threshold level and/or enhanced with surfactants/stabilizers, remain in suspension almost indefinitely. Furthermore, the surface area per unit volume of nanoparticles is much larger (million times) than that of microparticles. Multi wall carbon nano tube mixed with oil to enhanced thermal conductivity and critical heat transfer. Conventional heat transfer fluids have inherently poor thermal conductivity compared to solids. AFM is used (Guu, 2005) to analyze the surface roughness, micro crack and surface topography of the machined surface. Fractal dimensional analysis is also carried out on the machined surface using WsXm spectroscopy software and Power Spectrum Density (PSD) method is used to measure the surface roughness.

Carbon Nano Tubes (CNT's)

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. This CNT is 100 times stronger than steel (Mamalis et al., 2004) and weight is $1/6^{th}$ weight of steel. CNTs having high strength to weight ratio used in aero space industry. Young's modulus of CNTs is over 1 TPa vs 70 GPa for aluminum, steel 200 Gpa and 700 GPa for C-fibre. The strength to weight ratio is 500 times greater than aluminum and maximum strain will be 10% higher than any material. Thermal conductivity of CNT is 3,320 W/mK in the axial direction with small values in the radial direction. Electrical conductivity of CNTs is 109 A/cm^2 and copper is 106 A/cm^2. CNTs having very high current carrying capacity, excellent field emitter and high aspect ratio.

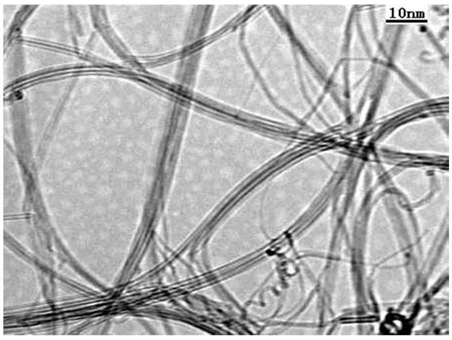

Figure 1. A TEM image of our Single Walled Nanotubes – SWCNTs 90wt% 1-2nm Outer Diameter.

Table 1. Specifications of SWCNTs.

Outer Diameter	1-2 nm
Length	5 µm to 30 µm
Purity	> 90 wt%
Ash	< 1.5 wt%
Specific Surface Area	> 407 m^2/g
Electrical Conductivity	> 100 S/cm
Bulk Density	0.14 g/cm^3

Most single-walled nanotubes (SWCNT) have a diameter of close to 1 nanometer, with a tube length that can be many thousands of time longer. The single wall carbon nano tube is shown in Fig. 1. The sources of single wall carbon nano tubes are received from Cheap tubes Inc., USA [www.cheptubes.com]. Table 1 shows the specification of SWCNT used in dielectric fluid. Table 2 shows the chemical composition of SWCNT in which 96.3% carbon content have a single wall carbon nano tube.

Table 2. Chemical composition of single wall carbon nano tubes.

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

AISI D2 Tool Steel

AISI D2 tool steel is a high-carbon, high-chromium tool steel alloyed with molybdenum and vanadium characterized by high wear resistance, high compressive strength, good through-hardening properties, high stability in hardening and good resistance to tempering-back. Table 3 lists the chemical composition (wt. %) of the material, while Table 4 lists the mechanical properties of the AISI D2 tool steel tested in Mettex lab, Chennai, according to OES-CML/WP/35 & IS 1586- 2000 standards.

Table 3. Chemical composition of the AISI D2 tool steel [wt. %].

Elements	C	Si	Mn	Mo	Cr	Ni	V	Co	Fe
Wt.%	1.5	0.3	0.3	1.0	12	0.3	0.8	1.0	Balance

Table 4. Mechanical properties of the AISI D2 tool steel at room temperature.

0.2% offset yield strength	1532 MPa
Tensile strength	1736 MPa
Hardness [HRC]	57

AISI D2 tool steel is recommended for tools requiring very high wear resistance, combined with moderate toughness (shock-resistance) and it can be supplied in various finishes, including the hot-rolled, pre-machined and fine machined condition.

Nanofluids

Behavior of fluids at micro level is differing from macro fluid in that surface tension, energy dissipation and fluidic resistance start to dominate the system. Molecular transport between them must often be through diffusion. Nanofluids have low Reynolds number. Conventionally fluids have poor thermal conductivity compared to solids. Conventional fluids contain macro or micro size particle which does not work effectively with micromachining techniques, since they can clog the tiny channel of these devices. Nanofluids are the new class of advanced heat transfer fluids engineered by dispersing nanoparticles smaller than 100 nm in diameter in conventional heat transfer fluids. A major challenge is rapid settling of these particles in fluids. Nanoparticles suspended much longer than micro particles remains indefinite. Surface area to volume ratio is million times larger compared with micro particles. For all samples, the nanofluids were prepared by dispersing 2 grams of MWCNTs into the SAE20W40 oil base fluid (1000 ml). The mixture was then ultrasonicated for 10 min at 100% amplitude using a 130W, 20 kHz ultrasonic processor (Nanotechnology research centre, SRM University, Chennai) and it was followed by 20 min stirring using a magnetic stirrer. The process was repeated until the total mixing time was 1 hour. The prepared samples were set at rest for 24 hours before conducting any viscosity and thermal conductivity measurements. These results indicate that CNTs can be used as an addictive in the lubricant. The CNT with lubricant mixture properties were tested and it shows that properties of lubricant were improved.

Table 5. Properties of nanofluids.

Thermal property	Without CNT nanofluids	With CNT nanofluids
Flash point (°C)	200	210
Fire point (°C)	235	250
Kinematic viscosity (m^2/s)	25.6	31.55
Dynamic viscosity (Pa.s)	21.02	25.91

The nanofluids are tested in Mettex lab, Chennai. A clear increase in the Flash and Fire point shows that the heat transfer capacity of the nanofluids is increased due to which the rejected heat in the atmosphere increases as well as the flash and fire point is raised. The viscosity of a fluid is an important property in the analysis of liquid behavior and fluid motion near solid boundaries. The viscosity is the fluid resistance to shear or flow and is a measure of the adhesive/cohesive or frictional fluid property. CNT based nanofluids have more viscosity which absorbs the heat developed by the grinding process that leads to improved surface finish and tool life.

Grinding process

Grinding with super abrasive wheels is an excellent way to produce ultra precision surface finish. However, super abrasive diamond grits need higher bonding strength while grinding, which metal-bonded grinding wheels can offer. Truing and dressing of the wheels are major problems and they tend to glaze because of wheel loading. Electrolytic in process dressing (ELID) is the most suitable process for dressing metal-bonded grinding wheels during the grinding process.

The basic ELID system consists of a power supply, a metal-bonded grinding wheel and an electrode. The electrode used could be 1/4 or 1/6 of the perimeter of the grinding wheel. Normally, copper or graphite is selected as the electrode material. The gap between the electrode and the grinding wheel is adjusted up to 0.1 to 0.3 mm. Proper gaps and coolant flow rate should be selected for efficient in-process dressing. Normally, arc-shaped electrodes are used in this type of ELID and the wheel used is either straight or cup type. Figure 2 shows the mechanism of ELID grinding of metal-bonded diamond wheel.

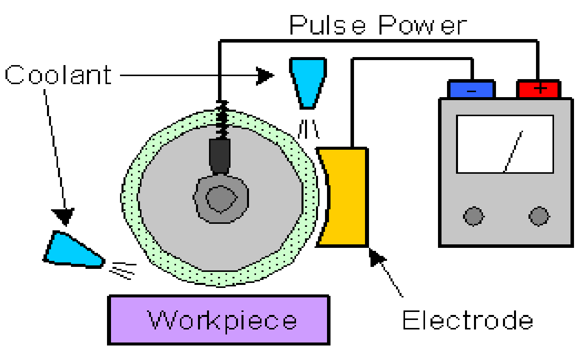

Figure 2. The mechanism of ELID grinding.

Surface grinding operation was performed on the work piece which is made up of D2 tool steel. This operation was performed on four samples. (First 2 samples were done without CNT nanofluids, second 2 samples with CNT nanofluids).

Figure 3. Experimental setup of grinding process.

The tool and cutter grinding process ELID setup (Fig. 3) is attached with negative terminal connected with electrode and positive terminal connected with grinding wheel and pulse current is generated from Pulse generator and maintained by CRO. The metal bonded diamond grinding wheel is used and AISI D2 tool steel is used as work piece material.

Table 6. Machine specifications.

Name of the Machine	Tool and Cutter Grinder
Make	PHI
Model	PTC-27
Longitudinal Travel	250 mm
Cross Travel	175 mm
T-Width Slot	10 mm
Table Dimension	500 x 113 mm
Grinding Wheel Size	150 x 13 x 31.75 Bore mm
Grinding Wheel	CBN Diamond bonded
Main Motor	0.5 hp, 3 Φ, 50 Hz, 440 V, 280 rpm

The flash point is increased when carbon nano tube is mixed with cutting fluid uniformly, so the cutting fluid can withstand more heat produced by grinding process. Also due to heat and friction the white layer formation can be controlled by using carbon nano tubes. The high electrical conductivity of carbon nanotube influences the electrolysis of ELID grinding process so that clean and good surface finish on metal takes place. These results show that the surface finish can be improved by using the mixture of SAE20W40 with CNT.

Experimental Details

The specimen was made of the D2 Tool steel, which is widely used in the mold and dies industry. The raw materials were machined using lathe process. The specimens were made to a size of diameter 20 mm and length 100 mm. These specimens were heated to 1030°C at a heating rate of 200°C/min in muffle furnace. It was kept at that temperature for one hour and then quenched. After quenching, the specimens were tempered at 520°C for two hours and then air cooled. The hardness of the specimen was increased to 57 HRC. The SAE20W40 oil was mixed in a proportion of 2 gram of SWCNT for 1 litre of oil and this was used as cutting fluid. The properties of the cutting fluid with and without nanotube are given in Table 5. The uniform mixture of carbon nano tube with cutting fluid is obtained by stir techniques. The machining was carried out at 2000 rpm and 1500 rpm speed using ELID technique. After machining the surface roughness of AISI D2 tool steel material was measured by AFM for with and without nanofluids.

Table 7. AFM specifications.

Name of the Measuring Equipment	Atomic Force Microsocpe
Type	Contact
Tip Type	Cantilever –Si_3N_4
Tip Diameter	0.2 to 0.5 nm
Tip Length	125 µm
Tip Thickness	4 µm
Make	NanoTech Electronica
Image Browser	WSxM 4.0 Develop
Tip Coating	Gold
Resonance Frequency	350 kHz

The AFM measurement tool tip is made of Si3N4, with a cantilever of lower stiffness, making it more sensitive. The topographic properties of the machined surface are then measured. The AFM is equipped with a photo detector to pick up a laser beam reflected from the cantilever. The AFM instrument (SPM, Nanotech Electronica, SRM University, Chennai, India) is shown in Fig. 4.

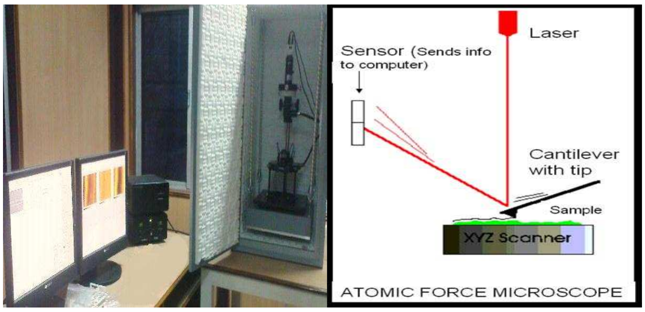

Figure 4. Measurement setup (left) and schematic diagram (right) of AFM.

AFM is a device used to view the object to the nanometer scale with the aid of atomic forces. This is used to obtain 3D topological view of the surface. Work piece is placed on the scanner. A cantilever beam is coated with gold of 0.8 nm having a silicon tip of 0.2 to 0.5 nm diameter and it is made to move over the top surface of the work piece. Contact type mode is used to measure the work piece surface.

Results and Discussions

Surface morphology

Surface morphology plays an important part in understanding the nature of machined surfaces. Before the l990s, the surface textures of specimen were evaluated mainly with a contact stylus profiler. This instrument has various limitations including a large stylus radius, a large contact force and low magnification in the plane, which will result in surface damage of the sample (Guu, Y.H). Morphology images are now obtained by Atomic force microscope for with and without using single wall carbon nano tube based cutting fluids in grinding process of AISI D2 tool steel materials. The image (Fig. 5a,c) shows that without using carbon nano tube based nanofluids a non uniform surface image is obtained and surface smoothness of 3.42 nm and 3.14 nm are obtained and the machined surface exhibited a deeper crack or void and more pronounced defects. The image (Fig. 5b,d) shows that, by using carbon nano tube based nanofluid, a uniform surface image is obtained and surface smoothness of 3.06 nm and 1.67 nm are obtained and the surface characteristics have minor hillocks and valleys.

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 micro geometry characteristics include machining damages such as ridge-rich surfaces, micro-voids, and micro-cracks. The ridge rich surface was formed by the material melted during the grinding 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 formation of micro-voids 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 micro-cracks 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 in carbon nano tube is because it has excellent thermal and mechanical property.

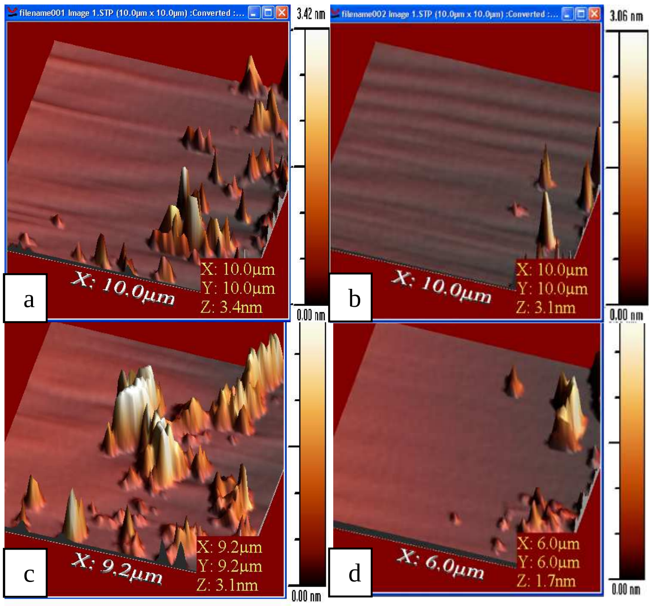

Figure 5. AFM surface morphology of different grinding conditions without carbon nano tube based nanofluids (a and c) (left) and with nano fluids (b and d) (right).

Surface Roughness of Carbon Nano Tube Based Machined Surface Using AFM

Surface roughness is fundamental to several physical properties and physical phenomena of a solid surface. By using the Atomic Force Microscope, it is possible to determine the surface topography with a spatial resolution which is measured on the AISI D2 tool steel using carbon nano tube based nanofluids on the machined surface and compared without using nanofluids. Images of with and without nanofluids of grinding process are shown in Figs. 6-9. The average surface roughness, Ra, of the machined specimen was calculated from the AFM surface topographic data in a scanning area of 10 µm x 10 µm by Eq. (6):

$$Ra = \sum_{n=1}^{n} (Z_n - Z) / N \qquad (1)$$

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

where Z_n denotes the height of a surface point, N is the number of points in an analyzed area. R_a is used to find out the surface finish of rough surface while R_{Rms} is used to find the surface finish of smooth surface. Mean height can be calculated from

$$Z = 1/N \sum_{n=1}^{n} Z_n \qquad (3)$$

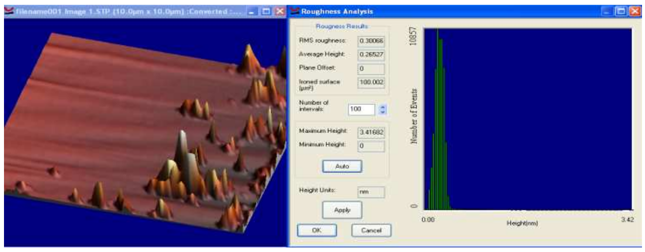

Figure 6. AFM images of surface roughness without carbon nano tube based nanofluids, speed = 2000 Rpm, Ra = 0.30066 µm.

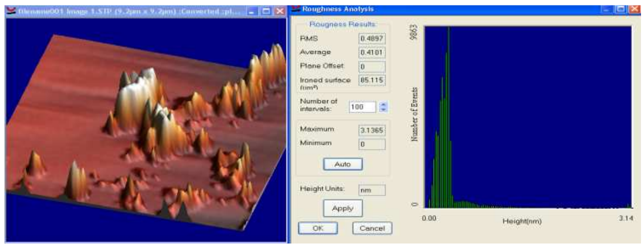

Figure 7. AFM images of surface roughness without carbon nano tube based nanofluids, speed = 1500 Rpm, Ra = 0.4897 µm.

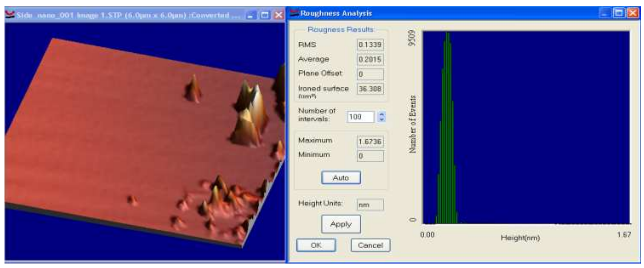

Figure 8. AFM images of surface roughness with carbon nano tube based nanofluids, speed = 2000 Rpm, Ra = 0.1339 µm.

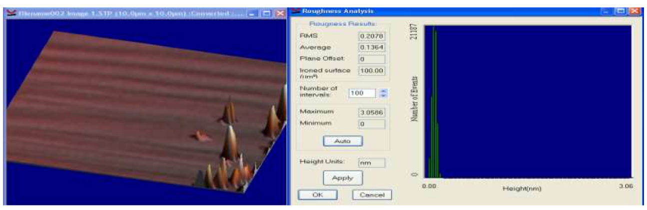

Figure 9. AFM images of surface roughness with carbon nano tube based nanofluids, speed = 1500 Rpm, Ra = 0.2078 µm.

The surface roughness was measured by tracing the AFM Si tip over the D2 tool steel work piece. The micro structure size length and Z depth over a few nanometer was measured. The hillocks and valleys shown in Figs. 6-9 are captured using AFM. The numbers of intervals are taken as 100. The 3D image shows the maximum and minimum height of surface profile. The most common method of measuring the surface roughness is Root mean square (Rms) method. The surface roughness of AISI D2 tool steel material with carbon nano tube based nanofluids for the speed of 2000 rpm is 0.30066 μm and 1500 rpm 0.4897 μm is obtained and without carbon nano tube based nanofluids for the speed of 2000 rpm is 0.1339 μm and 1500 rpm 0.2078 μm is obtained. The results show that grinding with optimum speed using carbon nano tube based nanofluids gives good surface finish.

Power Spectrum Density (PSD) Method

The surface profiles can be analyzed in wavelength–amplitude domain based on discrete Fourier transform, especially using the power spectra density (PSD) method. Power spectrum method is based on fractional Brownian motion. In this method, each image line is Fourier transformed, the power spectrum is evaluated and then all these power spectra are averaged. Fractal Dimension (FD) is computed from the slope. The Fourier method is ideal for the self-affine surfaces analysis and for simulation. Unfortunately, this method is slow and requires gridded data. The radial calculation scheme works only for isotropic surfaces.

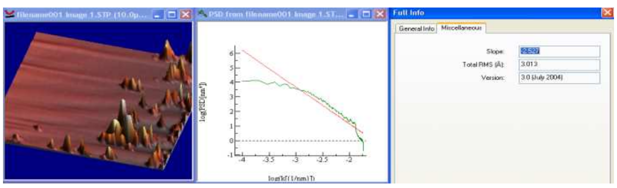

Figure 10. AFM images of PSD method base surface roughness without carbon nano tube based nanofluids, speed = 2000 Rpm, Rms = 3.013 Å.

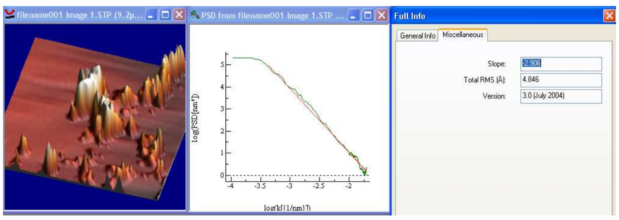

Figure 11. AFM images of PSD method based surface roughness without carbon nano tube based nanofluids, speed = 1500 Rpm, Rms = 4.846 Å.

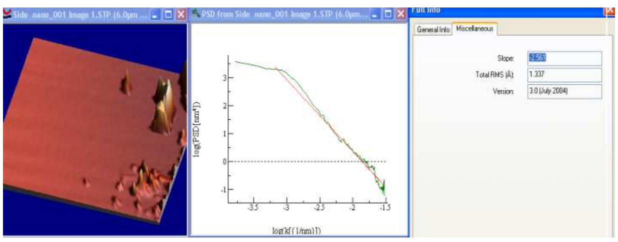

Figure 12. AFM images of PSD method based surface roughness with carbon nano tube based nanofluids, speed = 2000 Rpm, Rms = 1.337 Å.

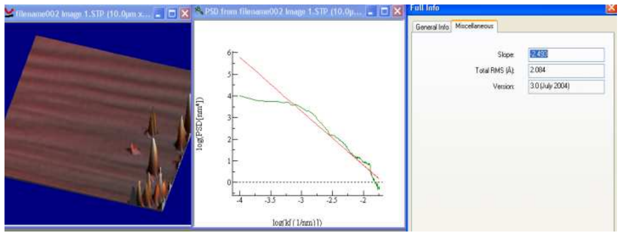

Figure 13. AFM images of PSD method based surface roughness with carbon nano tube based nanofluids, speed = 1500 Rpm, Rms = 2.084 Å.

For the grinded AISI D2 tool steel with CNT based and without CNT based cutting fluid the surface roughness was found using Root mean square (Rms) as shown in Figs. 10-13. All machined surfaces suggesting the existence of fractal components in the surface-topographies. Furthermore, it can be seen from this figure that the slopes of carbon nano tube based machined surface are smaller than without carbon nano tubes, which suggests that there exist larger lateral structures (grain size) on the surfaces. With using nanofluids, the slopes decrease from 2.906 to 2.493 and the fractal dimensions decrease from 1.153 to 0.9414. Conventionally in quantitative analyses of AFM images, the RMS roughness has been used to describe the surface morphology. Nano fluids based machining increased the surface finish, and also slope and fractal dimension value are decreased, which means good surface finish can be obtained using nano materials.

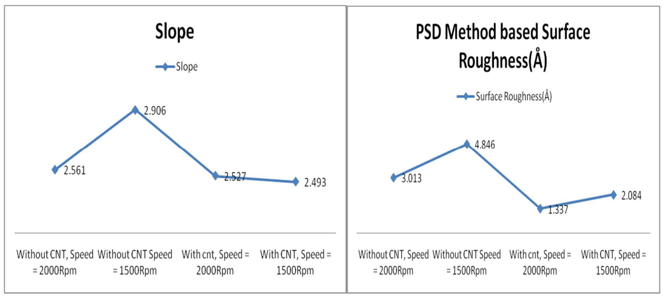

Figure 14. Slope and PSD method based surface roughness comparison for different machining conditions.

Figure 14 shows the consolidated values for PSD method based surface roughness and slope of the machined surface. The surface roughness and slope values show that there is decrease in height of hillocks when carbon nano tube is used as cutting fluid. This indicates that the surface finish is improved.

Fractal Dimensional (FD) of Carbon Nano Tube Based Machined Surface Using AFM

Fractal dimensional analyses are used to describe the intricacy of the morphology of the carbon nano tube used while machining. WSxM 4.0 develop 10.2-Image browser software is used to analyse the AFM image for with and without carbon nano tube based nanofluid machining surface in grinding process. The software calculates the analysis using the power spectrum density method. The curves with fractal characteristics can be described by

$$N(r) = r^{-D} \tag{4}$$

$$\text{That is } L(r) = N(r) = r^{2-D} \tag{5}$$

In this way D can be obtained by

$$D = \log N(r)/ \log(1/r) \quad (6)$$

$$D = -\log N(r)/ \log(r) \quad (7)$$

where:
r = Length of the measurement scale;
N(r) = Number of measurements taken;
L(r) = Length of the corresponding curve;
D = Dimension of fractal.

AFM image analysis is often brought to the evaluation of fractal dimension (D) which is summarized by the three steps:

1. Measure the quantities of the object using various step sizes.
2. Plot log (measured quantities) versus log (step sizes) and fit a least-square regression line through the data points.
3. Estimate FD as the slope of the regression line.

Table 8. PSD method based surface roughness.

Different Machining Conditions	Slope	PSD Method Based Surface Roughness(Å)
Without using carbon nano tube as nanofluids, Speed = 2000 Rpm	2.561	3.013
Without using carbon nano tube as nanofluids, Speed = 1500 Rpm	2.906	4.846
With using carbon nano tube as nanofluids, Speed = 2000 Rpm	2.527	1.337
With using carbon nano tube as nanofluids, Speed = 1500 Rpm	2.493	2.084

The fractal dimensions of the grinding machined surface with and without using nanofluids are evaluated from the slope of the plot of log P versus log(S), shown in Figs. 15, 17 and Figs. 16, 18.

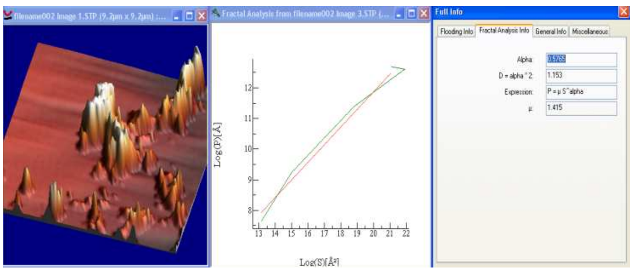

Figure 15. Fractal dimensional analysis of without using carbon nano tube nanofluids, speed = 2000Rpm, D = 0.9466.

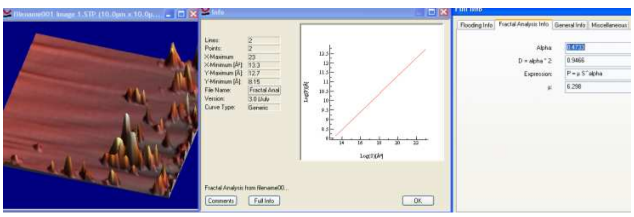

Figure 16. Fractal dimensional analysis of without using carbon nano tube nanofluids, speed = 1500 Rpm, D = 1.153.

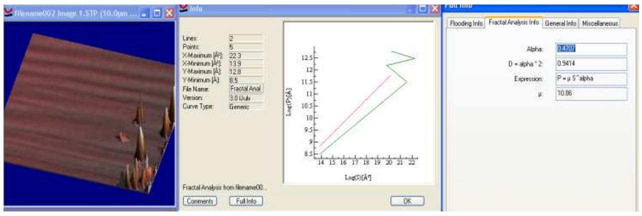

Figure 17. Fractal dimensional analysis of with using carbon nano tube nanofluids, speed = 2000 Rpm, D = 0.8583.

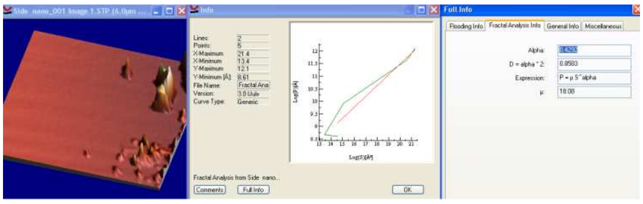

Figure 18. Fractal dimensional analysis of with using carbon nano tube nanofluids, speed = 1500 Rpm, D = 0.9414.

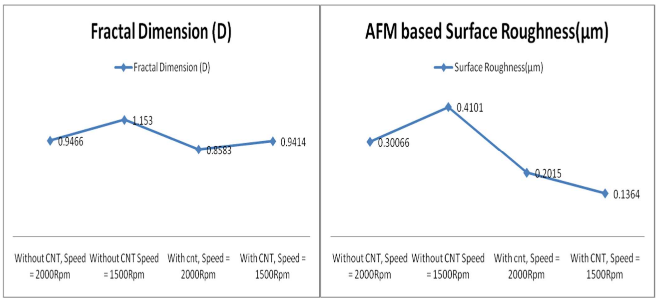

Figure 19. Fractal dimension and surface roughness analysis for different machining conditions.

Table 9. Comparison of fractal dimensions with different machining conditions.

Different Machining Conditions	Fractal Dimension (D)	Surface Roughness (µm)
Without using carbon nano tube as nanofluids, Speed = 2000 Rpm	0.9466	0.30066
Without using carbon nano tube as nanofluids, Speed = 1500 Rpm	1.1530	0.4897
With using carbon nano tube as nanofluids, Speed = 2000 Rpm	0.8583	0.1339
With using carbon nano tube as nanofluids, Speed = 1500 Rpm	0.9414	0.2078

Calculation algorithm for the fractal dimension D was basically introduced by Sevcik (1998) and further it was applied by Grzesik and Brol (2009) for roughness analysis purposes. The fractal dimensional value D is an index of the complicated morphological surface. D describes the total profile complexity and takes into account the changes of the normalized profile length as a function of the observation scale. If the D value is between 1 and 2, then the analyzed profiles have some fractal properties. Qualitatively, if the fractal dimension is higher, it suggests that the profile complexity is more pronounced. Analysis with the application of D dimension to the examination of differently machined profiles (Figs. 15-18) shows that the most complex profiles were obtained without using carbon nano tube nanofluids with the speed of 1500 rpm (D = 1.153). On the other hand, the lowest D values were reached after machining with carbon nano tube nanofluids with the speed of 2000 rpm high speed machining (D = 0.8583). The surface smoothness is increased by using carbon nano tube based nanofluids by 18.35% and compared to without using nanofluids in grinding process by 9.3%.

Conclusion

The surface morphology of different machined surface using carbon nano tube based nanofluids was studied by fractal dimension analysis and roughness characterization was also done. The concept of fractal dimension was used to explore the surface morphologies of nanofluids based grinding surface. The fractal dimension changed according to the smoothness of the machined surface. The fractal dimension D and the roughness Rms may decrease due to carbon nano tube based nanofluid used in machining process. AFM is a powerful tool to measure 3D roughness parameters conveniently. The height roughness Ra using AFM and Rms using PSD Method not only reflect the height fluctuation of a nano fluid based machined surface, but also the changes according to the material of the nano machined surface. AISI D2 tool steel material machined under nano fluid with an optimum speed of grinding wheel causes a smooth and even surface. However, without using nano fluid machined under the same speed, Ra and Rms values of the surface improved and the fractal dimension decreased.

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