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Modelling of Material Removal Rate in Electro Discharge Machining of Nonconductive ZrO_2 Ceramic with Kerosene and EDM Oil Dielectric Fluid

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ABSTRACT

In this study electro discharge machining (EDM), a noncontact material removing process, is used for structuring nonconductive ZrO_2 ceramic. Adhesive copper foil is applied on the workpiece surface as assisting electrode to initiate the sparks. Experiments are conducted according to Taguchi approach by varying the peak current (I_p), pulse-on time (T_{on}), pulse-off time (T_{off}) and gap voltage (V_g) for two different dielectric fluids kerosene and EDM oil. The optimized parametric conditions are determined for higher MRR by the analysis of variances (ANOVA) and signal to noise (S/N) ratio. The results showed that I_p is the most significant parameter of MRR for both the dielectric fluids. It is also shown that EDM of ZrO_2 with kerosene dielectric gives about 1.6 times more MRR compared to EDM oil. However, inferior surface finish is observed in SEM investigation when kerosene dielectric is used. Optimum values of I_p, T_{on}, T_{off} and V_g are identified for EDM of ZrO_2 with kerosene dielectric.

Keywords: *Nonconductive ceramic; Electro discharge machining; Assisting electrode; Kerosene.*

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Introduction

The use of nonconductive ceramics in industrial and engineering applications is increasing rapidly due to its extraordinary properties such as high hardness, low thermal conductivity, stability in high temperature, resistance to oxidation and wear. Cutting tools, self-lubricating bearings, turbine blades, internal combustion engines, heat exchangers, ballistic armour, ceramic composite automotive brakes, diesel particulate filters, a wide variety of prosthetic products, piezo-ceramic sensors are some examples of nonconductive ceramic parts [1]. Micro parts made of nonconductive ceramics have demands in biomedical field. Examples include femoral heads and acetabular cups for total hip replacement, dental implants and restorations, bone fillers and scaffolds for tissue engineering [2, 3]. But the machining of nonconductive ceramics is difficult for their high hardness and brittleness by the traditional machining techniques [4]. Thus, nonconventional techniques such as laser beam machining (LBM), ultrasonic machining (UM) can be used for producing new parts and components from nonconductive ceramics. Due to lower material removal rate (*MRR*) and incapability of producing three dimensional products using LBM and UM, recently electro discharge machining (EDM) has been applied for processing of nonconductive ceramics with assisting electrode (AE) technique [5]. Basically, EDM is a process of machining conductive materials. So, applying a conductive metallic layer on the ceramic workpiece, necessary conductivity for the spark is created. The energy produced by spark is used to machine the nonconductive ceramic material by means of melting, vaporization and spalling [6-9]. Assisting electrode can be continuously fed or firmly bonded on the ceramic surface [10]. In continuously feeding method, conductive metallic foil or sheet is fed to the machining area during the pulse on time and fed back just after the spark occurrence. In this method any dielectric fluid can be used and it is suitable for milling of large area. ED milling of Al_3O_2 is investigated using water based emulsion dielectric fluid and it shows that higher *MRR* with good surface quality can be obtained using suitable emulsion concentration. It is also observed that *MRR* increases in higher flow velocity of fluid with negligible change in surface roughness [11]. For machining holes, cavities or particular shapes on nonconductive ceramics, continuous AE fed method is difficult to apply. Therefore, AE is firmly adhered on the ceramic surface before the machining and both the ceramic workpiece and tool electrode are submerged in carbonic dielectric. Adhesive copper or aluminium foil, coating of graphite or carbon, silver varnish and copper, silver or gold sputtered on the workpiece surface can be used as AE [5-12].

Dielectric is characterized as an electrical insulator but polarized when it is placed in an electric field. During discharges, dielectric fluid is disassociated to positive and negative charges shifting into the electrodes.

So, dielectric fluid should have high strength, ability of quick recovery after breakdown, effective quenching and flushing ability and good degree of fluidity. Hydrocarbon compounds or deionised water are used as dielectric in EDM [13]. Sometimes, metallic powders are mixed with dielectrics as catalyst to enhance its properties, to increase the discharge stability and to improve the surface quality [14]. Carbonic dielectric plays the most important role in EDM of nonconductive ceramics when AE is fixed on the workpiece. Initial sparks occur between the tool electrode and AE. After the finishing of metallic AE, at higher temperature (1000-2000°C) and in absence of oxygen the carbonic dielectric breaks into carbon particles creating a more complex pyrolytic carbon on ceramic surface which has sufficient electrical conductivity for spark to progress the process. [6]. At very high temperature, ZrO_2 may also react with C and creates conductive ZrC temporarily [3]. Due to the effective and continual creation of conductive layer, EDM of nonconductive ceramics has been successfully done. Kerosene is widely used dielectric in EDM of nonconductive ceramics because of its capability of producing effective carbonic layer. But, it produces toxic gases which are harmful to the human skins and eyes [11]. EDM oils are highly refined carbonic dielectrics in which some additives are mixed. Harmful gases are not produced by EDM oil during machining. Thus, EDM oils are widely used in EDM of conductive materials. It also can be used for EDM of nonconductive materials. Effect of two EDM oils ionoplus and IME63 are investigated in micro-EDM of ZrO_2 and different material removal rates are estimated [10]. But, to optimize the process parameters using different carbonic dielectrics in EDM of ZrO_2 detailed study is not conducted yet. The empirical modelling of the process is an effective way of selecting the best parameters to get optimum outputs and to increase production rate significantly. Precise removal of material (i.e. *MRR*) is essential to fabricate intricate product [15]. This study aims to investigate the effect of input parameters on the continuous machining of nonconductive ceramics using kerosene and EDM oil dielectric fluids: and to optimize parameters for *MRR* using Taguchi method in EDM of ZrO_2 ceramic.

Experimental

The schematic diagram of the experimental setup for EDM of nonconductive ceramic with the AE is shown in Figure 1. The experiment has been conducted using NC die-sinking EDM machine (EX22, Mitsubishi, Japan). In this study, 92% pure ZrO_2 ceramic plate (20 mm x 15 mm x 10 mm) is used as workpiece material. The properties of the workpiece material are listed in Table 1. The copper tool electrode of square x-section (3 mm x 3 mm) is used for both the dielectrics. The workpiece and the tool electrode were cleaned by acetone before machining. Since the workpiece is electrically nonconductive, its surface is covered by an adhesive copper foil to occur the sparks. After the removal of this external layer, a new conductive layer is created instantaneously on the machined surface using cracked carbon combined with the debris of tool electrode material.

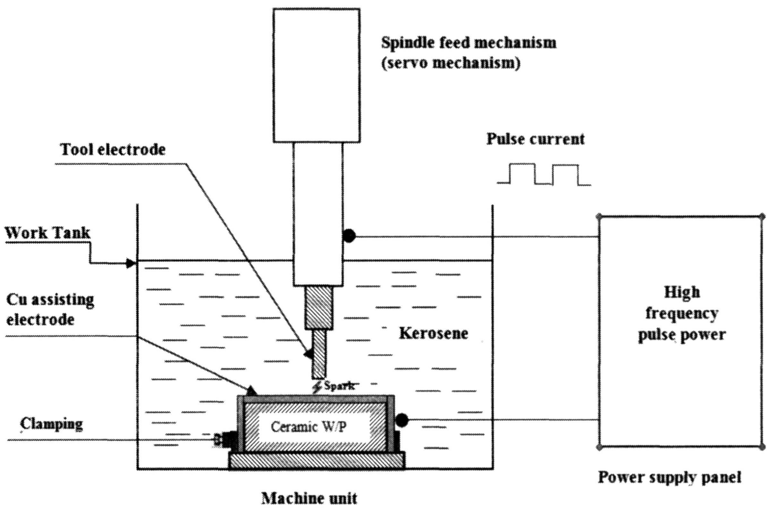

Figure 1: Schematic diagram of the experimental setup [15]

Table 1: Physical properties of ZrO_2 [15]

Property [unit]	Value
Hardness [Hv]	1270
Melting temperature [°C]	2720
Specific heat capacity [J/Kg°C]	540
Specific gravity [Kg/m^3]	610
Electrical resistivity [Ω-cm]	10^{10}

This layer acts further as an AE. Cu foil has excellent electrical conductivity and easy to remove after machining without any damage. After machining, the workpiece is cleaned again by acetone before weighing. Electronic balance (B204-S Mettler Toledo, Switzerland) is used to take the weight of workpiece before and after machining. The machining parameters used in the experiments are listed in the Table 2. Based on the observations of our previous investigation, in this study values of four electrical parameters I_p, T_{on}, T_{off} and V_g are selected keeping other parameters constant [15]. Commercial grade kerosene and mineral based EDM oil (Arox, USA) are used for optimization of *MRR* between two different dielectrics.

Table 2: Machining conditions

Conditions	Description/ values
Workpiece	ZrO_2
Tool electrode	Cu
Toll electrode polarity	- ve
Assisting electrode (AE)	Adhesive copper foil
AE thickness (μm)	60
Dielectric fluid	Kerosene (K), EDM oil (E)
Peak current, I_p (A)	1.3, 1.4, 1.5
Pulse-on time, T_{on} (μs)	10, 11, 12
Pulse-off time, T_{off} (μs)	10, 11, 12
Gap voltage, V_g (V)	10, 11, 12
Jump distance (mm)	0.6
Jump up time (s)	0.25

In this study, L18 orthogonal array (1 factor x 2 levels + 4 factors x 3 levels) based on Taguchi approach is used for design of experiment (DOE). Optimization is carried by analysis of variances (ANOVA) and signal to noise (S/N) ratio using Design Expert version 6.0.8. *S/N* ratio is expressed by Equation 1.

$$S/N = -10\mathrm{Log}_{10}\,(\mathrm{MSD}) \qquad (1)$$

Where, *MSD* = mean squared deviation from the target value of the quality characteristics. In the engineering application, the value of *S/N* ratio is intended to be larger for larger the better. Hence, the value of *MSD* should be smaller. For smaller *MSD*, Equation 2 is used.

$$\text{MSD} = \frac{\left(\frac{1}{y_1^2} + \frac{1}{y_2^2} + \frac{1}{y_3^2} + \ldots + \frac{1}{y_n^2}\right)}{n} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \tag{2}$$

Where y_1, y_2 .... = results of individual experiments, n = number of repetitions (15).

Results and Discussions

ZrO_2 ceramic workpiece machined by EDM is shown in Figure 2 and SEM image of machined surface is shown in Figure 3. Cavities of depth 2 mm are created on the ZrO_2 workpiece.

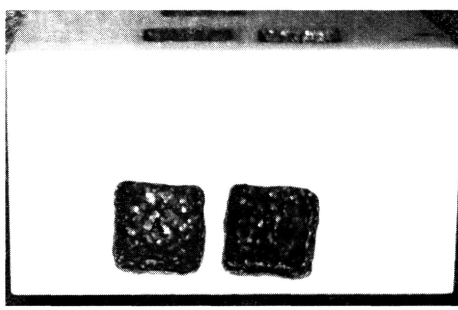

Figure 2: Three millimetres square sized cavities on ZrO_2 ceramic workpiece machined by EDM using adhesive Cu foil as AE and Cu tool electrode with -ve polarity in (A) kerosene (B) EDM oil dielectric

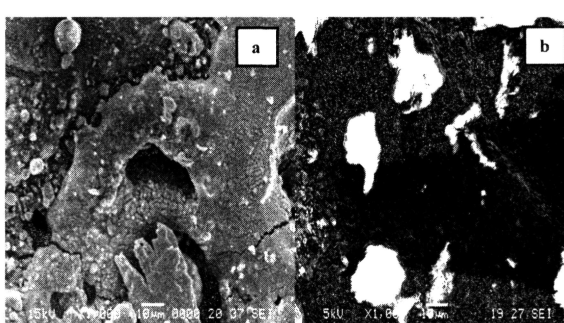

Figure 3: Magnified SEM image of EDMed ZrO_2 (Figure 2) with (a) kerosene (window A) showing rougher surface (b) EDM oil (window B)

It is observed that the machining continued although the adhesive Cu foil is finished. Thus, carbonic layer on the machined surface is produced continually from carbonic dielectric fluid.

Table 3 shows the *MRR* and *S/N* ratios in different EDM conditions on the ZrO_2 ceramics according to L18 orthogonal array based on the Taguchi approach. F test of ANOVA is given in Table 4 to show the significant

Table 3: L18 Orthogonal array of parameters with *MRR* and *S/N* ratios

Run No	Factors					Response	S/N ratio
	A	B	C	D	E	*MRR* (mm³/min)	
	Dielectric fluid	Peak current, I_p (A)	Pulse-on time, T_{on} (μs)	Pulse-off time, T_{off} (μs)	Voltage, V (V)		
1	Kerosene	1.3	10	12	10	0.08	-21.94
2	Kerosene	1.3	11	10	11	0.12	-18.42
3	Kerosene	1.3	12	11	12	0.21	-13.56
4	Kerosene	1.4	10	10	12	0.12	-18.42
5	Kerosene	1.4	11	11	10	0.25	-12.04
6	Kerosene	1.4	12	12	11	0.39	-8.18
7	Kerosene	1.5	10	10	10	0.51	-5.85
8	Kerosene	1.5	11	11	11	0.55	-5.19
9	Kerosene	1.5	12	12	12	0.7	-3.10
10	EDM oil	1.3	10	11	12	0.06	-24.44
11	EDM oil	1.3	11	12	10	0.18	-14.89
12	EDM oil	1.3	12	10	11	0.13	-17.72
13	EDM oil	1.4	10	12	11	0.1	-20.00
14	EDM oil	1.4	11	10	12	0.16	-15.92
15	EDM oil	1.4	12	11	10	0.3	-10.46
16	EDM oil	1.5	10	11	11	0.25	-12.04
17	EDM oil	1.5	11	12	12	0.31	-10.17
18	EDM oil	1.5	12	10	10	0.32	-9.90

parameters associated with each machining condition. The levels of parameters to optimize *MRR* are also determined from *S/N* ratios of the response. In this study, confidence level is considered to be 95%. Values of "Prob>F" less than 0.05 indicate that model terms are statistically significant. In other word, the probability of success is 95% or more and the model terms have a significant effect on the *MRR*. Table 4 shows that "Prob>F" of model is <0.0001 which means there is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. The "Pred R-Squared" of 0.83 is close to the "Adj R-Squared" of 0.93 which is expected for good estimation. That means this model can be used to navigate design space.

The average table is used to determine the rank of the importance relative to the parameters each other. In this study, there are five variables involved which are dielectric fluids, peak current (I_p), pulse-on time (T_{on}), pulse-off time (T_{off}) and gap voltage (V). For each level of variables, values of S/N ratio are calculated as given in Table 5. It shows that I_p has the highest rank among all variables followed by T_{on} with the rank 2. V is ranking 4 whereas the T_{off} has the least effect in *MRR*. The rank of dielectrics is 3. It can be concluded that dielectric fluids are very important for material removal in EDM of nonconductive ZrO_2 ceramic. The formation of carbonic layer on the EDMed ceramic workpiece depends upon the carbon-carbon bonds of dielectric. Percentage of alkenes in kerosene is higher than EDM oil. Thus, kerosene can easily be disassociated to free carbon black which rapidly generates the carbonic layer. F-value of 39.06 (greater than the critical value of 4.84 based on 1 and 11 degrees of freedom and a 0.05 significance level) in ANOVA result indicates that interaction effect of I_p and T_{on} on *MRR* is highly significant. F-values of interaction effect of I_p and T_{off} and I_p and V are 12.30 and 12.94 respectively. That means, interaction effect of I_p and T_{on} is more significant than the interaction effect of I_p and T_{off} or I_p and V. From the contour plot as shown in Figure 4, it is observed that *MRR* increases with increase of both I_p and T_{on} in EDM of ZrO_2. Higher current and higher pulse-on time combinedly produce higher thermal energy for longer duration. The intense temperature difference results high thermal stresses on the ceramic surface. At the beginning, compressive stress dominates because of the resistance exerted from the less temperature zone of the material. At a certain stage the tensile stress dominates and materials are removed from the zones where thermal stresses exceed the yield strength of the materials. It also has been proved that the stress is proportional to the peak current [7, 16-17]. The discharge force increases with an increase in the peak current. Thus, the material removal increases with an increase in the current supplied.

Table 4: ANOVA for response surface reduced 2FI model (reduced)

Source	Sum of squares	DF	Mean square	F value	Prob > F
Model	272.62	6	45.44	40.97	< 0.0001
A	11.12	1	11.12	10.03	0.009
B	133.01	1	133.01	119.94	< 0.0001
C	91.02	1	91.02	82.08	< 0.0001
BC	43.31	1	43.31	39.06	< 0.0001
BD	13.64	1	13.64	12.30	0.0049
BE	14.35	1	14.35	12.94	0.0042
Residual	12.20	11	1.11		
Cor Total	284.82	17			

Std. Dev.	1.05	R-Squared	0.96
Mean	5.86	Adj R-squared	0.93
C.V.	17.96	Pred R-squared	0.83
PRESS	48.43	Adeq precision	23.61

Table 5: S/N ratio values for *MRR* by factor level

Level	Dielectric fluids	Peak current, I_p (A)	Pulse-on time, T_{on} (μs)	Pulse-off time, T_{off} (μs)	Voltage, V (V)
1	-11.86	-7.71	-10.49	-13.05	-14.27
2	-15.06	-14.17	-12.77	-12.96	-13.59
3		-18.50	-17.12	-14.37	-12.51
Delta (Max-Min)	3.20	10.79	6.63	1.41	1.76
Rank	3	1	2	5	4

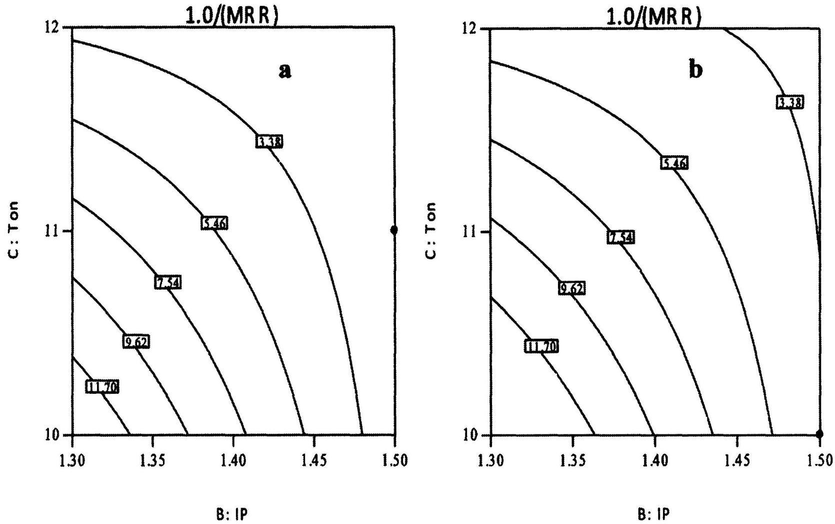

Figure 4: Contour plot of *MRR* in EDM of ZrO_2 with (a) kerosene at T_{off} = 11, V = 11 (b) EDM oil at T_{off} = 11, V = 11

An average *MRR* of 0.32 mm^3/min is obtained in EDM of ZrO_2 when kerosene dielectric is used whereas the average *MRR* with EDM oil is found to be 0.20 mm^3/min. That means *MRR* in kerosene dielectric is about 1.6 times more than EDM oil. But the SEM image of the machined surface indicates that EDM with kerosene dielectric causes the inferior surface quality. Therefore, for better surface finish the EDM oil would be used.

Optimization of parameters

The objective of optimization in this study is to obtain the highest *MRR* in EDM of ZrO_2 that indicate the best combinations of I_p, T_{on}, T_{off}, V_g and dielectric fluids. According to S/N ratios response graph of *MRR* as shown in Figure 5, EDM of ZrO_2 with kerosene dielectric gives highest *MRR* than machining with EDM oil. The optimum combination of process parameters are obtained based on Figure 5 which is given in Table 6. In our previous study, the optimum parameters for *MRR* in EDM of ZrO_2 with kerosene dielectric were found to be 1.5 A I_p, 12 µs T_{on}, 12 µs T_{off} and 10 V V_g [15]. The different T_{off} values is obtained in two studies perhaps due to the experimental conditions or set up error.

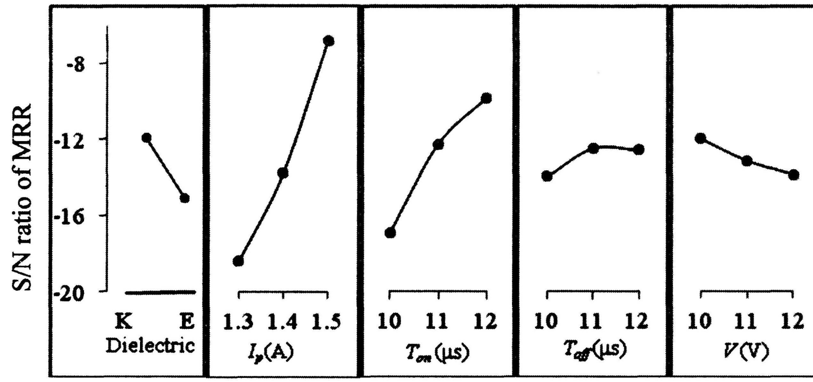

Figure 5: S/N ratios response graph of *MRR* by factor level

Table 6: Optimum result of process parameters

No.	Dielectric fluid	Peak current I_p (A)	Pulse-on time T_{on} (μs)	Pulse-off time T_{off} (μs)	Voltage, V (V)
1	kerosene	1.5	12	11	10

Conclusions

Nonconductive ZrO_2 ceramic is machined by die-sinking EDM applying assisting electrode. Adhesive copper foil assisting electrode and copper tool electrode with –ve polarity is used for experimentation. The effect of input parameters such as peak current, pulse-on time, pulse-off time and gap voltage on *MRR* are investigated using kerosene and EDM oil dielectric fluid. The parameters are optimized by ANOVA and S/N ratio analysis according to Taguchi approach. Following specific conclusions can be drawn from this study.

1. ZrO_2 can be machined by EDM using carbonic dielectrics kerosene or EDM oil. Both the dielectrics produce carbonic layer on the ceramic surface during the process.
2. Average *MRR* in kerosene dielectric is about 1.6 times more than EDM oil with 0.32 and 0.20 mm³/min respectively. But the SEM image of the machined surface indicates that kerosene gives the inferior surface. EDM oil is more environment friendly due to the generation of less harmful gases. Therefore, the EDM oil would be used to obtain better surface finish and to protect the environment.

3. The optimized values for maximum MRR are found to be 1.5 A peak current, 12 μs pulse-on time, 11 μs pulse-off time and 10 V gap voltage respectively with kerosene dielectric.
4. Peak current is the most significant parameter in EDM of ZrO_2 either in kerosene or EDM oil dielectric.

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JOURNAL OF MECHANICAL ENGINEERING (JMechE)

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Contributions are invited from various disciplines that are allied to mechanical engineering. The contributions should be based on original research works. All papers submitted to JMechE are subjected to a reviewing process through a worldwide network of specialized and competent referees. To be considered for publication, each paper should have at least two positive referee's assessments.

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ABSTRACT

The first section of the manuscript should be an abstract, where the aims, scope and conclusions of the papers are shortly outlined, normally between 200 and 300 words. TNR-10 italic

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Leave one blank line between the heading and the first line of the text. No indent on the first para after the title; 10 mm indent for the subsequent para. At the end of the section, leave two blank lines before the next section heading. The text should be right and left justified. The recommended font is Times New Roman, 10 points. In 152 mm x 277 mm paper size, the margins are: left and upper: 22 mm each; right: 20 mm, lower: 25 mm.

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$$y = A + Bx + Cx^2 \tag{1}$$

Last point: the references. In the text, the references should be a number within square brackets, e.g. [3], or [4]–[6] or [2, 3]. The references should be listed in numerical order at the end of the paper.

Journal references should include all the surnames of authors and their initials, year of publication in parenthesis, full paper title within quotes, full or abbreviated title of the journal, volume number, issue number and pages.

Examples below show the format for references including books and proceedings

Examples of references:

[1] M. K. Ghosh and A. Nagraj, "Turbulence flow in bearings," Proceedings of the Institution of Mechanical Engineers 218 (1), 61-4 (2004).
[2] H. Coelho and L. M. Pereira, "Automated reasoning in geometry theorem proving with Prolog," J. Automated Reasoning 2 (3), 329-390 (1986).
[3] P. N. Rao, Manufacturing Technology Foundry, Forming and Welding, 2nd ed. (McGraw Hill, Singapore, 2000), pp. 53-68.
[4] Hutchinson, F. David and M. Ahmed, U.S. Patent No. 6,912, 127 (28 June 2005).