Chapter 3
Micro-Electrical Discharge Machining for Machining Micro-Holes

M. S. Nagrale and S. A. Mastud

Abstract It is very challenging to machine high aspect ratio and complex-shaped holes with micro-electrical discharge machining process. Micro-hole drilling plays a vital role in the production of various aspect ratio (length/depth) micro-holes. This work presents an attempt to fabricate high aspect ratio micro-holes using micro-EDM process on a brass workpiece with tungsten carbide electrode. In the present study, the effect of different machining and operating parameters, namely, spindle speed, feed, input voltage and capacitance on the performance of micro-EDM process is studied. The performance of micro-EDM process is evaluated on the basis of material removal rate (MRR) and the tool wear rate (TWR). It was found that there is significant effect of capacitance and feed on the MRR. The MRR improved with increasing values of capacitance and feed rates, while the TWR decreases with increasing discharge energy (capacitance and voltage).

Keywords Micro-electro discharge machining (micro-EDM) · Micro-hole · Taguchi method · Tool wear rate · Material removal rate

3.1 Introduction

Micro-machining technologies are gaining importance to produce micro-parts with enhanced product functionality in a limited space. The selection of the micro-machine technique to fabricate micro-holes depends on various parameters, such as aspect ratio for drilling micro-holes, size and shape of workpiece, workpiece material and electrode material [1]. Many researchers are attracted towards research in micro-drilling due to its increasing need of high aspect ratio holes in the aircraft, aerospace and medical applications. Micro-electro discharge machining (micro-EDM) is one of the popular non-conventional machining techniques for drilling accurate and

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I. Singh et al. (eds.), *Trends in Manufacturing Processes*,
Lecture Notes on Multidisciplinary Industrial Engineering,
https://doi.org/10.1007/978-981-32-9099-0_3

complex-shaped micro-holes. Micro-EDM has a growing popularity due to its advantages, including enhanced precision, low setup cost and significant design freedom [2–6]. Micro-EDM can fabricate a micro-hole using as small as 5 μm diameter holes on any conductive material, irrespective of its melting point and hardness [4]. Apart from these advantages, there are still some limitations in fabrication of micro-EDM to achieve a high aspect ratio holes and tolerances. Jung and Kwon [2] studied the influence of various machining and operating parameters, namely, voltage, capacitance, feed rate and spindle speed on the performance of the micro-EDM process. The Taguchi's grey relational method is used for the analysis of experimental data, and an optimal condition for the high aspect ratio micro-EDM was found. There was an effect of clearance and tool wear on diameter of micro-hole when the same electrode diameter was used. From the grey relation they found that the input voltage and capacitance are the most significant machining parameters. Ferraris et al. [7] proposed an innovative method for the deep-drilling machining using micro-EDM. A tubular electrode coated with low electrically conductive material is used for the reduction of undesirable discharge by suppressing the spark between the tool flank and workpiece. The authors found reduction of tool wear by two-fold with 30% improvement in aspect ratio with coated electrode tool. Lim et al. [3] made three different types of fine electrode for on-machine tool fabrication and assessed their performance in micro-EDM using different parameters. A stationary sacrificial block, rotating sacrificial disk and guided running wire electrodes are used for the preparation of electrode. The authors concluded that a rotating electrode gave best performance for high aspect ratio tool electrode fabrication, and the machining depth is found to be inversely proportional to the feed rate. Yahagi et al. [8] investigated the influence of the high spindle speed on the performance of the micro-drilling EDM. They report that the material removal rate and accuracy can be improved with high rotation of tool electrode; as a result, a much deeper micro-hole with low tool wear rate is possible with high spindle speed.

Numerous researches have reported on the micro-drilling using different electrodes on different workpiece materials [9, 10]. D'urso and Merla [11] demonstrated the influence of different workpiece and electrode material on the micro-EDM process while achieving micro-holes. Four different workpiece materials and three electrode materials with two different shapes were considered to study the performance of micro-EDM. They found an electrode material has a great influence on the TWR than the other parameters. Plaza et al. [12] did an experimental study with the Ti6Al4V alloy material used in aerospace industries and a helical electrode. The influence of helical electrode parameters, namely, helix angle and flute depth, on the process parameters is discussed. Fu et al. [13] did a work to machine a micro-hole with different electrode material under different machining conditions, namely, rough, semi-finish and finish. A relationship between side gap, feed and electrode accuracy was proposed and used to analyse the influence of these parameters on the TWR. The above-mentioned literatures show that there is a lot of work performed to study the influence of various process and machining parameters on the micro-EDM process. But there is a need to investigate and find the optimum process parameters for the setup.

The present study focusses on a detailed investigation of individual and combined effect of process parameters, including input voltage, capacitance, spindle speed and feed rate on a material removal rate and tool wear ratio for a high aspect ratio micro-EDM process. A tungsten carbide electrode was used for fabricating deep holes in brass material. Experiments were planned by using mixed-level Taguchi orthogonal array (OA) design method to analyse the effects of input voltage, capacitance, spindle speed and feed rate on material removal rate (MRR) and tool wear rate (TWR).

3.2 Experimental Setup and Method

3.2.1 Experimental Setup

A Sinergy nano systems Hyper-10 EDM machine is used for the machining of the micro-hole in a set of experiments. Hyper-10 EDM is a table-top multipurpose miniature machine tool that performs multiple machining processes, like micro-turning, micro-milling, micro-grinding and micro-EDM drilling, with high precision. Figure 3.1 shows the conceptual process of micro-EDM to fabricate a high aspect ratio hole. A relaxation-type circuit pulse generator is used to provide a discharge between electrode and workpiece. A hybrid precision original motion controller with original GUI system is installed to control the system with a standard NC code. A computer containing HYPER-10 software is connected to an EDM controller to control the displacement in X, Y and Z direction. The maximum travel range of the machine has its size of $130 \times 75 \times 80$ mm^3 with the resolution of 0.1 μm in X, Y and Z direction, respectively, with a 5 micron position accuracy. A BLDC motor of capacity up to 3000 rpm rotational spindle speed is installed in the spindle system to achieve micro-machining. The length and diameter of electrodes and a fabricated micro-hole are measured by using Mitutoyo-MF series measuring microscope with 5 μm accuracy. Rapid I vision measuring machine system is used to process the images and dimensions of the hole.

3.2.2 Machining Electrode Tool and Workpiece

A high melting point tungsten carbide solid rod of length 40 mm and diameter 500 μm is used for machining micro-holes. A commercially available Total FINA ELF EDM 3 dielectric fluid having high flash point, high auto ignition temperature, low pour point and high dielectric strength has been used. This dielectric fluid flushes the minute chips eroded from the workpiece. It serves as a conducting medium when ionized and conveys the spark. It concentrates the energy to a very narrow region. Brass material of 2.5 mm thickness plate is used as a workpiece. The properties of the workpiece, tool electrode and dielectric fluid are summarized in Tables 3.1 and 3.2.

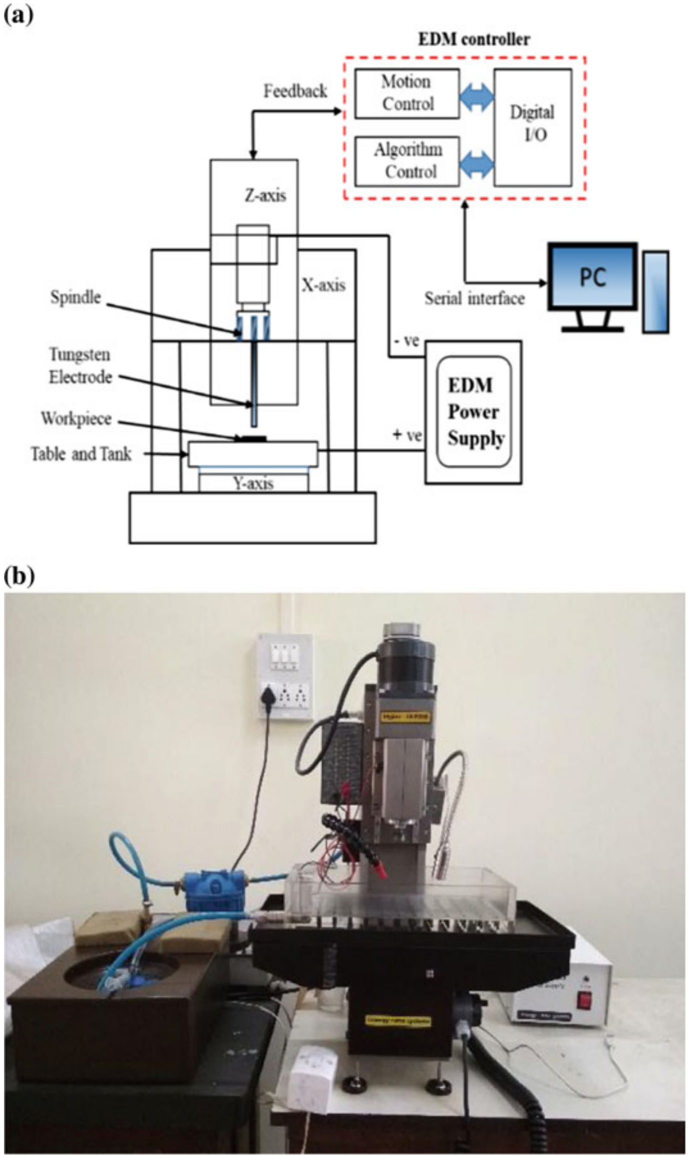

Fig. 3.1 **a** Schematic diagram of experimental setup. **b** Photograph of experimental setup

Table 3.1 Properties of tool and work material

	Workpiece	Electrode tool
Material composition (wt%)	Cu: 60%, Zn: −35% + others	90% W
Density (g/cm^3)	8.47	15
Melting point (°C)	620	2850
Electrical resistivity (Ω cm)	–	65×10^{-6}
Thermal conductivity (W/mK at 25 °C)	109	75
Hardness	60	90

Table 3.2 Properties of the dielectric fluid EDM oil 3 [14]

Volumetric mass at 15 °C (kg m^3)	813
Viscosity at 20 °C (mm^2/S)	7
Flash point (°C)	134
Auto ignition temperature (°C)	243.33
Distillation range IBP/FBP (°C)	277/322

3.2.3 Experimental Method for Micro-Hole Drilling

The purpose of the experiments is to fabricate high aspect ratio micro-holes. In EDM process, the discharging happens when the gap between workpiece material and tool electrode is sufficiently close to generate a spark. The z-axis of the machine is used to make a sufficient gap between workpiece material and electrode. The gap is adjusted with the required value of input voltage, as it measures when the spark generates between the gap. For higher MRR and controlled performance, negative electrode polarity is selected. For the experiments, input voltage, capacitance, feed and spindle rotation were selected as process parameters for the performance analysis of micro-EDM process. MRR is the ratio of volume of material removed from part to the machining time, whereas TWR is the ratio of volume of material removed from electrode to the volume of material removed from part. Material removal rate (MRR) and tool wear ratio (TWR) are calculated using the following equations:

$$MRR = \frac{\pi D_m^2 L}{4t} \tag{3.1}$$

where D_m is the mean diameter of the hole ($D_m = \frac{d1+d2}{2}$), and L is the length of the hole.

$$TWR = \frac{D_e^2(L_i - L_f)}{D_m^2 L} \times 100 \quad (3.2)$$

3.2.4 *Experimental Design and Analysis*

A Taguchi method-based experimentation scheme was used to determine the main effects and statistical significance of various machining parameters to fabricate a high aspect ratio hole with possible minimum diameter. Table 3.3 shows the selected machining parameters for the experimentation. An L18 orthogonal array of Taguchi method was used to perform different trial conditions for experiments with four factors and three levels. Two levels of capacitance and three levels of other parameters were selected to fix the trial conditions. For complete analysis of experimental data, standard analysis of variance (ANOVA) approach for raw data analysis and signal-to-noise (S/N) linked with a loss function for multiple runs were used. The S/N ratio determines the most robust set of operating conditions from variation within results. In the present work, the raw data analysis and S/N data analysis have been performed, and the effect of selected process parameters on the EDM process has been investigated through the main effect plots based on raw data. The optimum condition for each of the quality characteristics has been established through S/N data analysis aided by the raw data analysis. A high value of S/N ratio implies that signal is much higher than the random effect of noise factor. The S/N ratio results may be investigated in three different ways: “smaller the better”, “larger the better” and “nominal the best” and are given as follows [15]:

Larger is better,

$$(\text{S/N}) = -10\log(MSD) \quad (3.3)$$

where

Table 3.3 Machining conditions and input levels for EDM drilling

Process parameters	Experimental conditions		
	1	2	3
Capacitance (nF)	3	4	
Voltage (V)	125	150	175
Feed rate (µm/s)	5	10	15
Spindle speed (rpm)	500	1000	1500

$$MSD = \frac{1}{R}\sum_{j=1}^{R}\left(\frac{1}{y_j^2}\right) \tag{3.4}$$

Smaller is better,

$$(\text{S/N}) = -10\log(MSD) \tag{3.5}$$

$$MSD = \frac{1}{R}\sum_{j=1}^{R}\left(y_j^2\right) \tag{3.6}$$

Nominal is better,

$$(\text{S/N}) = -10\log(MSD) \tag{3.7}$$

$$MSD = \frac{1}{R}\sum_{j=1}^{R}\left(y_j - y_o\right)^2 \tag{3.8}$$

3.3 Results and Discussion

The main purpose of this work is to achieve the highest possible high aspect ratio micro-hole. From the preliminary experiments, a brass plate of 250 µm thickness was selected as a work material. Table 3.4 illustrates the quantitative results of MRR and TWR for different experiments. From the quantitative results, it was found that the highest material removal rate (MRR) and the lowest value of tool wear rate (TWR) are achieved with 3 nF capacitance, 150 V voltage, 15 µm/s feed rate and 1500 rpm spindle speed.

According to Taguchi methodology, the parameters with large values represent better performance for micro-EDM and termed as “larger-the-better”, such as material removal rate. On the other hand, the TWR should be minimum for the better economy and high performance. Hence, smaller values of TWR indicate better performance and termed as “smaller-the-better”. All the experiments are repeated two times, and an optimal combination of the machining and process parameters was evaluated (Fig. 3.2).

Table 3.4 Experimental values of MRR and TWR for different experiments

Experiment no.	Capacitance (nF)	Voltage (V)	Feed (m/s)	Spindle speed (rpm)	MRR (mm^3/min)	TWR
1	3	125	5	500	0.0433	0.10154
2	3	125	10	1000	0.0765	0.08750
3	3	125	15	1500	0.0757	0.08153
4	3	150	5	500	0.0728	0.10329
5	3	150	10	1000	0.0888	0.13061
6	3	150	15	1500	0.1458	0.04239
7	3	175	5	1000	0.0700	0.07135
8	3	175	10	1500	0.0896	0.10018
9	3	175	15	500	0.1388	0.10827
10	4	125	5	1500	0.0639	0.07922
11	4	125	10	500	0.1046	0.06461
12	4	125	15	1000	0.1333	0.06179
13	4	150	5	1000	0.0495	0.08008
14	4	150	10	1500	0.0862	0.07365
15	4	150	15	500	0.0497	0.12420
16	4	175	5	1500	0.0581	0.17253
17	4	175	10	500	0.1137	0.10564
18	4	175	15	1000	0.0938	0.09924

3.3.1 Effect of Process Parameters on MRR

Figure 3.3 depicts the effect of process parameters with S/N ratio curve. The figure confirms that MRR increases with lower capacitance and the peak S/N ratio value is found at lower capacitance of 3 and 4 nF. The S/N ratio is found maximum with highest voltage, and MRR increases with the increment in voltage and feed. At high voltage, the explosive energy is high; hence the discharge spark increases, which results in increased MRR. From the figure, feed versus S/N ratio, it is clear that MRR increases significantly with feed rate of 5–10. After this the S/N ratio value reduces with marginal value for the experiment. The plot also shows that at lower value of spindle speed, the material removal rate was found higher. From the above results it is concluded that voltage and feed are influential parameters on MRR.

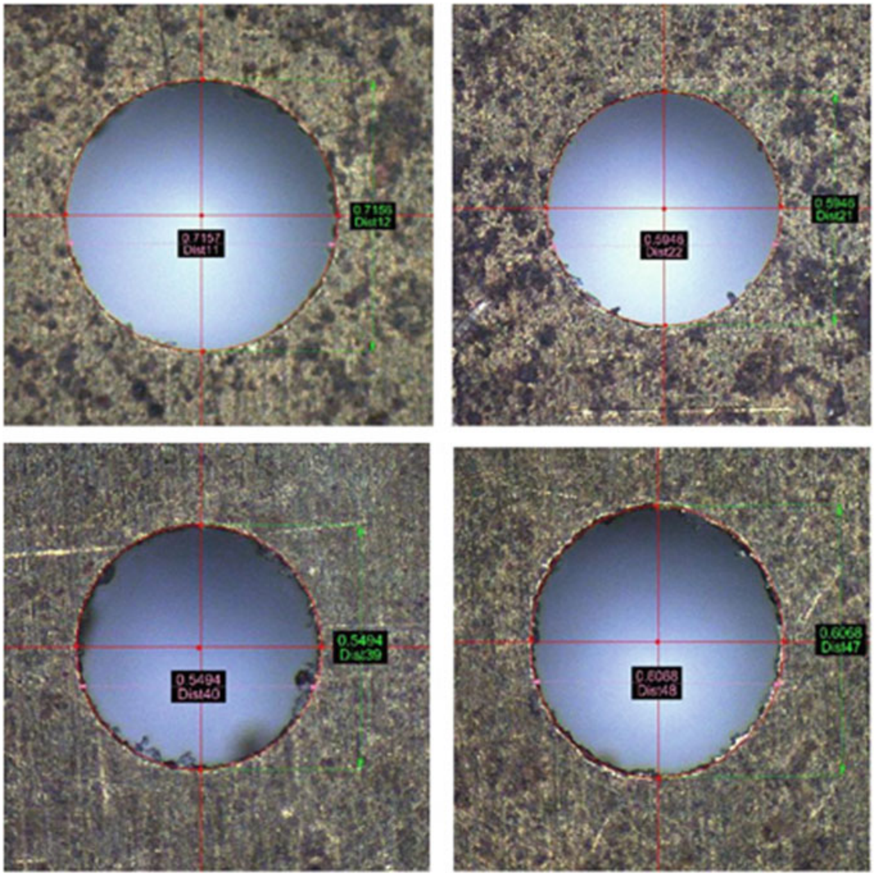

Fig. 3.2 Microscopic view at entry and exit of micro-hole

3.3.2 Effect of Process Parameters on TWR

Figure 3.4 shows the S/N ratio plot for tool wear rate (TWR). As explained in Sect. 3.3, for the TWR, "smaller the better" is considered. There is a significant effect of voltage, spindle speed and feed rate on the TWR than the capacitance. From the plot it is shown that for lower capacitance 4 nF, the S/N ratio is lower; hence it is concluded that higher capacitance value lowers the TWR with reduction in cost of EDM process. The S/N ratio reduces with increase in voltage. On the other hand, with increase in feed rate and spindle speed, the S/N ratio increases but after 1000 rpm spindle speed, the effect is marginal. It is concluded from the above results that there is a significant effect of voltage, feed rate and spindle speed on the tool wear rate. The MRR is found maximum and TWR is found minimum with 3 nF capacitance, 150 V voltage, 15 μm/s feed rate and 1500 rpm spindle speed. 10% increase in the

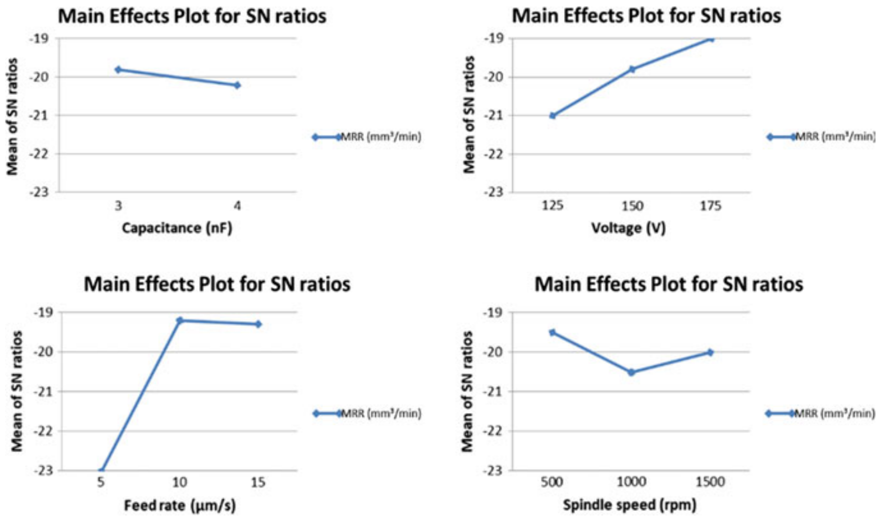

Fig. 3.3 S/N ratio plot of different process parameters for material removal rate

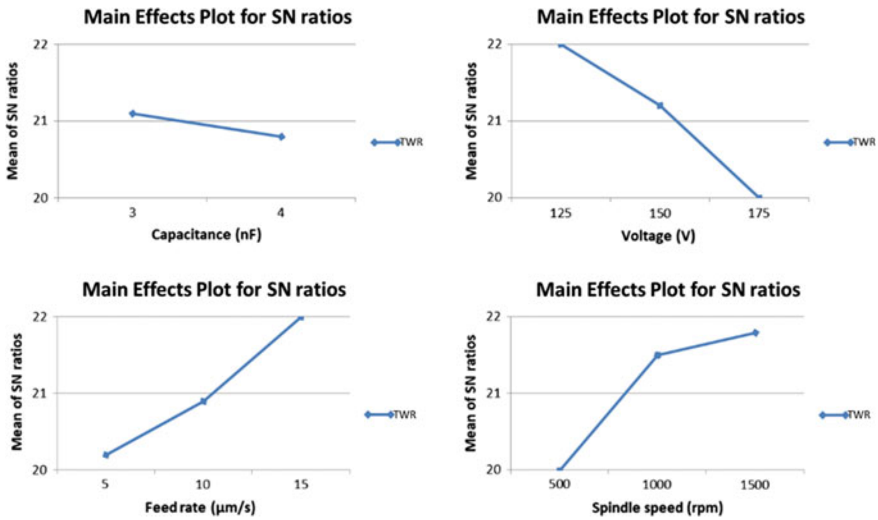

Fig. 3.4 S/N ratio plot of different process parameters for tool wear rate (TWR)

Table 3.5 Analysis of variance for signal to noise ratios

Source	DF	SS	MS	F	P
Voltage	2	21.357	10.6787	1.13	0.360
Capacitance	1	0.301	0.3006	0.03	0.862
Feed rate	2	7.264	3.6320	0.39	0.690
Spindle speed	2	7.632	3.8159	0.41	0.677

MRR is found as the discharge energy increases with the increase in voltage and capacitance.

3.3.3 Analysis of Variance (ANOVA)

The relative significant process parameters are determined with the analysis of variance (ANOVA) approach. The F-values are calculated for MRR and TWR and illustrated in Table 3.5. From Table 3.5, only one parameter voltage has significant effect on MRR. Therefore, the results confirm that voltage is the most significant optimal parameter for EDM process design.

3.4 Conclusion

A different set of experiments is performed to fabricate micro-hole with micro-EDM process. The influence of various machining and process parameters, such as voltage, capacitance, feed rate and spindle speed, on the performance of EDM, like MRR and TWR, has been examined. A Taguchi analysis is performed to attain an optimal machining and process parametric combinations. From the results, the following outcomes are observed during micro-EDM process.

Voltage and feed rate are the most influencing factors on the material removal rate (MRR) and micro-EDM process. Material removal rate increases with increase in voltage and feed. Also, MRR has been found to be increased with lower spindle speed of 500 rpm, but after 500 rpm of spindle speed the effect is marginal. There is very less effect of capacitance on the MRR.

There is a significant effect of voltage, feed rate and spindle speed on the tool wear rate (TWR). A smaller value is found for 4 nF capacitance but the effect is marginal. With an increment in voltage, the S/N ratio achieved smaller value, while the S/N ratio increases with increase in feed rate. Tool wear rate is less with lower spindle speed as the S/N has a smaller value for 500 rpm.

Based on the Taguchi analysis, the F-values are determined from ANOVA, and optimal parametric conditions are achieved for this type of EDM process. From the analysis, it is concluded that for higher MRR and lower TWR, 3 nF capacitance, 150 V voltage, 15 μm/s feed rate and 1500 rpm spindle speed parametric combination is found effective. Voltage has the highest F value. With this combination the highest value of aspect ratio is achieved as 5.

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