A CASE STUDY ON APPLICATION OF FUZZY LOGIC IN ELECTRICAL DISCHARGE MACHINING (EDM)

Thesis submitted in partial fulfillment of the requirements for the Degree of

Bachelor of Technology (B. Tech.)

In

Mechanical Engineering

By

DURGA MADHABA PADHY
Roll No. 107ME033

Under the Guidance of

DR. SAURAV DATTA

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA 769008, INDIA

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA 769008, INDIA

Certificate of Approval

This is to certify that the thesis entitled **A CASE STUDY ON APPLICATION OF FUZZY LOGIC IN ELECTRICAL DISCHARGE MACHINING (EDM)** submitted by ***Sri Durga Madhaba Padhy*** has been carried out under my supervision in partial fulfillment of the requirements for the Degree of ***Bachelor of Technology (B. Tech.)*** in ***Mechanical Engineering*** at National Institute of Technology, NIT Rourkela, and this work has not been submitted elsewhere before for any other academic degree/diploma. *However, experimental part reported here has been jointly conducted by Sri Durga Madhaba Padhy and Sri Harekrushna Dalai.*

Dr. Saurav Datta

Assistant Professor
Department of Mechanical Engineering
National Institute of Technology, Rourkela

Rourkela-769008

Date:

Acknowledgement

I wish to express my profound gratitude and indebtedness to *Dr. Saurav Datta*, Assistant Professor, Department of Mechanical Engineering, National Institute of Technology, Rourkela, for introducing the present topic and for their inspiring guidance, constructive criticism and valuable suggestion throughout this project work.

I am also thankful to *Prof. Ranjit Kumar Sahoo*, Head, Department of Mechanical Engineering, National Institute of Technology, Rourkela, for his constant support and encouragement. I am also grateful to *Prof. Chandan Kumar Biswas*, Associate Professor, Department of Mechanical Engineering, National Institute of Technology, Rourkela, for his help and support in providing us valuable inputs and permitting us to use the Production Engineering Laboratory for the experiments.

I would also like to thank *Mr. Kunal Nayek*, Staff Member and *Sri Shailesh Debangan*, PhD Scholar of the Production Engineering Laboratory for their assistance and help in carrying out experiments.

Last but not least, my sincere thanks to *Sri Ranjit Kumar Sahu*, M. Tech. (Production) Scholar, Department of Mechanical Engineering of this institute who has patiently extended all sorts of help for accomplishing this undertaking.

DURGA MADHABA PADHY
Department of Mechanical Engineering
National Institute of Technology
Rourkela – 769008

Abstract

Electrical Discharge Machining (EDM) is one of the most accurate manufacturing processes available for creating complex or simple shapes and geometries within parts and assemblies. EDM works by eroding material in the path of electrical discharges that form an arc between an electrode tool and the work piece. EDM manufacturing is quite affordable and a very desirable manufacturing process when low counts or high accuracy is required. Turn around time can be fast and depends on manufacturer back log. The EDM system consists of a shaped tool or wire electrode, and the part. The part is connected to a power supply. Sometimes to create a potential difference between the work piece and tool, the work piece is immersed in a dielectric (electrically non-conducting) fluid which is circulated to flush away debris.

EDM comes in two basic types: wire and probe (die sinker). Wire EDM is used primarily for shapes cut shapes through a selected part or assembly. With a wire EDM machine, if a cutout needs to be created, an initial hole must first be drilled in the material, and then the wire can be fed through the hole to complete the machining. Sinker (die sinking) EDMs are generally used for complex geometries where the EDM machine uses a machined graphite or copper electrode to erode the desired shape into the part or assembly. Sinker EDM can cut a hole into the part without having a hole pre-drilled for the electrode.

In the present work a multi-objective optimization problem has been solved to simultaneously satisfy requirements of quality and productivity in EDM operation.

Experiments (EDM on UTS 304 grade stainless steel) have been ducted using L_9 orthogonal array design using various process control parameters: discharge current (I_P), pulse on time (T_{ON}), duty factor (τ) (of the machine) and discharge voltage (V); varied in three different levels. Surface roughness of the EDM product and Material Removal Rate (MRR), have been measured for each experimental run. Problem has been formulated in maximization of MRR (in order to increase productivity) and at the same time minimizing roughness value of the machined surface. This invites a multi-objective optimization problem which aims at determination of optimal process environment (optimal parameter setting) which can simultaneously satisfy multiple requirements as discussed above.

Multi-objective optimization is really difficult to solve due to the complex process behavior. The control parameters (process factors) interact in a complicated manner thereby influencing various process outputs. Direct (main effect) as well as interactive effect of process parameters are to be examined carefully to select the most favorable process environment to achieve desired level of output. Taguchi optimization method is very popular in production engineering field; however, it fails to solve multi-objective optimization problems. Therefore, to solve a multi-objective optimization problem it is customary to convert multiple objectives into a single performance index (single objective function) which can be solved by Taguchi method. Literature highlights application of grey relation theory, desirability function approach, and utility theory in combination with Taguchi method to solve such multi-response optimization problems. These approaches are based on the assumption that individual responses are not correlated. The responses do not influence each other. But in practical case this assumption is totally invalid. However, it is felt indeed difficult to establish such relationship that may exist among various output measures of the process/ product.

Therefore, a fuzzy logic approach has been adopted here to predict the responses so that imprecision and uncertainly in experimentation can be handled conveniently. As Taguchi method is not capable of dealing with multi-objective optimization problem, fuzzy approach has been used to convert both the responses into an equivalent single response. The optimal parametric combination to improve both MRR and SF (Surface Roughness) has been evaluated through Taguchi method.

Index

1. Overview of Electric Discharge Machining (EDM)

Electric discharge machining (EDM) (sometimes also referred to as spark machining, spark eroding, burning, die sinking or wire erosion) is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks). Material is removed from the work piece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage. One of the electrodes is called the tool-electrode, or simply the 'tool' or 'electrode', while the other is called the work piece-electrode, or 'work piece'.

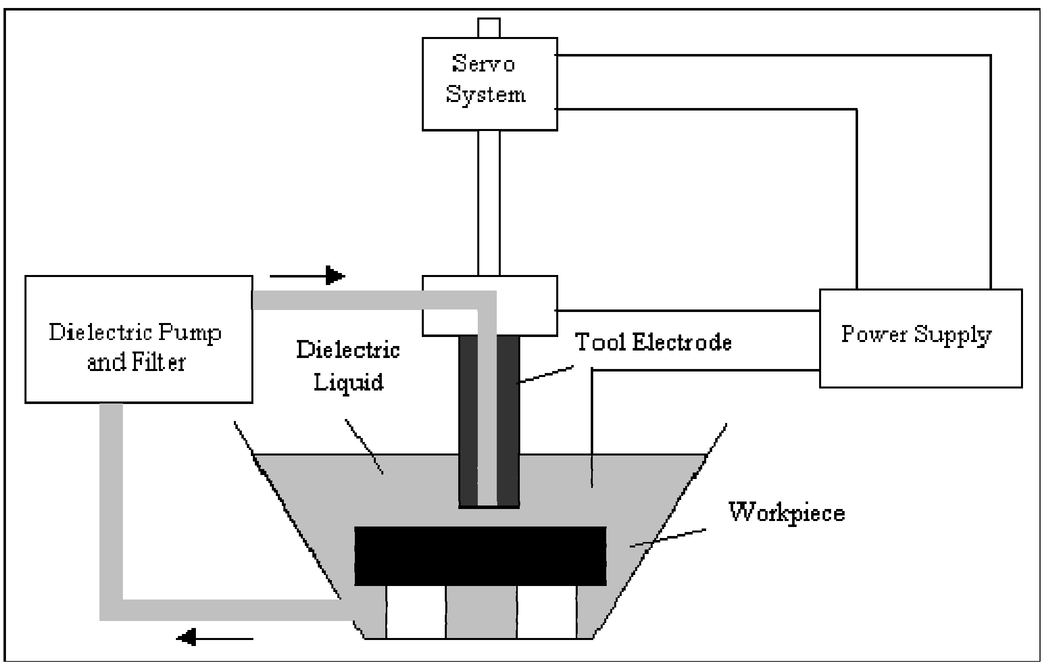

Figure 1: Basic Elements of an EDM system

When the distance between the two electrodes is reduced, the intensity of the electric field in the volume between the electrodes becomes greater than the strength of the dielectric (at least in some point(s)), which breaks, allowing current to flow between the two electrodes. As a result, material is removed from both the electrodes. Once the current flow stops (or it is stopped depending on the type of generator), new liquid dielectric is usually conveyed into the inter-electrode volume enabling the solid particles (debris) to be carried away and the insulating proprieties of the dielectric to be restored. Adding new liquid dielectric in the inter-electrode volume is commonly referred to as flushing. Also, after a current flow, a difference of potential between the two electrodes is restored to what it was before the breakdown, so that a new liquid dielectric breakdown can occur.

Electrical discharge machining is a machining method primarily used for hard metals or those that would be very difficult to machine with traditional techniques. EDM typically works with materials that are electrically conductive, although methods for machining insulating ceramics with EDM have also been proposed. EDM can cut intricate contours or cavities in pre-hardened steel without the need for heat treatment to soften and re-harden them. This method can be used with any other metal or metal alloy such as titanium, inconel etc.

EDM is often included in the 'non-traditional' or 'non-conventional' group of machining methods together with processes such as electrochemical machining (ECM), water jet cutting (WJ, AWJ), laser cutting and opposite to the 'conventional' group (turning, milling, grinding, drilling and any other process whose material removal mechanism is essentially based on mechanical forces).

Ideally, EDM can be seen as a series of breakdown and restoration of the liquid dielectric in-between the electrodes. However, caution should be exerted in considering such a statement because it is an idealized model of the process, introduced to describe the fundamental ideas underlying the process. Yet, any practical application involves many aspects that may also need to be considered. For instance, the removal of the debris from the inter-electrode volume is likely to be always partial. Thus the electrical proprieties of the dielectric in the inter-electrodes volume can be different from their nominal values and can even vary with time. The inter-electrode distance, often also referred to as spark-gap, is the end result of the control algorithms of the specific machine used. The control of such a distance appears logically to be central to this process. Also, not all of the current flow between the dielectric is of the ideal type described above: the spark-gap can be short-circuited by the debris. The control system of the electrode may fail to react quickly enough to prevent the two electrodes (tool and work piece) to get in contact, with a consequent short circuit. This is unwanted because a short circuit contributes to the removal differently from the ideal case. The flushing action can be inadequate to restore the insulating properties of the dielectric so that the flow of current always happens in the point of the inter-electrode volume (this is referred to as arcing), with a consequent unwanted change of shape (damage) of the tool-electrode and work piece. Ultimately, a description of this process in a suitable way for the specific purpose at hand is what makes the EDM area such a rich field for further investigation and research.

To obtain a specific geometry, the EDM tool is guided along the desired path very close to the work; ideally it should not touch the work piece, although in reality this may happen due to the performance of the specific motion control in use. In this way a large number of current discharges (colloquially also called sparks) happen, each contributing to the removal of material from both tool and work piece, where small craters are formed. The size of the craters is a function of the technological parameters set for the specific job at hand. They can be with typical dimensions ranging from the nanoscale (in micro-EDM operations) to some hundreds of micrometers in roughing conditions.

The presence of these small craters on the tool results in the gradual erosion of the electrode. This erosion of the tool-electrode is also referred to as wear. Strategies are needed to counteract the detrimental effect of the wear on the geometry of the work piece. One possibility is that of continuously replacing the tool-electrode during a machining operation. This is what happens if a continuously replaced wire is used as electrode. In this case, the correspondent EDM process is also called wire EDM. The tool-electrode can also be used in such a way that only a small portion of it is actually engaged in the machining process and this portion is changed on a regular basis. This is, for instance, the case when using a rotating disk as a tool-electrode. The corresponding process is often also referred to as EDM grinding.

A further strategy consists in using a set of electrodes with different sizes and shapes during the same EDM operation. This is often referred to as multiple electrode strategy, and is most common when the tool electrode replicates in negative the wanted shape and is advanced towards the blank along a single direction, usually the vertical direction (i.e. z-axis). This resembles the sink of the tool into the dielectric liquid in which the work piece is immersed, so, not surprisingly; it is often referred to as die-sinking EDM (also called conventional EDM and ram EDM). The corresponding machines are often called sinker EDM. Usually, the electrodes of this type have quite complex forms. If the final geometry is obtained using a usually simple shaped electrode which is moved along several directions and is possibly also subject to rotations often the term EDM milling is used.

In any case, the severity of the wear is strictly dependent on the technological parameters used in the operation (for instance: polarity, maximum current, open circuit voltage). For example, in micro-EDM, also known as μ-EDM, these parameters are usually set at values which generate severe wear. Therefore, wear is a major problem in that area.

The problem of wear to graphite electrodes is being addressed. In one approach a digital generator, controllable within milliseconds, reverses polarity as electro-erosion takes place. That produces an effect similar to electroplating that continuously deposits the eroded graphite back on the electrode. In another method, a so-called "Zero Wear" circuit reduces how often the discharge starts and stops, keeping it on for as long a time as possible.

Sinker EDM, also called cavity type EDM or volume EDM consists of an electrode and work piece submerged in an insulating liquid such as, more typically, oil or, less frequently, other dielectric fluids. The electrode and work piece are connected to a suitable power supply. The power supply generates an electrical potential between the two parts. As the electrode approaches the work piece, dielectric breakdown occurs in the fluid, forming a plasma channel, and a small spark jumps.

These sparks usually strike one at a time because it is very unlikely that different locations in the inter-electrode space have the identical local electrical characteristics which would enable a spark to occur simultaneously in all such locations. These sparks happen in huge numbers at seemingly random locations between the electrode and the work piece. As the base metal is eroded, and the spark gap subsequently increased, the electrode is lowered automatically by the machine so that the process can continue uninterrupted. Several hundred thousand sparks occur per second, with the actual duty cycle carefully controlled by the setup parameters. These controlling cycles are sometimes known as "on time" and "off time", which are more formally defined in the literature.

The on time setting determines the length or duration of the spark. Hence, a longer on time produces a deeper cavity for that spark and all subsequent sparks for that cycle, creating a rougher finish on the work piece. The reverse is true for a shorter on time. Off time is the period of time that one spark is replaced by another. A longer off time, for example, allows the flushing of dielectric fluid through a nozzle to clean out the eroded debris, thereby avoiding a short circuit. These settings can be maintained in micro seconds. The typical part geometry is a complex 3D shape, often with small or odd shaped angles. Vertical, orbital, vectorial, directional, helical, conical, rotational, spin and indexing machining cycles are also used.

Some of the advantages of EDM include machining of:

- Complex shapes that would otherwise be difficult to produce with conventional cutting tools
- Extremely hard material to very close tolerances
- Very small work pieces where conventional cutting tools may damage the part from excess cutting tool pressure.
- There is no direct contact between tool and work piece. Therefore delicate sections and weak materials can be machined without any distortion.
- A good surface finish can be obtained.
- Very fine holes can be easily drilled.

Some of the disadvantages of EDM include:

- The slow rate of material removal.
- The additional time and cost used for creating electrodes for ram/sinker EDM.
- Reproducing sharp corners on the work piece is difficult due to electrode wear.

- Specific power consumption is very high.
- Power consumption is high.
- "Overcut" is formed.
- Excessive tool wear occurs during machining.
- Electrically non-conductive materials can be machined only with specific set-up of the process

2. Literature Review

Electrical discharge machining (EDM) is one of the most widely used non-traditional machining processes. The main attraction of EDM over traditional machining processes such as metal cutting using different tools and grinding is that this technique utilizes thermoelectric process to erode undesired materials from the work piece by a series of discrete electrical sparks between the work piece and the electrode.

The traditional machining processes rely on harder tool or abrasive material to remove the softer material whereas non-traditional machining processes such as EDM uses electrical spark or thermal energy to erode unwanted material in order to create desired shape. So, the hardness of the material is no longer a dominating factor for EDM process. A schematic of an EDM process is shown in Figure 2, where the tool and the work piece are immersed in a dielectric fluid.

EDM removes material by discharging an electrical current, normally stored in a capacitor bank, across a small gap between the tool (cathode) and the work piece (anode) typically in the order of 50 Volts/10 Amps.

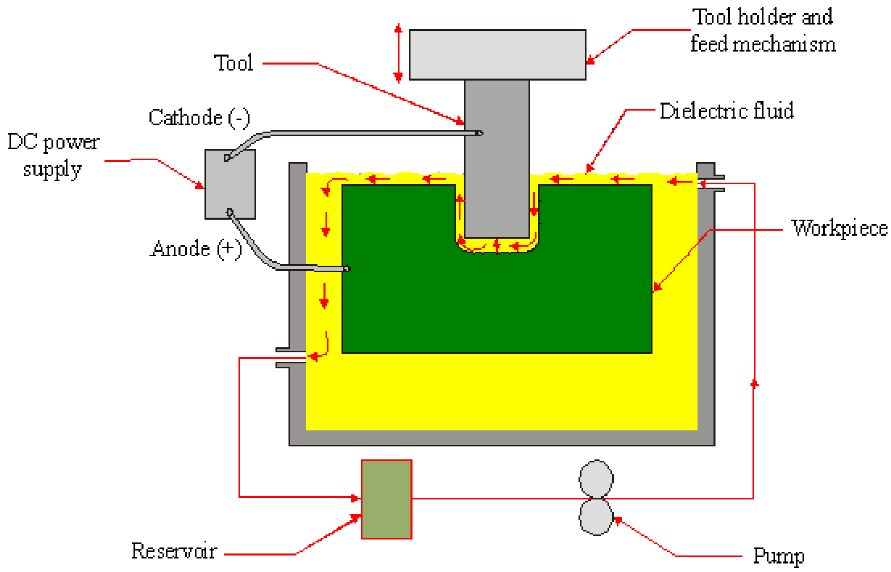

Figure 2: Schematic of EDM process

Marafona and Wykes (2000) reported an investigation into the optimization of the process which used the effect of carbon which was migrated from the dielectric to tungsten–copper electrodes. This work led to the development of a two-stage EDM machining process where different EDM settings were used for the two stages of the process giving a significantly improved material removal rate for a given tool wear ratio.

Tzeng and Chen (2007) described the application of the fuzzy logic analysis coupled with Taguchi methods to optimize the precision and accuracy of the high-speed electrical discharge machining (EDM) process. A fuzzy logic system was used to investigate relationships between the machining precision and accuracy for determining the efficiency of each parameter design of the Taguchi dynamic experiments. From the fuzzy inference process, the optimal process condition for the high-speed EDM process was determined. In addition, the analysis of variance (ANOVA) was also employed to identify factor B (pulse time), C (duty cycle), and D (peak value of discharge current) as the most important parameters, which account for about 81.5% of the variance. The factors E (powder concentration) and H (powder size) were found to have relatively weaker impacts on the process design of the high-speed EDM. Furthermore, a confirmation experiment of the optimal process showed that the targeted multiple performance characteristics were significantly improved to achieve more desirable levels.

Kumar and Singh (2007) compared the performance of copper -chromium alloy with copper and brass as EDM electrode materials for machining OHNS die steel using kerosene and distilled water as dielectric media. Keeping all other machining parameters same, the hardened work material was machined with the three electrodes at different values of discharge current. It was found that copper -chromium alloy shows better results than copper and brass in terms of material removal rate, dimensional accuracy (lateral overcut) and surface finish in both the dielectric media. Tool wear rate of this alloy was lower which results in better accuracy and trueness of the machined profiles because the mirror image of the tool electrode was reproduced in the work piece. Regarding the use of distilled water as a dielectric medium, though material removal rate was low and tool wear rate was high, but hardness and finish of the machined surface showed a marked improvement.

Saha (2008) reported parametric analysis of the dry EDM process on experimental results. Experiments based on the Central Composite Design (CCD) were conducted to develop empirical models of the process behavior. Process optimization was performed using Genetic Algorithms (GA). Surface roughness and MRR were optimized.

Rao et al. (2008) optimized the metal removal rate of die sinking electric discharge machining (EDM) by considering the simultaneous affect of various input parameters. The experiments were carried out on Ti6Al4V, HE15, 15CDV6 and M-250. Experiments were conducted by varying the peak current and voltage and the corresponding values of metal removal rate (MRR) were measured. Multi-perceptron neural network models were developed using Neuro solutions package. Genetic algorithm concept was used to optimize the weighting factors of the network. It was observed that the developed model was within the limits of the agreeable error when experimental and network model results were compared for all performance measures considered. It was further observed that the maximum error when the network was optimized by genetic algorithm reduced considerably. Sensitivity analysis was carried out to find the relative influence of factors on the performance measures. It was observed that type of material is having more influence on the performance measures.

Pradhan and Biswas (2008) investigated the relationships and parametric interactions between the three controllable variables on the material removal rate

(MRR) using RSM method. Experiments were conducted on AISI D2 tool steel with copper electrode and three process variables (factors) as discharge current, pulse duration, and pulse off time. To study the proposed second-order polynomial mode for MRR, the authors used the central composite experimental design to estimation the model coefficients of the three factors, which are believed to influence the MRR in EDM process. The response was modeled using a response surface model based on experimental results. The significant coefficients were obtained by performing analysis of variance (ANOVA) at 5% level of significance. It was found that discharge current, pulse duration, and pulse off time significant effect on the MRR.

Tebni et al. (2009) proposed a simple and easily understandable model for predicting the relative importance of different factors (composition of the steel and Electro Discharge Machining processing conditions) in order to obtain efficient pieces. A detailed application on the tool steel machined by EDM was given in the study. This model was based on thermal, metallurgical, mechanical, and *in situ* test conditions. It gave detailed information on the effects of electrochemical parameters on the surface integrity and sub-surface damage of the material (Heat Affected Zone, HAZ), the level of residual stresses, and the surface texture. This approach was an efficient way to separate the responsibilities of the steel maker and machining process designer for increasing the reliability of the machined structures.

Popa et al. (2009) reported the importance of the EDM technology in the industry of machine building. It is mostly used in the machining of stamps and special processes in which the conventional technologies are inefficiently. It's known that only condition of machining with this method is that the material should be electro conductive. The main parameters that are followed during the process are the precision and the roughness of the surface. The collective tried to emphasize the importance variation of the roughness concerning some machining parameters. Some of the measurements were conducted at ETH Zurich using an electronic microscope.

Singh and Garg (2009) investigated the effects of various process parameters of WEDM like pulse on time (TON), pulse off time (TOFF), gap voltage (SV), peak current (IP), wire feed (WF) and wire tension (WT) to reveal their impact on material removal rate of hot die steel (H-11) using one variable at a time approach. The optimal set of process parameters was predicted to maximize the material removal rate.

Pradhan and Biswas (2009) used Response Surface Methodology (RSM) to investigate the effect of four controllable input variables namely: discharge current, pulse duration, pulse off time and applied voltage Surface Roughness (SR) of on Electrical Discharge Machined surface. To study the proposed second-order polynomial model for SR, a Central Composite Design (CCD) was used to estimation the model coefficients of the four input factors, which were alleged to influence the SR in Electrical Discharge Machining (EDM) process. Experiments were conducted on AISI D2 tool steel with copper electrode. The response was modeled using RSM on experimental data. The significant coefficients were obtained by performing Analysis of Variance (ANOVA) at 5%

level of significance. It was found that discharge current, pulse duration, and pulse off time and few of their interactions had significant effect on the SR.

Iqbal and Khan (2010) established empirical relations regarding machining parameters and the responses in analyzing the machinability of the stainless steel. The machining factors used were voltage, rotational speed of electrode and feed rate over the responses MRR, EWR and Ra. Response surface methodology was used to investigate the relationships and parametric interactions between the three controllable variables on the MRR, EWR and Ra. Central composite experimental design was used to estimate the model coefficients of the three factors. The responses were modeled using a response surface model based on experimental results. The significant coefficients were obtained by performing Analysis Of Variance (ANOVA) at 95% level of significance. The variation in percentage errors for developed models was found within 5%. The developed models showed that voltage and rotary motion of electrode was the most significant machining parameters influencing MRR, EWR and R_a. These models could be used to get the desired responses within the experimental range.

Literature depicts various aspects of EDM have been attempted by previous investigators. Process modeling, simulation have been intensively studied before. Input-out functional relationship has been established. Degree of influence of various controllable process factors (on process responses) has also been checked. As a continuation of the foregoing research it is felt necessary to examine aspects of parametric optimization of the process. It is well known that in any machining process productivity is very important. However, productivity should not be increased by compromising product quality. A poor quality product can not be accepted by the customers. Hence, there should be an optimal balance between quality as well as productivity.

In the present work Material Removal Rate (MRR) has been considered as productivity measure; whereas roughness average (R_a) of the machined surface has been treated as quality parameter of the finished product. The goal is to determine the best process condition to maximize MRR and simultaneously to minimize roughness average values. It is basically a multi-response optimization problem. Traditional Taguchi method is based on quadratic quality loss function and Signal-to-Noise (S/N Ratio) of the objective function (single objective). There exists certain degree of uncertainly in Taguchi's various loss functions [Panda et al. (2010)]. Moreover, Taguchi method can not solve multi-response optimization problems. To overcome this; general trend is to convert multiple objectives into a single objective function which can be optimized by Taguchi philosophy. The conversion procedure of multi-objectives into a single objective further invites imprecision, uncertainly into the computation. The interdependence (correlation) of various responses is difficult to find out. At each stage uncertainty is amplified and situation may arise that evaluated optima is far from the actual one.

In order to overcome this shortcoming a fuzzy reasoning of the multiple performance characteristics has been developed based on fuzzy logic. As a result optimization of complicated multiple performance characteristics can be transformed into the optimization of a single multi-performance characteristics index (MPCI) which has been optimized by Taguchi method.

3. Experimentation

The selected work piece material for this research work is UTS 304 grade stainless steel (density 8030 Kg/m^3). Experiments have been conducted on Electronica Electraplus PS 50ZNC die sinking machine. An electrolytic pure copper with a diameter of 30 mm has been used as a tool electrode (positive polarity) and work piece materials used were stainless steel rectangular plates of dimensions $100 \times 50\,mm$ and of thickness $4\,mm$. Commercial grade EDM oil (specific gravity 0.763 and freezing point 94^{0}C) has been used as dielectric fluid. Lateral flushing with a pressure of 0.3 Kgf/cm^2 has been used. Discharge current (I_P), pulse on time (T_{ON}), duty factor (τ) of the machine and discharge voltage (V) have been treated as controllable process factors. Table 1 reveals domain of experiments. Design of Experiment (DOE) has been selected as per Taguchi's L_9 orthogonal array (Table 2), in which interactive effect of process parameters have been neglected. Experimental data have been furnished in Table 3.

Table 1: Domain of Experiments

Factor(s)	Notation/ Units	Code	Levels of Factors		
			1	2	3
Discharge Current	I_P (A)	A	06	08	10
Pulse on Time	T_{ON} (µs)	B	300	400	500
Duty Factor	τ	C	8	10	12
Discharge Voltage	V (Volt)	D	40	45	50

Table 2: Design of Experiment (DOE)

Sl. No.	Design of Experiment (L_9 orthogonal array)			
	A	B	C	D
01	1	1	1	1
02	1	2	2	2
03	1	3	3	3
04	2	1	2	3
05	2	2	3	1
06	2	3	1	2
07	3	1	3	2
08	3	2	1	3
09	3	3	2	1

Table 3: Experimental Data

Sl. No.	Experimental Data	
	MRR (mm^3/min)	R_a (µm)
01	8.4682	8.66
02	8.7173	8.38
03	7.7210	8.42
04	13.4496	9.88
05	14.6949	10.72
06	11.7061	8.10
07	18.9290	11.22
08	15.4421	11.68
09	19.6762	9.02

4. Fuzzy Expert System

A fuzzy rule based system consists of four parts: ***knowledge base***, ***fuzzifier***, ***inference engine*** and ***defuzzifier***. Detailed analysis on fuzzy can be found in numerous literature [Zadeh (1965, 1976); Mendel (1995); Cox (1992)]. The four parts are described below.

- **Fuzzifier**

The real world input to the fuzzy system is applied to the fuzzifier. In fuzzy literature, this input is called crisp input since it contains precise information about the specific information about the parameter. The fuzzifier convert this precise quantity to the form of imprecise quantity like 'large', 'medium', 'high' etc. with a degree of belongingness to it. Typically the value ranges from 0 to 1.

- **Knowledge base**

The main part of the fuzzy system is the knowledge base in which both rule base and database are jointly referred. The database defines the membership functions of the fuzzy sets used in the fuzzy rules where as the rule base contains a number of fuzzy IF – THEN rules.

- **Inference engine**

The inference system or the decision making input perform the inference operations on the rules. It handles the way in which the rules are combined.

- **Defuzzifier**

The output generated by the inference block is always fuzzy in nature. A real world system will always require the output of the fuzzy system to the crisp or in the form of real world input. The job of the defuzzifier is to receive the fuzzy input and provide real world output. In operation, it works opposite to the input block.

In general, two most popular fuzzy inference systems are available: Mamdani fuzzy model and Sugeno fuzzy model. The selection depends on the fuzzy reasoning and formulation of fuzzy IF-THEN rules. Mamdani fuzzy model [Mamdani, 1975] is based on the collection of IF-THEN rules with both fuzzy antecedent and consequent predicts. The benefit of this model is that the rule base is generally provided by an expert and hence to a certain degree it is translucent to explanation and study. Because of easiness; Mamdani model is still most commonly used technique for solving many real world problems.

The first step in system modeling was the identification of input and output variables called the system variables. In the selection procedure, the inputs and the outputs are taken in the form of linguistic format. A linguistic variable is a variable whose values are words or sentences in natural or man-made languages. Linguistic values are expressed in the form of fuzzy sets. A fuzzy set is usually defined by its membership functions. In general, triangular or trapezoidal membership functions are used to the crisp inputs because of their simplicity and high computational efficiency [Yager and Filev (1999)]. The triangular membership function as described below can be used in the model.

$$\text{Triangle}(x; a, b, c) = \left\{ \begin{array}{c} 0, x \le a \\ \frac{x-a}{b-a}, a \le x \le b \\ \frac{c-x}{c-b}, b \le x \le c \\ 0, c \le x \end{array} \right\} \quad (1)$$

Here a, b, and c are the parameters of the linguistic value and x is the range of input parameters.

5. Data Analysis

In the proposed model, initially the fuzzifier uses membership functions to fuzzify the (Signal-to-Noise) S/N ratio (of MRR and R_a i.e. roughness average) based on the experimental parameter combinations (Table 2). S/N ratios of aforesaid two responses have been shown in Table 4. To consider two different performance characteristics in the Taguchi method, the S/N ratios corresponding to the MRR and surface roughness have been processed by the fuzzy logic unit. Next, the interface engine performs a fuzzy reasoning on fuzzy rules to generate a fuzzy value. Finally the defuzzifier converts the fuzzy value into a **MPCI** (***Multi-Performance Characteristic Index***). In the following, the concept of fuzzy reasoning is described briefly on the two-input-one-output fuzzy logic unit. The fuzzy rule base consists of a group of IF-THEN control rules with the two inputs, $x1$ and $x2$, and one output y, i.e.

Rule 1: IF $x1$ is A1 and $x2$ is B1 THEN y is C1 else

Rule 2: IF $x1$ is A2 and $x2$ is B2 THEN y is C2 else

…………………………………………………………..

…………………………………………………………..

Rule n: IF $x1$ is An and $x2$ is Bn THEN y is Cn else

Ai, Bi and Ci are fuzzy subsets defined by the corresponding membership functions, i.e., μ_{Ai}, μ_{Bi}, μ_{ci}. In this reporting, three subsets have been assigned in the two inputs (Figure 3-4). Five fuzzy subsets are assigned in the output (Figure 5). Various degree of membership to the fuzzy sets has been calculated based on the values of $x1$, $x2$, y (Table 5). Nine fuzzy rules (Table 6 & Figure 6) have been derived directly based on the fact that larger is the S/N ratio, the better is the performance characteristic. By taking the max-min compositional operation, the fuzzy reasoning (Figure 6) of these rules yields a fuzzy output. Supposing that $x1$ and $x2$ are the two input values of the fuzzy logic unit, the membership function of the output of fuzzy reasoning can be expressed as:

$$\mu_{C0}(y) = (\mu_{A1}(x1) \wedge \mu_{B1}(x2) \wedge \mu_{c1}(y)) \vee ..(\mu_{An}(xn) \wedge \mu_{Bn}(xn) \wedge \mu_{cn}(y))$$

Here ^ is the minimum operation and $\vee$ is the maximum operation.

Finally, a defuzzification method, called the center-of-gravity method, is adapted here to transform the fuzzy interface output μ_{C0} into a non-fuzzy value y_0, i.e.

$$y_0 = \frac{\sum y.\mu_{C0}(y)}{\sum \mu_{C0}(y)}$$

In this work, the non-fuzzy value y_0 is called an MPCI. Based on the above discussion, the larger is the MPCI; the better is the performance characteristic.

Table 7 shows the results for the MPCI using the parametric combinations shown in Table 2. Figure 7 represents S/N ratio plot of MPCI; S/N ratio has been calculated using Higher-the-Better (HB) criteria. Optimal setting has been evaluated from this plot. Predicted optimal combination becomes: A3 B3 C2 D2. Optimal result has been verified through confirmatory test. According to Taguchi' prediction predicted value of S/N ratio for overall desirability becomes -1.42905 (higher than all entries in Table 7) whereas in confirmatory experiment it is obtained a value of -1.3720. So quality has improved using the optimal setting. Mean response table for S/N Ratio of MPCI has been shown in Table 8; which indicates that discharge voltage and pulse on time are most important factors influencing overall MPCI. Next important process factor seems to be the discharge current. Duty factor's influence has been found least.

Table 4: S/N Ratios of MRR and SF

Sl. No.	S/N Ratio	
	MRR (Higher-the-Better)	R_a (Lower-the-Better)
01	18.55	-18.75
02	18.80	-18.46
03	17.75	-18.50
04	22.57	-19.89
05	23.34	-20.60
06	21.36	-18.16
07	25.54	-20.99
08	23.77	-21.34
09	25.87	-19.10

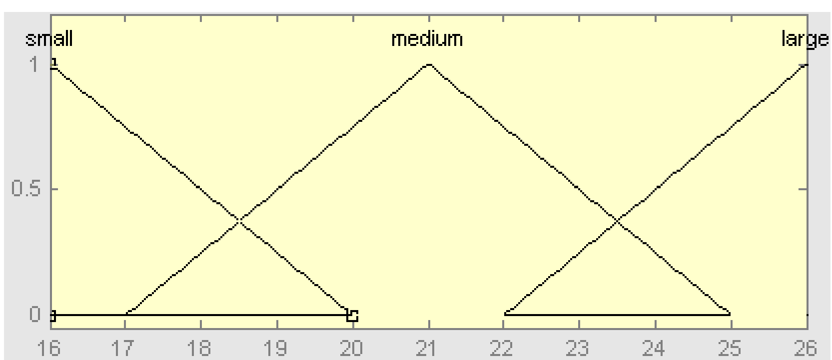

Figure 3: Membership Function for MRR

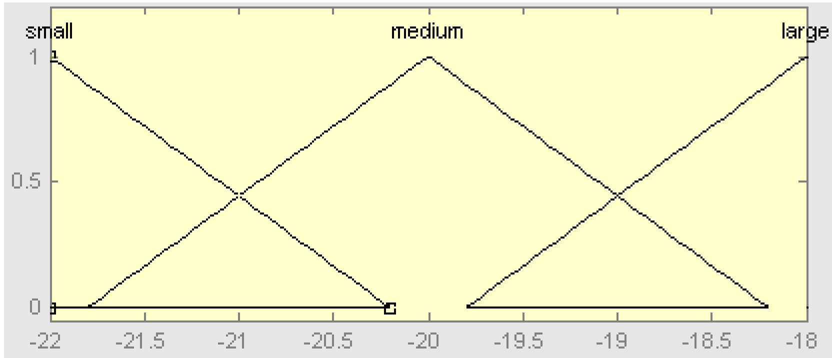

Figure 4: Membership Function for Roughness Average

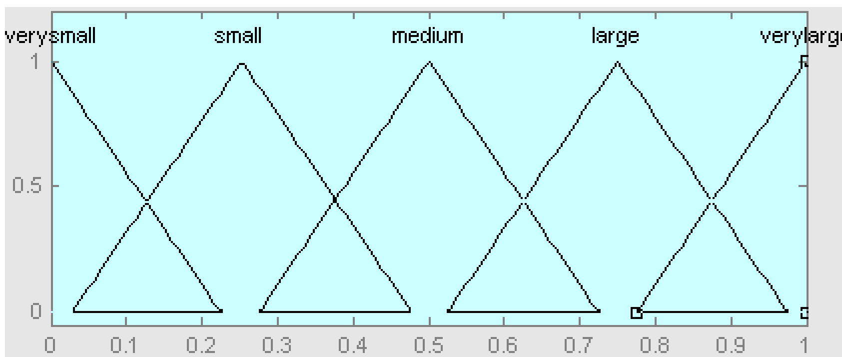

Figure 5: Membership Function for MPCI

Table 5: Input-Output and Fuzzy Intervals

Sl. No.	System's linguistic variable	Variables	Linguistic values	Fuzzy interval
1	Inputs	S/N ratio of MRR	Small	16 -- 20 (dB)
			Medium	17 -- 25 (dB)
			Large	22 -- 26 (dB)
2		S/N ratio of surface roughness	Small	-22 -- -20.2 (dB)
			Medium	-21.8 -- -18.2 (dB)
			Large	-19.8 -- -18 (dB)
3	output	MPCI	Very Small	0 -- 0.225
			Small	0.025 -- 0.475
			Medium	0.275 -- 0.725
			Large	0.525 -- 0.975
			Very Large	0.775 -- 1

Table 6: Fuzzy Rule Base

MPCI		S/N Ratio of MRR		
		Small	Medium	Large
S/N Ratio of Surface Roughness	Small	Very Small	Small	Medium
	Medium	Small	Medium	Large
	Large	Medium	Large	Very Large

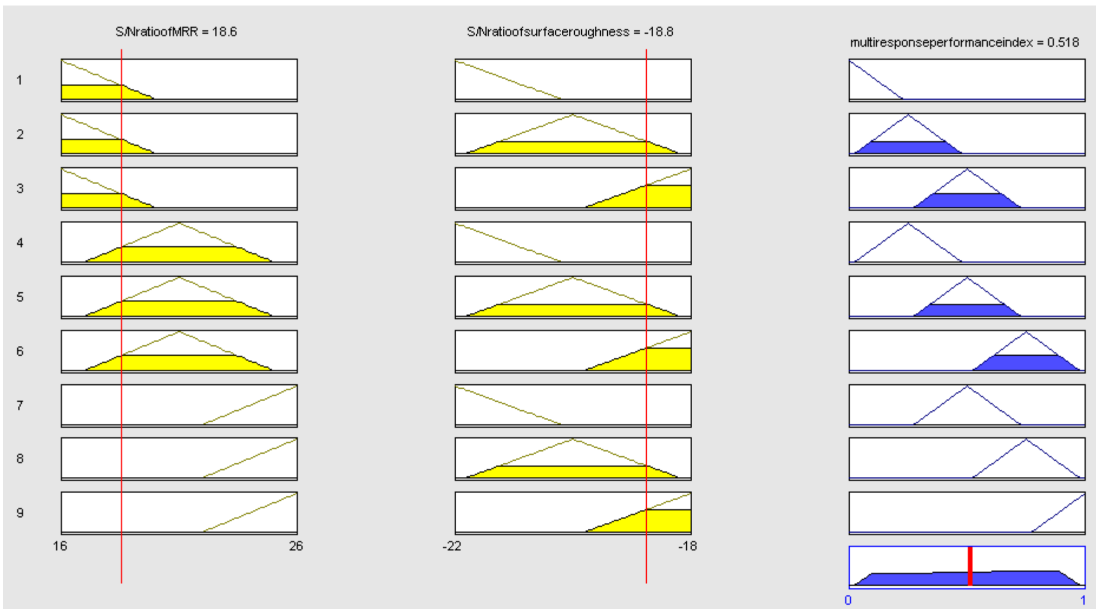

Figure 6: Fuzzy Logic Reasoning

Table 7: Results for the MPCI

Sl. No.	MPCI	S/N Ratio
01	0.518	-5.71340
02	0.583	-4.68663
03	0.506	-5.91699
04	0.553	-5.14550
05	0.528	-5.54732
06	0.750	-2.49877
07	0.626	-4.06851
08	0.487	-6.24942
09	0.781	-2.14698

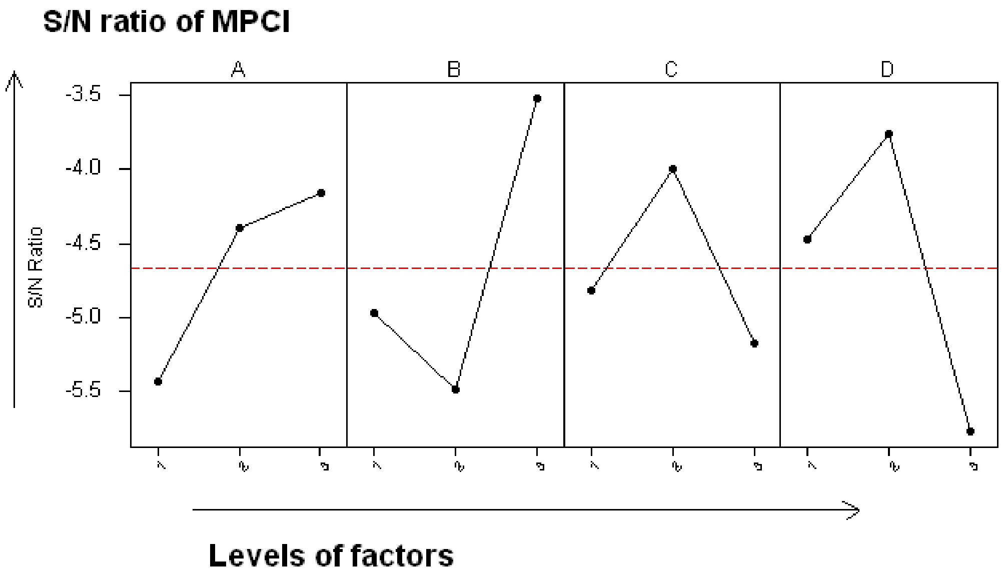

Figure 7: S/N Ratio Plot of MPCI (Evaluation of Optimal Setting)

Table 8: Response Table for Signal to Noise Ratios

Level	A	B	C	D
1	-5.43901	-4.97581	-4.82053	-4.46924
2	-4.39720	-5.49446	-3.99304	-3.75131
3	-4.15497	-3.52091	-5.17761	-5.77064
Delta	1.28404	1.97354	1.18457	2.01933
Rank	3	2	4	1

6. Conclusion

The foregoing study highlights the application of a fuzzy logic analysis in combination with Taguchi's robust design for simultaneous optimization of multiple-performance characteristics of EDM on stainless steel. Optimization (maximization) of MPCI of the overall process has been carried out through the proper system model simulation to fulfill multiple requirements for quality as well as productivity. Based on the experimental study and data analysis the following conclusions may be drawn:

I. Fuzzy logic unit can convert multiple responses into an equivalent simple performance index (MPCI).
II. Discharge voltage and pulse on time are most important factors influencing overall process response (MPCI).
III. The proposed approach can be utilized for quality improvement and off-line quality control.
IV. The methodology can be helpful for automation of the process.

7. References

1. http://en.wikipedia.org/wiki/Electrical_discharge_machining
2. http://www.nedians.8m.com/EDM.htm
3. http://www.engineersedge.com/edm.shtml
4. http://www.google.com
5. J Marafona, C wykes (2000), "A new method of optimizing material removal rate using EDM with copper-tungsten electrodes", *International Journal of Machine Tools and manufacture*, Vol. 40, pp. 153-164.
6. Yih-fong Tzeng, FU-chen Chen (2007), "Multi-objective optimization of high speed electrical discharge machining process using a Taguchi fuzzy based approach", *Materials and Design*, Vol. 28, pp. 1159-1168.

7. S Kumar, TP Singh (2007), "A comparative study of the performance of different EDM electrode materials in two dielectric media", *(IE) (I) Journal-PR*, Vol. 8, PP. 3-8.
8. SK Saha (2008), "Experimental investigation of the dry electric discharge machining (Dry EDM) process", M. Tech. Thesis, IIT Kanpur, Kanpur 208016, India.
9. GKM Rao, GR Janardhana, DH Rao, MS Rao (2008), "Development of hybrid model and optimization of metal removal rate in electrical discharge machining using Artificial Neural Networks and Genetic Algorithm", *ARPN Journal of Engineering and Applied Sciences*, Vol. 3, No. 1, pp. 19-30.
10. MK Pradhan, CK Biswas (2008), "Modeling of machining Parameters for MRR in EDM using response surface methodology", Proceedings of NCMSTA' 08 Conference (National Conference on Mechanism Science and Technology, from Theory to Application), November 13-14, 2008, NIT Harripur, India.
11. W Tebni, M Boujelbene, E Bayraktwe, S Ben Salem (2009), "Parametric approach model for determining electrical discharge machining (EDM) conditions, effects of cutting parameters on the surface integrity", *The Arabian Journal for Science of Eng*ineering, Vol. 34, No.1C, pp. 101-114.
12. Marcel Sabin Popa, Glad Contiu, Grigore Pop, (2009), "Surface quality of the EDM processed materials, XXIX IMEKO World Congress, Fundamental and Applied Metrology, September 6-11, 2009, Lisbon, Portugal.

13. H Singh, R Garg, (2009), “Effects of process parameters on material removal rate in WEDM”, *Journal of Achievement in Materials and Manufacturing Engineering*, Vol. 32, No. 1, pp. 70-74.
14. MK Pradhan, CK Biswas (2009), “Modeling and analysis of process parameters on surface roughness in EDM of AISI D2 tool steel by RSM approach”, *International Journal of Engineering and Applied Sciences*, Vol. 5, No. 5, pp. 346-351.
15. AKM Asif Iqbal, Ahsan Ali khan (2010), “Modeling and analysis of MRR, EWR and surface roughness in EDM milling through Response Surface Methodology”, *American Journal of Engineering and Applied Science*, Vol. 3,No. 4, pp. 611-619.
16. NM Abbas, DG Solomen ,MF Bahari, (2007), A Review on Current research trends in Electrical Discharge Machining (EDM), *International Journal of machine Tools and Manufacture*, Vol. 47, pp. 1214-1228.
17. HS Payal, R Choudhury, S Singh (2008), “Analysis of electro discharge machined Surfaces of EN-31 tool steel”, *Journal of Scientific and Industrial Research*, Vol. 67, pp. 1072-1077.
18. BN Panda, A Jena, SS Mahapatra, (2010), “Prediction of surface finish and material removal rate in Wire Electrical Discharge Machining (WEDM) using fuzzy approach”, *International Journal of Manufacturing Technology and Industrial Engineering (IJMTIE)*, Vol. 1, No. 2, pp. 109-116.
19. LA Zadeh, (1965), “Fuzzy sets information and control”, Vol. 8, pp. 338-353.

20. LA Zadeh, (1976), “Fuzzy-algorithm approach to the definition of complex or imprecise concept”, *International Journal of Man-Machine Studies*, Vol. 8, pp. 249-291.

21. JM Mendel, (1995), “Fuzzy Logic Systems for Engineering: A Tutorial”, *IEEE Proc*, Vol. 83, pp. 345-377.

22. EA Cox, (1992), “Fuzzy Fundamentals”, *IEEE Spectrum*, Vol. 29, pp. 58-61.

23. EH Mamdani and S Assilia, (1975), “An experiment in linguistic synthesis with a fuzzy logic controller”, *International Journal of Man-Machine Studies*, Vol. 7, pp.1-13.

24. RR Yager and DP Filev, (1999), “Essential of fuzzy modeling and control”, John Willey and Sons Inc., New York.

25. JSR Jang, CT Sun and E Mizutan, (2005), “Neuro-fuzzy and soft computing”, Prentice Hall of India, New Delhi.

26. BN Panda, A Jena and SS Mahapatra, (2010), “Prediction of surface finish and material removal rate in Wire Electrical Discharge Machining (WEDM) using fuzzy approach”, *International Journal of Manufacturing Technology and Industrial Engineering*”, Vol. 1, No. 2, pp. 109-116.

27. YM Puri and NV Deshpande, (2004), “Simultaneous optimization of multiple quality characteristics of WEDM based on fuzzy logic and Taguchi technique”, Proceedings of the Fifth Asia Pacific Industrial Engineering and Management Systems Conference 2004.

28. Yih-fong Tzeng and Fu-chen Chen, (2007), “Multi-objective optimization of high-speed electrical discharge machining process using a Taguchi fuzzy-based approach”, *Materials and Design*, Vol. 28, pp. 1159-1168.

8. Communication

D. M. Padhy, R. K. Sahu, S. Datta, S. S. Mahapatra, “*Use of Fuzzy Expert System Combined with Taguchi Philosophy for Parametric Optimization of EDM on UTS 304 Grade Stainless Steel*", International Conference on Industrial Engineering (ICIE 2011); Theme: Modern Trends in Industrial Engineering, to be held during November 17-19, 2011, to be organized by Department of Mechanical Engineering, S. V. National Institute of Technology, Surat, in Association with Indian Institute of Industrial Engineering (IIIE), NHQ-Mumbai.