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Material Removal Rate Optimization During Production of Implants

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Abstract

The need for more efficient and efficient manufacturing processes to convert biocompatible materials into artificial components of the human body (implants) with a high level is rapidly increasing. The processing of biocompatible materials as one of the key processes in implant manufacturing needs to be improved due to the significant impact of the machined surface quality on compatibility and osseointegration with human organs as well as with respect to tissues, bones and the environment of the human body. The challenges of processing biocompatible materials due to their application as bio-implants in the human body and the nature of the material properties and microstructures have been studied and solved by various researchers. In this research work a review on ongoing trends and developments of the machining of biocompatible materials are discussed. A range of possible machining technologies and strategies on various biocompatible materials using conventional (milling, turning and drilling) and non-conventional or advanced such as electrical discharge machining (EDM) are presented and discussed. In this work, a multi-objective crow search algorithm is proposed which is used to maximize the material removal rate and minimize the surface roughness in order to develop implant devices either it is made up of metal, polymer or ceramics. The result analysis shows approx. 3% of surface roughness minimization as compared to existing work.

Keywords

Biomedical materials, Implants, Machining, Electric Discharge Machining, Optimization.

I. INTRODUCTION

An implant is a medical device manufactured to replace a missing biological structure, to support a damaged biological structure or to improve an existing biological structure. Medical implants are artificial devices, as opposed to a transplant, which is transplanted biomedical tissue. The surface of the implants that come into contact with the body can be made with a biomedical material such as titanium, silicone or apatite, whichever is more functional [1]. In some cases, the systems contain electronic components, e.g. artificial pacemakers and cochlear implants. Some implants are bioactive, such as subcutaneous drug delivery devices in the form of implantable pills or drug eluting stents. Some of the examples are given in figure 1.1.

Over the last few years more and more large medical companies and their suppliers shifted part productions from conventional machining to EDM. This article explores growth of EDM as a manufacturing technique for medical implants and other medical device components. Compared to other machining processes, EDM offers a variety of advantages when cutting complex medical components including surgical tools and implants. Let's take a closer look at the process characteristics before we delve into specific examples.

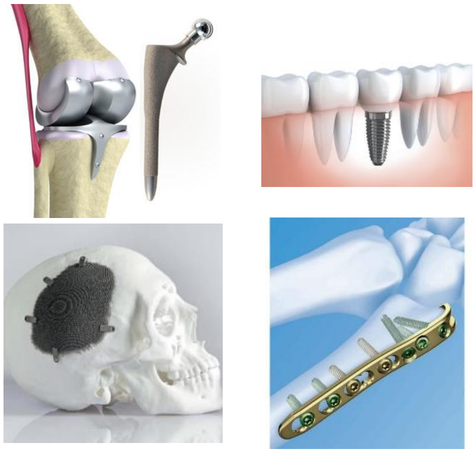

Figure 1: Biomedical Implant Devices

EDM is an ideal companion for the production of tools, molds or similar items. EDM can complicate complex and unusual shapes made from extremely hard materials. Previous EDM machining was only used in machine tool applications, but with the evolution of the machine it has been widely used to cut extremely complex shapes for automotive and aircraft components [2][3].

Since EDM is a thermal process, hard materials such as hardened steel, hard metal and electrically conductive ceramics can also be machined. EDM also allows the machining of complex shapes. Since the tool electrode does not have to rotate to remove material such as milling or grinding, holes with sharp angles and irregular contours can be easily machined. The reaction forces generated in the EDM space are insignificant, which also facilitates the machining of thin and flexible parts, deep grooves and holes and micro-parts that are difficult to machine by milling [4].

In general, the machining accuracy of erosion is very high in the order of several micrometers. On the other hand, the material removal rate of EDM is low compared to other machining processes. Therefore, erosion is preferably used in the construction of molds and dies, in the drilling of fuel nozzles and in the manufacture of aircraft engines, where complex shapes in hard materials and with high precision are required. Be worked on.

Benefits of EDM Machining

- Cutting of extremely hard conductive materials that can prove challenging on conventional machining methods.
- EDM machining provides very smooth finish, with no burrs or rough patches so EDM is an excellent choice when finish or appearance matter in the final product.
- Drastic reduction in production time and unit cost and also provides increased throughput from the machine.
- The precision inherent in the EDM process allows complex designs to be machined cost-effectively.
- EDMs come with inbuilt precision and accuracy which allows machining of complex designs in cost-effective manner.

In this modern era of digitalization of technologies and global competitiveness, enterprises and industries need to reduce time and save money and the only way they see it is through optimization of process parameters. EDM process suffers from a number of limitations such as higher power consumption, high cost on initial investment and large floor space. Further, it can machine only conductive materials and is more expensive when compared to a traditional process like milling and turning. Therefore, a careful selection of the different parameters and careful planning is recommended before commencing the machining process.

Selection of suitable machining parameters is critical to achieve optimum machining results. Many researchers and academicians have tried performing optimization for various manufacturing processes (both conventional and non-conventional) through traditional and non-traditional optimization methods considering various process parameters to obtain optimum results. For EDM, MRR (Material Removal Rate), and Ra (Roughness Parameter, average roughness) are considered as the most important parameters and the need to maximize MRR and minimize Ra has always been the goal for many researchers and industries.

II. LITRATURE REVIEW

Aharwal et al. [5] optimized the machining parameters on the electric discharge machine (EDM) using AlSiC as the workpiece and pure copper as the electrode. The processing parameters examined in this thesis are the material removal rate (MRR) and the surface roughness. The control parameters used are discharge voltage (v), discharge current (Ip), pulse charge factor (Tau), pulse activation time (ton). The Taguchi technique (L16b orthogonal matrix) was used for the experimental design and the genetic algorithm for optimization. Material removal rate analysis provides optimal values when the current is high and the voltage is low, while the surface roughness is best when both are low.

Mohan et al [6] investigated the influence of the rotating tube electrode on the machining properties of Sic / 6025 aluminum composite materials. In his study, he found the positive effect of peak current on surface roughness (SR), rate of material removal (MRR) and tool wear rate (TWR). TWR, MRR and SR were greater when treated with positive versus negative polarity. The pulse duration was inversely proportional to TWR, MRR and SR. The speed and diameter of the electrode hole had a great influence on the material removal rate and the decrease in SR and TWR. The genetic algorithm was used to achieve an optimal stock removal rate, better surface quality and minimal tool wear.

Khan et al [7] evaluated tool wear along the tool length versus wear along its cross section. The wear of brass and copper tools increased with increasing current and voltage, but the wear along its cross section was greater than that along its length. As the current wear rate increases, this has also increased, demonstrating that with increasing current, both material removal and tool wear increase, but tool wear increases relatively more. The highest wear rate was found for steel when using brass as the tool electrode. A faster material removal rate was observed using a brass electrode on an aluminum part. When machining steel using a copper electrode, the material removal rate was low due to the low thermal conductivity of the workpiece.

Muttamara et al [8] compared the effect of creating conductive layers on aluminum oxide using graphite, copper and copper infiltrated graphite according to the properties of EDM. When copper infiltrated graphite was used in the processing of 95% pure alumina, the material removal rate was much higher and the tool wear rate was lower than that of graphite and copper electrode. The material removal rate was increased by 60% using a straight polarity graphite electrode, while the material removal rate was increased by 80% using copper infiltrated graphite with straight polarity and the same conditions. No copper elements were found on the conductive layers with graphite and copper infiltrated graphite, while the results were investigated by energy dispersive spectroscopy (EDS). Using straight polarity copper infiltrated graphite, a surface roughness of 25 μm was achieved.

Priyaranjan et al [9] evaluated that when machining AISI 329 stainless steel, good machinability and better hole quality are achieved by using copper as a tool electrode compared to the brass electrode. Brass electrodes wear out faster than copper electrodes due to their low melting point, high specific electrical resistance, and low thermal conductivity.

Chan et al. [10] presented an approach for optimizing feed rate based on material removal rate (MRR). Considering a toolpath with predefined feed rates, raw material geometry and cutter shape, the MRR histogram can be calculated efficiently with very fine resolution using a GPU-based geometric modeling core. Based on the evaluation of the finest MRR histogram, error-controlled splitting algorithms are developed to segment the toolpath step-by-step into a user-defined number of sub-regions. Different sub-intervals are assigned to different feed rates, so that an almost constant MRR is achieved while the shape of the given toolpath remains unchanged. Experimental tests on real examples confirm the effectiveness of this method.

As from literature review it is studied and concluded following problems that has to be tackled:

- In past research, different EDM methodologies are discussed such as wire-EDM, die sink-EDM, powder-mixed EDM, dry-EDM, etc. So, there is need to explore parameter optimization and to study their effect on performance parameters under optimal EDM factors and thereby developing a mathematical model and study their combined effect for each response considering all the parameters along with the process constraints simultaneously.
- Most of the past research work mainly used Taguchi optimization method of parameters to study their effects on the EDM process responses. More and consistent use of recent optimization techniques is also required specially to attempt multi-objective problems of EDM process.
- But in recent scenario, bio-inspired optimization techniques are used for multi-criteria decision-making such as genetic algorithm (GA), particle swarm optimization (PSO), ant colony optimization (ACO), crow optimization, etc.

III. METHODOLOGY

The optimized level of production of implant devices is considered to be potential and research efforts have already been made to develop it further. These methods generally pose technical problems based on a poor understanding of optimal material removal rate operation. Following steps are to tb followed for optimized material removal rate for implant production are:

- Step 1: Choosing the appropriate material for design of bioimplants.
- Step 2: Designing and manufacturing of implant using EDM process.
- Step 3: Optimizing the material removal rate as well surface roughness of the material. This is performed on considering the optimal level of voltage, current, pulse on time as well pulse off time.

Material Selection

The work piece material used was aluminum silicon carbide composite in the form of a 55×55×22 mm³ block. The centrifugal casting method was used for the preparation of Al-SiC material. Various combinations of Aluminum and Silicon have been tried before selecting 90% aluminum and 10% silicon carbide which has desired mechanical properties. These properties and data were collected from research work [5].

Machining

The experimental study was carried out using dielectric fluid as EDM oil on Electric discharge Machine, (Table: 550x350 sq mm, X: 300mm, Y: 200mm, Z: 250mm, MOFSET pulse generator). These machining process were collected from research work [5].

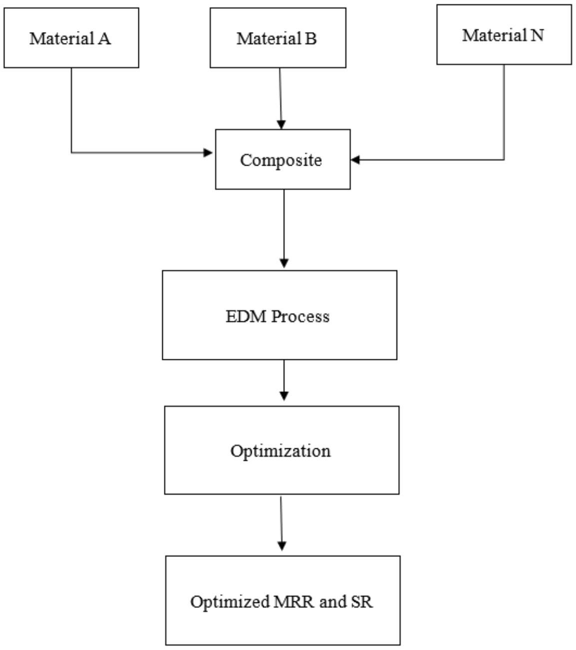

Figure 2: Flow chart of Implant Production

Multiobjective Parameter Optimization

For a multi-objective optimization problem, the aim is to find a vector $X^* = \{x_1, x_2 \dots x_n\}$ which will satisfy the constraints

$$\begin{cases} g_i(X) \geq 0 & i = 1, 2, \cdots, Q \\ h_j(X) = 0 & j = 1, 2, \cdots, P \end{cases} \qquad (1)$$

and will minimize the vector function:

$F(X) = \{ f_1(X), f_2(X) \dots f_M(X)\}$

$X = \{x_1, x_2 \dots x_n\} \in \Omega$

Where X= decision variables, the set Ω denotes the feasible region and M is the number of objective functions to be minimized.

The quality of a solution is explained in terms of trade-offs between conflicting objectives. Let X' and X'' be two solutions of the M-objective minimization problem, both of which satisfy the aforementioned constraints.

In this work multi-objective crow optimization is used to optimize parameters.

Multi-objective Crow optimization (CO)

The measured data collected from simulated mathematical model for the optimizing MRR and SR. The result obtained from optimization which is implemented in MATLAB. In order to obtain the best solution for maximum MRR output and minimum SR output.

Maximize MRR and Minimize SR [5]:

$$MRR = 19.9 + 5.305\ Ip - 0.464\ V + 0.0394\ Ton + 0.886\ Tau \qquad (2)$$

$$SR = 2.926 + 0.2303\ Ip + 0.0235\ V + 0.004323\ Ton - 0.0222\ Tau \qquad (3)$$

Where,

I_P = Peak Current

V = Gap Voltage

T_{on} = Pulse on Time

Tau = Duty Factor

Crow optimization works in four steps as:

- Formation of crows flock
- Each crow remembers its hiding places
- Crows follow each other to steal their food
- Crows protect their hiding place from other

Let the flock of crows be n. The position of each crow (C_i) at any time (T_{itr}) in the search space is ($x^{Ci}_{itr} = x_1, x_2 \ldots\ldots\ldots\ldots x_d$). Each crow has its hiding place in memory such that ($m^{Ci}_{itr} = m_1, m_2 \ldots\ldots\ldots\ldots m_d$). This is the best position that C_i has obtained so far. Now at any time T_{itr}, C_j wants to visit its hiding place and at same time C_i decided to follow C_j to see its hiding place. In this situation, two states may happen:

State A: Crow C_j does not realize that it has been followed by C_i

$$x^{C_i}_{itr+1} = x^{C_i}_{itr} + r_{Ci} * F^{C_i}_{itr} * (m^{C_j}_{itr} - x^{C_i}_{itr}) \qquad (4)$$

where r_{Ci} = random number with uniform distribution between 0 and 1.

$F^{C_i}_{itr}$= Flight length of C_i at time T_{itr}.

State B: Crow C_j realize that it has been followed by C_i and it tries to fool C_i by going to another position in search space

$$x^{C_i}_{itr+1} = x^{C_i}_{itr} + r_{Ci} * F^{C_i}_{itr} * \left(m^{C_j}_{itr} - x^{C_i}_{itr}\right), when\ r_{Cj} \geq A^{C_i}_{itr} \qquad (5)$$

Otherwise a random position is chosen

where r_{Cj} = random number with uniform distribution between 0 and 1.

$A^{C_j}_{itr}$= Probability of awareness of C_j.

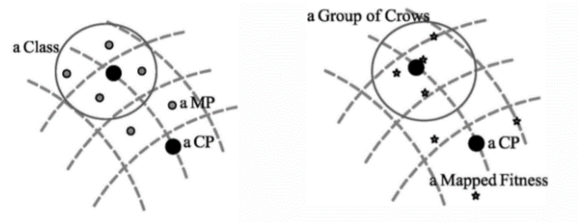

Figure 3: Crow Group

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Algorithm: Multiobjective crow optimization
Initialization
Generate and classity MPs, MWVs and CPs
Initialize the position of crows and classity them
Form S-groups
Main Loop
While iter < max iteration
Select greedy crows
Perform the chasing process
Form N-groups
Update S-groups End
```

IV. RESULT ANALYSIS

In this research work, the material properties and experimental results are taken from [5] which used a metal matrix composite aluminium silicon carbide can be made by combining Aluminium and Silicon Carbide by using either powder metallurgy method or centrifugal casting method. The material characteristics depend on the proportion of constituent elements. Presence of silicon makes the material cheaper and harder. As the silicon constituent is increased in the composite, the product becomes harder but then, the machinability of the product becomes more and more difficult. In order to find out the proportion of silicon carbide in order have good machining as well, it is important to study the machinability by testing various combinations of constituents. Each experiment is carried out with a particular set of input parameters and depth of machining for all combination of experiments. input parameters' level is shown in Table I.

Table I: Input Parameter Values

EDM Factors	Units	Level_1	Level_2	Level_3	Level_4
Peak current	Ampere	5	10	12	15
Gap voltage	Volts	40	45	50	55
Pulse on time	μSecond	100	150	200	250
Duty factor	-	20	25	27	30

In this work two responses namely Material Removal Rate (MRR) and Surface Roughness (SR) are taken into consideration.

Material Removal Rate (MRR)

MRR is calculated by difference of work specimen's pre machining weight and post machining weight, So MRR is calculated by equation:

$$\text{MRR} = \left(\frac{W_i - W_f}{t \times \rho}\right) mm^3/\text{min} \tag{6}$$

Where,

W_i = Pre machining weight of specimen (kg).

W_f = Post machining weight of specimen (kg.).

t = Machining Time(min.).

ρ = Density of En-24 (7.84×10^{-6} kg/mm^3).

Material removal rate is directly proportional to pulse-on time, discharge current and supply voltage and inversely proportional to spark-off time.

Surface Roughness (SR)

The quality of surface after machining is evaluated with surface quality measure such as surface roughness.

A prediction model for surface roughness and MRR are established by taking surface roughness/MRR as a dependent variables and input variables (pulse-on time, supply voltage, current and duty factor) as independent variables. Linear regression equations are established between them using MATLAB 2018 software, and the statistical tests (F-test and t-tests) are carried out to test the significance levels.

In linear regression analysis, the general form of equation is as shown in below in equation (7):

$$Ra = a_1x_1 + a_2x_2 + a_3x_3 + \ldots\ldots\ldots\ldots.. + a_nx_n + k \tag{7}$$

In both the above case, a_1, a_2, a_3, and a_n are parameters and x_1, x_2, x_3, and x_n represent the selected input variables, and 'k' is a constant.

Table II: Experimental Data Values [5]

Exp. No.	Ip	V	Ton	Tau	MRR	SR
1	5	40	100	20	44.16	4.8
2	5	45	150	25	58.41	5.27
3	5	50	200	27	54.37	5.4
4	5	55	300	30	60.96	5.8
5	10	40	150	27	81.97	6.1

6	10	45	100	30	88.77	6.3
7	10	50	300	20	77.97	7.4
8	10	55	200	25	76.77	7
9	12	40	200	30	96.96	7.2
10	12	45	300	27	93.56	7.6
11	12	50	100	25	87.47	6.9
12	12	55	150	20	81.97	7.4
13	15	40	300	25	118.55	7.9
14	15	45	200	20	108.96	7.7
15	15	50	150	30	105.96	7.3
16	15	55	100	27	98.96	7.3

This MO-COA is used to optimize process parameter for maximize MRR and minimize SR simultaneously. While, COA is used to optimize process parameter for minimize single function only. Hence for maximizing MRR, inverse of its value is taken. when the iteration stage is finished up, the algorithm yields the best search space with best fitness. Multi Objective Crow Optimization Algorithm for MRR and SR is shown in below section. By changing weightage for MRR and SR different solutions can be found. The experimental data has been shown in Table-II [5].
MRR and SR Optimization Result

For optimization of MRR and SR is performed with different iteration values and their graphs are shown below.

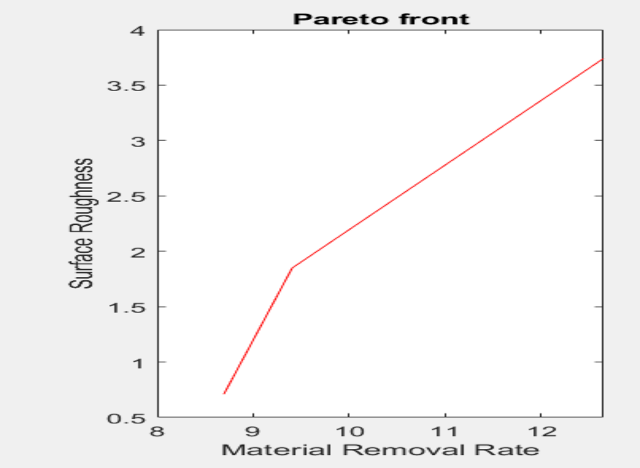

Figure 4: MRR versus SR for 1000 Iteration

Figure 4 shows that with increase in MRR there is increase in SR.

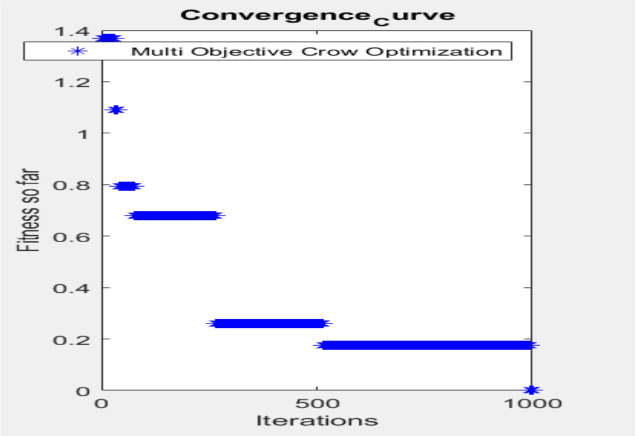

Figure 5: Convergence Curve for 1000 Iteration

For validation purposes, four separate experiments were conducted, and the data were recorded. The value of MRR is computed using prediction model and measured and both are compared. It is observed that the maximum percentage of error was 3% for MRR.

V. CONCLUSION

The various machining techniques have an effect on the physical properties of the implants which may have a significant influence on the biocompatibility. From this research it was observed that MRR is affected significantly by pulse on time. From review of literature it was observed that researchers have used design of experiments and optimization method during machining of different workpiece materials. But very few researchers have tried to establish the relationship between input parameter (gap cur-rent, gap voltage, pulse on time and pulse off time) and EDM performance measures during machining of implant materials. In this research work a multi-objective optimization of responses such material removal rate and surface roughness by using crow optimization methods.

Following conclusion are derived from result analysis:

- MRR optimization error rate was reduced to 3%
- Optimization of EDM factors and parameters can improve the performance as well as reduces the environmental impact and production cost.
- The multi-objective optimization during EDM machining of different workpiece materials under different scenarios can leads to the direction of manufacturing more biocompatible devices.

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