# Investigation of Machining Parameters in Abrasive Jet Machining On Ti-6Al-4V USING GRA AND PCA

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**Abstract -** Abrasive Jet Machining (AJM) is an unconventional machining process which is to drilling of metals and non metals. In this paper drilling was done on Ti-6Al-4V with unlike SOD's, Pressures and Nozzle Diameters in order to determine the process capability of AJM.AJM removes metal from the work piece through the action of focused beam of abrasive loaded gas. Micro particles are propelled by a pressurized air of velocity due to this reason AJM applicable for cutting, etching, drilling, polishing and cleaning. In this paper optimization of process parameters of Abrasive Jet Machining of Ti-6Al-4V by Taguchi methodology is presented. The Values obtained in Taguchi Analysis was compared with the Analysis of Variance (ANOVA).Various levels of Experiments are conducted using L27 Orthogonal Array for both MRR and Kerf

**Key Words**: Abrasive Jet Machining, Ti-6Al-4V, SOD, and Pressure. L27 orthogonal Array, PCA and GRA

## 1. INTRODUCTION

In Abrasive Jet Machining, fine abrasive particles (typically ~0.025mm) are accelerated in a gas stream (commonly air) towards the work surface. As the particles impact the work surface, they cause small fractures, and the gas stream carries both the abrasive particles and the fractured (wear) particles away. A high-velocity jet of dry air, nitrogen, or carbon dioxide Containing abrasive particles is aimed at the work piece surface under controlled conditions. The jet velocity is in the range of 150-300 m/s and pressure is from two to ten times atmospheric pressure. Abrasive Jet Machining is used for drilling, deburring, etching, and cleaning of hard and brittle metals, alloys, and non-metallic materials (e.g., germanium, silicon, glass, ceramics, and mica). No heat is required in the process of machining a piece with an abrasive jet. As a result, parts from an assembly do not experience structural changes from overheating. There are no toxic wastes given off by abrasive water jets, and no oils are necessary in the process of machining. Aluminium oxides, silicon carbides, Boron Carbides, Crushed glass, Sodium bicarbonate, Dolomite are Various Abrasive Particles used for Machining in Abrasive Jet Machining. Re use of abrasives is not recommended since the cutting ability of abrasive decrease after the usage and also the contamination of wear materials clogging the nozzle and the cutting unit orifice. The Major Process Parameters that affects the MRR in AJM are Gas Pressure, Velocity of Abrasive Particles, Abrasive mass flow rate, Mixing ratio, Nozzle Tip Distance.

## 2. LITERATURE REVIEW

The literature study of Abrasive Jet Machine reveals that the machining process was started a few decades ago. Till date there has been a complete and detailed experiment and theoretical study on this process. Most of the studies argue over the hydrodynamic characteristics of abrasive jets, hence determining the influence of all operational variables on the process usefulness including abrasive size, kinds and concentration, impact speed and angle of strike. Other papers found new problems concerning carrier gas typologies, nozzle shape, size and wear rate, jet velocity and pressure, standoff distance (SOD). These papers state the overall process performance in terms of material removal rate(MRR), geometrical tolerances and surface finish of work pieces, as well as in terms of nozzle wear rate or nozzle life. Finally, there are several significant and important papers which focus on either leading process mechanisms in machining of both ductile and brittle materials, or on the development of systematic experimental statistical approaches and artificial neural networks to predict the relationship between the settings of operational variables and the machining rate and accuracy in surface finishing. Some researchers have also done the CFD simulation of machining process

The study of the results of machining under various operating conditions approves that a commercial AJM machine was used, with nozzles having diameter ranging from 0.45 to 0.65 mm, the nozzle materials being either tungsten carbide or sapphire, which have high tool lives. SIC and aluminum oxides were the two abrasives used. Other parameters studied were standoff distance (5–10 mm), spray angles (60° and 90°) and pressures (5 and 7 bars) for materials like ceramics, glass, and electro-discharge machined (EDM) die steel. The holes drilled by AJM may not be circular and cylindrical but almost elliptical and bell mouthed in shape. High material removal rate conditions may not necessarily r small narrow clean-cut machined areas.

## 3. METHODOLOGY

### DESIGN OF EXPERIMENT (DOE)

**Design of experiments** (DOE) is a systematic method to determine the relationship between factors affecting a process and the output of that process. In other words, it is used to find cause-and-effect relationships. This information is needed to manage process inputs in order to optimize the output.

### TAGUCHI METHOD

Taguchi method is a process to be optimized has several control factors which directly decide the target or desired value of the output. The optimization then involves determining the best control factor levels so that the output is at the target value such that problem is optimized

### GREY RELATIONAL ALGORITHM (GRA):

Grey analysis is one of the optimization techniques being used in this processing. It is one of the traditional approaches of finding out the optimized solutions.

Grey analysis uses a specific concept of information. It defines situations with no information as black, and those with perfect information as white. However, neither of these idealized situations ever occurs in real world problems. In fact, situations between these extremes are described as being grey, hazy or fuzzy. Therefore, a grey system means that a system in which part of information is known and part of information is unknown. With this definition, information quantity and quality form a continuum from a total lack of information to complete information – from black through grey to white. Since uncertainty always exists, one is always somewhere in the middle, somewhere between the extremes, somewhere in the grey area.

So, always the parameter va**lues are limited within a certain range of values (usually '0' to '1').**

The normalization of any parameter can be done based on 3 main classifications. They are,

Higher the better condition is used in certain conditions, where the importance of the desired parameter is better at its highest limits.
The normalized value, $X^0_i(k)$ can be calculated as

$$x^*_i(k) = \frac{x^o_i(k) - \min x^o_i(k)}{\max x^o_i(k) - \min x^o_i(k)}$$

Lower the better condition is used in certain conditions, where the importance of the desired parameter is better at its lowest limits.

$$x^*_i(k) = \frac{\max x^o_i(k) - x^o_i(k)}{\max x^o_i(k) - \min x^o_i(k)}$$

However, if there is a definite target value (desired value) to be achieved, the original sequence will be normalized. It is also termed as nominal the better.

$$x^*_i(k) = 1 - \frac{|x^o_i(k) - x^o|}{\max x^o_i(k) - x^o}$$

Where $i = 1$**...**, $m$; $k =$ **1...**, $n$. $m$ is the number of experimental data items and $n$ is the number of parameters

Max $x^o{}_i(k)$ the largest value of $x^o{}_i(k)$, min $x^o{}_i(k)$ the smallest value of $x^o{}_i(k)$, and $x^o$ is the desired value

For the given experimental details, output parameter like **METAL REMOVAL RATE** is treated to be higher the better.

Whereas another parameter **kerf** is treated to be lower the better.

The grey relation coefficient $\xi_i(k)$ for the $k^{th}$ performance characteristics in the $i^{th}$ experiment can be expressed as:

$$\xi_i(k) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{oi}(k) + \zeta \Delta_{max}}$$

For the current process, **ζ=0.5, since there are two** output process parameters.

The grey grade can be defined as the average of Grey relational coefficients of desired parameters.

Here, the average is done for the grey relation coefficients of all the four parameters, by using the following formulae. Grey grade,

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k)$$

n = No of parameters
k = deviation of parameters

### PRINCIPLE COMPONENT ANALYSIS:

Pearson and Hotelling initially developed PCA to explain the structure of variance-covariance by way of the linear combinations of each quality characteristic. Principal component analysis (PCA) is a mathematical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. The number of principal components is less than or equal to the number of original variables.

The normalization of any parameter is same as that of GRA

By using the normalized response array, the Correlation coefficient array(R) is obtained using the following formula

**Where J=1,2,…,n; L=1,2,…,n.**

Cov ($x_i(j)$, $x_i(l)$) is the covariance of sequences $x_i(j)$ and $x_i(l)$

$\sigma_{x_i}(j)$, $\sigma_{x_i}(l)$ is the standard deviation of sequence $x_i(j)$ and $x_i(l)$ respectively.

The Eigen values and eigenvectors are determined from the correlation coefficient array,

$$(R - \lambda_\kappa I_m)V_{i\kappa} = 0$$

Where $\lambda_\kappa$ Eigen values, $\sum_{\kappa=1}^{n} \lambda_\kappa = n$,

**κ =1,2,…,n;** $V_{i\kappa} = [a_{\kappa1} a_{\kappa2} \dots a_{\kappa n}]^T$ is the eigenvector corresponding to the Eigen value $\lambda_\kappa$.

The uncorrelated principal component is formulated as:

$$Z_{m\kappa} = \sum_{i=1}^{n} x_m(i) \cdot V_{i\kappa}$$

Where $Z_{m1}$ is called the first principal component, $Z_{m2}$ is called the second principal component and so on. V relates to the respective Eigen vector &x determines the normalized value.

The multi-response performance index (MPI) is calculated for $j^{th}$ trial by using the formula:

$$MPI_j = \sum_{i=1}^{n} W_i \times Z_{ij}$$

**Where, j=1,2,…,m.**

$Z_{ij}$ is the $i^{th}$ principal component corresponding to $j^{th}$ trial.

$W_i$ is the proportion of overall variance of the responses explained by $i^{th}$ principal component.

## 4. EXPERIMENTATION, ANALYSIS & RESULTS

Pressure, nozzle diameter and sod are as process parameters and MRR and kerf accuracy are as output parameters

**Table 1: AJM Process Parameters and Levels**

| Machining Parameters | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Air Pressure | 6 | 8 | 10 |
| Nozzle Diameter | 2 | 3 | 4 |
| Standoff distance | 3 | 6 | 9 |

**Table 2: MRR and kerf values**

| Column | Factors | | | Process characteristics | |
|---|---|---|---|---|---|
| Trail No | Air Pressure (bar) | Standoff distance(mm) | Nozzle Diameter(mm) | MRR(gram/sec) | Kerf accuracy |
| 1 | 6 | 3 | 2 | 0.000083711 | 1.9 |
| 2 | 6 | 3 | 3 | 0.00072012 | 2.7 |
| 3 | 6 | 3 | 4 | 0.00113255 | 3.4 |
| 4 | 6 | 6 | 2 | 0.00012202 | 3 |
| 5 | 6 | 6 | 3 | 0.00152016 | 3.2 |
| 6 | 6 | 6 | 4 | 0.00250614 | 3.8 |
| 7 | 6 | 9 | 2 | 0.00012588 | 3.7 |
| 8 | 6 | 9 | 3 | 0.00199562 | 4.2 |
| 9 | 6 | 9 | 4 | 0.00240666 | 4 |
| 10 | 8 | 3 | 2 | 0.00013897 | 1.9 |
| 11 | 8 | 3 | 3 | 0.00089394 | 2.7 |
| 12 | 8 | 3 | 4 | 0.00255535 | 3 |
| 13 | 8 | 6 | 2 | 0.00046337 | 2.8 |
| 14 | 8 | 6 | 3 | 0.00163727 | 2.9 |
| 15 | 8 | 6 | 4 | 0.00427647 | 3.6 |
| 16 | 8 | 9 | 2 | 0.00013411 | 3 |
| 17 | 8 | 9 | 3 | 0.0024635 | 4.2 |
| 18 | 8 | 9 | 4 | 0.0027649 | 5.9 |
| 19 | 10 | 3 | 2 | 0.00015724 | 1.9 |
| 20 | 10 | 3 | 3 | 0.00143754 | 1.5 |
| 21 | 10 | 3 | 4 | 0.00176127 | 1.9 |
| 22 | 10 | 6 | 2 | 0.00097618 | 2.7 |
| 23 | 10 | 6 | 3 | 0.00248885 | 1.5 |
| 24 | 10 | 6 | 4 | 0.00311056 | 2.7 |
| 25 | 10 | 9 | 2 | 0.00012277 | 2.9 |
| 26 | 10 | 9 | 3 | 0.00012277 | 2.3 |
| 27 | 10 | 9 | 4 | 0.00308931 | 4.06 |

### Calculation using GRA

**Table 3: Grey relation coefficients and CG values**

| Column | GRC MRR | GRC KERF | GG |
|---|---|---|---|
| 1 | 0.333333 | 0.846154 | 0.589744 |
| 2 | 0.370861 | 0.647059 | 0.50896 |
| 3 | 0.40005 | 0.536585 | 0.468317 |
| 4 | 0.335376 | 0.594595 | 0.464985 |
| 5 | 0.432004 | 0.564103 | 0.498053 |
| 6 | 0.542161 | 0.488889 | 0.515525 |
| 7 | 0.335583 | 0.5 | 0.417792 |
| 8 | 0.478928 | 0.44898 | 0.463954 |
| 9 | 0.528563 | 0.468085 | 0.498324 |
| 10 | 0.336288 | 0.846154 | 0.591221 |
| 11 | 0.382627 | 0.647059 | 0.514843 |
| 12 | 0.54915 | 0.594595 | 0.571872 |
| 13 | 0.354749 | 0.628571 | 0.49166 |
| 14 | 0.442687 | 0.611111 | 0.526899 |
| 15 | 1 | 0.511628 | 0.755814 |
| 16 | 0.336026 | 0.594595 | 0.46531 |
| 17 | 0.536248 | 0.44898 | 0.492614 |
| 18 | 0.581045 | 0.333333 | 0.457189 |
| 19 | 0.337277 | 0.846154 | 0.591715 |
| 20 | 0.424772 | 1 | 0.712386 |
| 21 | 0.45459 | 0.846154 | 0.650372 |
| 22 | 0.388458 | 0.647059 | 0.517758 |
| 23 | 0.539748 | 1 | 0.769874 |
| 24 | 0.64261 | 0.647059 | 0.644834 |
| 25 | 0.335416 | 0.611111 | 0.473264 |
| 26 | 0.335416 | 0.733333 | 0.534375 |
| 27 | 0.638451 | 0.462185 | 0.55031 |

Mean Grey relation grades are calculated by taking average of each level of the each parameter individually

**Table 4: Mean Gray Relation Grade array**

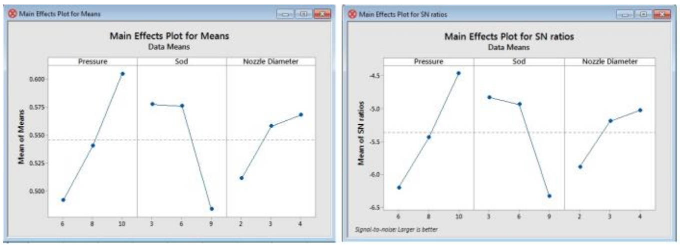
| FACTOR | LEVEL 1 | LEVEL 2 | LEVEL 3 |
|---|---|---|---|
| Pressure | 0.491739 | 0.540825 | 0.604988 |
| Stand of Distance | 0.577715 | 0.576156 | 0.483682 |
| Nozzle Diameter | 0.511494 | 0.557995 | 0.568063 |

The levels indicating maximum value for each parameter is considered as the optimum level for that particular parameter. With the above table, the optimum combination is obtained as **{A3, B1, and C3}.**

**Table 5:** optimal values obtained with GRA

| PRESSURE (bar) | SOD (mm) | NOZZLE DIAMETER (mm) | MRR( gram/sec) | Kerf |
|---|---|---|---|---|
| 10 | 3 | 4 | 0.00176127 | 1.9 |

The mean effect graphs for all the 3 parameters are plotted as Fig 1: Main effects plot for means]




### Calculation Using PCA

The Eigen values obtained by analyzing the data using principle component technique are tabulated below

**Table 6: Eigen values of normalized parameters**

| | | |
|---|---|---|
| Eigen value | 1.4444 | 0.5556 |
| Proportion | 0.722 | 0.278 |
| Cumulative | 0.722 | 1.000 |

**Table 7: Eigen vectors of normalized parameters Eigen vectors**

| Variable | PC 1 | PC 2 |
|---|---|---|
| NM SR | -0.707 | -0.707 |
| NM MRR | 0.707 | -0.707 |

The principle components and multi performance index values are calculated using the formulas is tabulated below.

Mean MPIs are calculated using the below obtained MPIs by taking the average of the MPIs for each level of input parameter individually. They are obtained as follows

**Table 8: Principle components and multi performance index values**

| Column | Z1 | Z2 | MPI |
|---|---|---|---|
| 1 | 0.64273 | -0.6427 | 0.28537 |
| 2 | 0.45952 | -0.4724 | 0.20043 |
| 3 | 0.34639 | -0.3606 | 0.14984 |
| 4 | 0.40687 | -0.6215 | 0.12098 |
| 5 | 0.19162 | -0.6761 | -0.0496 |
| 6 | -0.0492 | -0.5956 | -0.2011 |
| 7 | 0.22485 | -0.5786 | 0.0015 |
| 8 | -0.071 | -0.7459 | -0.2587 |
| 9 | -0.0864 | -0.697 | -0.2562 |
| 10 | 0.63341 | -0.652 | 0.27605 |
| 11 | 0.43409 | -0.5621 | 0.15714 |
| 12 | 0.45748 | -0.4745 | 0.1984 |
| 13 | 0.37756 | -0.6508 | 0.09167 |
| 14 | 0.22008 | -0.744 | -0.0479 |
| 15 | -0.1281 | -0.6744 | -0.28 |
| 16 | 0.0492 | -0.8828 | -0.2099 |
| 17 | -0.3374 | -1.0766 | -0.5429 |
| 18 | -0.4521 | -0.4521 | -0.4521 |
| 19 | 0.63033 | -0.6551 | 0.27297 |
| 20 | 0.36369 | -0.6647 | 0.0778 |
| 21 | 0.47546 | -0.4886 | 0.20744 |
| 22 | 0.47871 | -0.9353 | 0.08562 |
| 23 | 0.30144 | -1.1126 | -0.0917 |
| 24 | 0.57187 | -0.585 | 0.25025 |
| 25 | 0.35985 | -0.9256 | 0.00249 |
| 26 | 0.00378 | -1.0246 | -0.2821 |
| 27 | -0.2112 | -0.8025 | -0.3755 |

**Table 9: mean MPI array**

| FACTORS | LEVEL 1 | LEVEL 2 | LEVEL 3 |
|---|---|---|---|
| Pressure | -0.00082 | -0.08995 | 0.016364 |
| Sod | 0.102975 | -0.09305 | -0.08433 |
| Nozzle Diameter | -0.202829 | -0.01353 | 0.26371 |

The levels indicating maximum value for each parameter is considered as the optimum level for that particular parameter. With the above table, the optimum combination is obtained as **{A3, B1, and C3}.**

**Table 10: optimal values obtained with PCA**

| PRESSURE (bar) | SOD (mm) | NOZZLE DIAMETER (mm) | MRR( gram/sec) | Kerf |
|---|---|---|---|---|
| 10 | 3 | 4 | 0.00176127 | 1.9 |

## 5. RESULTS & CONCLUSIONS

Experiments are designed and conducted on AJM with tungsten carbide nozzle and titanium alloy as work material to optimize the drilling parameters. The kerf accuracy and material removal rate are the responses.

The results obtained are same with both grey relational analysis & principle component analysis with the optimum values of pressure, sod, nozzle diameter to be 10bar, 3mm and 4mm respectively

The optimization of AJM parameters with multiple performance characteristics (high MRR, low KERF) for the drilling of titanium alloy (Ti6Al4V) was carried out. The optimum conditions for obtaining higher GREY RELATIONAL grade such as A3B1C3, (Pressure 10 bar, Sod 3mm and Nozzle diameter 4mm ) were obtained. ANOVA study has been carried out to obtain the significant factors for MRR, Kerf and GRG. It is found that pressure, sod and nozzle diameter is the most influential factor for MRR. The same parameters are proved to be effective during PRINCIPLE COMPONENT ANALYSIS also. With the optimal level of AJM process parameters, it has been found that GRA based Taguchi method coupled with PCA is best suitable for solving the quality problem of machining in the drilling of titanium alloy(Ti6Al4V) to obtain pressure 10 bar, sod 3mm and nozzle diameter 4mm

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