# Modeling of Micro Wire Electro Discharge Machining in Aerospace Material

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**Abstract**

From the last few decades there has been an increasing demand of compact, integrated and small size products by micro-manufacturing technique. Micro-wire EDM is a versatile method for manufacturing a variety of micro-products. It is a complex process. In the present investigation, the modeling of micro-wire EDM has been carried out to determine MRR and validated with experimental results for aerospace material. The temperature distribution and residual stress have also been determined. The multi-response optimization of process parameters has been carried out using grey Taguchi Method with PCA method.`

**Introduction**

During the last decade, there has been continuing demand of compact, integrated and micro-product by micro-manufacturing technique. The micro wire EDM has been an important manufacturing process to meet the demands in tools, the development of micro size components, the growing need for micro-feature generation. A large number of investigators have carried out research in the field of micro wire EDM. The main aim of micro wire EDM operation is to achieve a better stability and higher productivity with desired accuracy and minimum surface damage[1,2]. D. Bitonoto et. al[3] presented a dimensionless model which identified the key parameters of optimum pulse time factor and erodability in terms of thermo physical properties of the cathode material. Beck[4] provided the exact transient temperature distribution in a body due to uniform disc heat source. The solutions obtained was with basic heat conduction, which can be used in many related solutions for steady state and transient cases. Kansel et. al[5] used finite element method for predicting temperature inside the work-piece in powder mixed electrical discharge machining(PMEDM). The effects of various process parameters on temperature distribution along the radius and depth of the AISI D2 die steel were reported. The spark radius plays an important role in the micro-EDM operation and an important factor in thermal modeling. In actual practice it is very difficult to measure spark radius due to very short pulse duration of few microseconds[7]. Pandey and Jilani[8] predicted spark radius by developing an equation based on boiling point temperature. Ikai and Hashiguchi[9] have derived a semi-empirical equation of spark radius termed as equivalent heat input radius which is a function of discharge current, I(A) and discharge on-time, ton(μs). It is more realistic when compared with the other approaches. According to Donald et al[10] the spark theory on a wire-EDM is basically the same as that of the vertical EDM process. In this process many sparks can be observed at one time. This is because actual discharges occur more than one hundred thousand times per second, with discharge sparks lasting in the range of 1/1,000,000 of a second or less. The volume of metal removed during this short period of spark discharge depends on the desired cutting speed and the surface finish required. K. Salonitis et al[11] developed a thermal modeling of the material removal rate and surface roughness for die-sinking EDM operation for multi-discharge condition.

In the present investigation, FEM modeling has been carried out for micro wire EDM operation of INCONEL 718 and Al. The temperature distribution, MRR and residual stress distribution have been determined from the model. The model is partially validated. The optimization of MRR and residual stress has been carried out using grey-relational combined with PCA approach.

**Thermal modeling using ANCYS**

Micro wire EDM is a complex machining process. Experimental investigation of wire-EDM conducted is shown in Fig.1. The images of micro-slots obtained by wire-EDM are shown in Fig2. A simplified 2D axisymmetric FEM model has been carried out(Fig.3). The present model is a simplified 2D axi-symmetric model. PLANE55 element is chosen for modeling. PLANE55 is used as a plane, axisymmetric thermal solid element with a 2D thermal conduction capability. The element has four nodes with a single degree of freedom(temperature) at each node. Inconel-718 and Aluminium are taken as the work-pieces. The material properties are given in Table1 and Table 2 respectively. Before going to modeling certain assumption are to be taken as follows [7]:

Fig. 1 Aluminum work piece is cut by wire EDM.

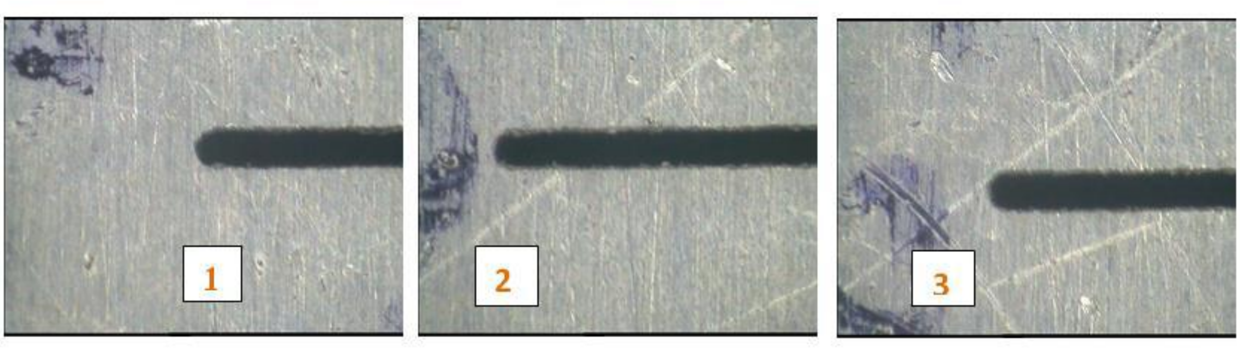


Fig. 2 Images of Micro cut on the work piece

Table.1 properties of INCONEL718

| Material properties | value | unit |
|---|---|---|
| Thermal conductivity (K) | 11.4 | W/m-K |
| Specific heat (C) | 435 | kJ/kg-K |
| Density (ρ) | 8190 | Kg/m3 |
| Melting point (t) | 1609 | K |
| Poisson’s ratio (μ) | 0.33 | |

Table.2 properties of Aluminum (Al) work piece

| Material properties | value | unit |
|---|---|---|
| Thermal conductivity (K) | 205 | W/m-K |
| Specific heat (C) | 910 | kJ/kg-K |
| Density (ρ) | 2700 | Kg/m3 |
| Melting point (t) | 923 | K |
| Young’s modulus (E) | 70 | GPa |
| Poisson’s ratio (μ) | 0.33 | |

1. Work piece material is assumed to be homogeneous and isotropic.

2. Only one spark is produced at a time on the top surface of the work piece (single spark phenomenon) and it is extended to multi spark model

3. All the sparks within the specific machining time period are identical and acts at the same point.

4. A fraction of total heat flux during sparking is utilized for melting the work piece. Shape of the heat

flux is same as the Gaussian distribution.

5. Flushing efficiency is 100% and there is no recast layer formation on the machined surface.

The governing equation for temperature prediction is given by

$$\frac{1}{\alpha}\frac{\partial T}{\partial t}=\frac{\partial}{}$$

Type equation here.

$$\frac{1}{=}\frac{\partial T}{}\;\frac{\partial 2T}{+}\;\frac{1}{}\frac{\partial T}{+}\;\frac{\partial 2T}{} \qquad (1)$$

Where ∝(thermal diffusivity)=k/ρc; ρ is the density of the work piece; c is the specific heat of the work piece; T is the temperature of the work piece; r and z are the co-ordinate axes; t is the time.

A rectangular work piece of size 100μmx20μm was modelled by picking key points on the ANCYS work bench. The optimum mesh size is taken as 1μm for the analysis.

**i. Boundary conditions:**

· In the Fig.1, Boundary 2 and 3 are considered to be

insulated. i.e =0, where n is the normal direction of

boundary layer2 and 3.

· Heating is axy-symmetric to the axis of the spark, so heat flowing from the counter part of the domain is equal to the heat flowing out of the counterpart. Therefore no heat gain or loss from the counter part of the surface domain. i.e. =0 at r=0.

· On the upper layer, at boundary1, spark is directly contacted with the surface. Hence heat flux boundary condition is applied.

· At boundary 2, heat transfer takes place due to convection only. So convective boundary condition is

applied at different conditions which shown in eq.2;

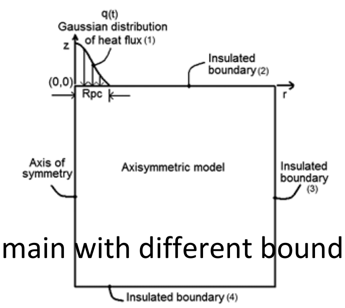



Fig.3 work piece domain with different boundary condition

## ii. Heat input

Important factors which contribute to the accurate calculation of the MRR in single spark EDM model include the amount of heat input, radius of plasma spark and the thermo-physical properties of material [2]. In this present work, the Gaussian distribution of heat flux input has been used to approximate the heat from the plasma. The heat flux calculation equation is derived [1] as given in Eq.3

$q(r) = \exp$ [illegible] (2)

Where fraction of total EDM spark power going to the cathode, V is the discharge voltage and I is spark current.

In the present analysis value is taken in between 0.09 to 0.2.

## iii. Solution methodology

The equ.2 with boundary conditions are used which outlined earlier and solved by Finite Element Method (FEM) to predict the temperature distribution at the end of each transient heat transfer analysis cycle. ANSYS13 software is used for the FEM analysis. A continuum of size ten times the spark radius is considered for the analysis. Four nodded, axi-symmetric, thermal solid element (PLANE 55) is used for discretization of the continuum. After convergence test was done optimum size of each element is taken as 1µm2. The transient heat transfer problem was solved by applying the heat flux at boundary 1 and convective boundary along boundary 2, the ramped loading is applied within the Ton time for the analysis.

The process parameters for INCONEL 718 is given in Table3.

Table.3 Process parameters used for modeling of INCONEL 718 material

| Process parameters | Values | units |
|---|---|---|
| Voltage | 30 | V |
| Current | 2 | A |
| Heat input to the work piece | 0.2 | |
| Spark radius | 5 | µm |
| Pulse-on time | 2 | µs |
| Pulse-off time | 100 | µs |

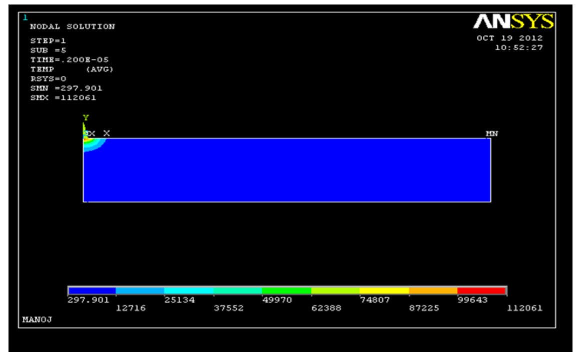



Fig. 4 Temperature distribution of earlier distribution model for INCONEL-718

The comparison results of the two developed

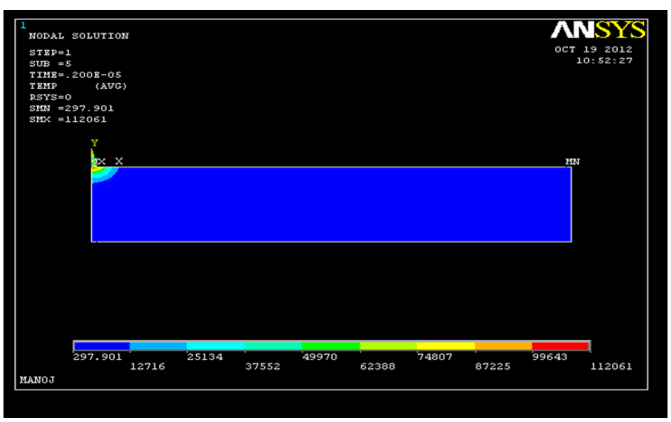



**Fig.5** our developed thermal modeling for inconel718 material

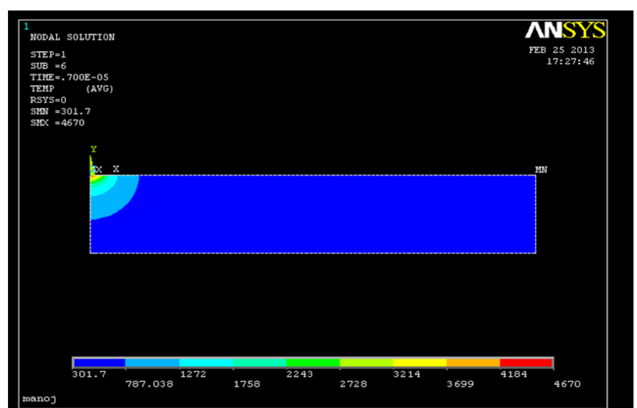
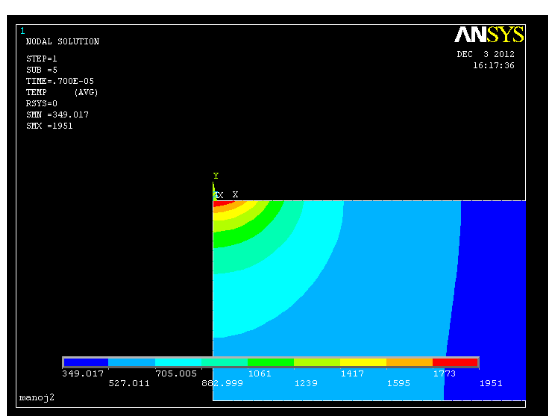



**Fig.6** Temperature distribution in Aluminum (Al) work piece with V=22V, I=1.5A and P=0.2

From Fig.4 and Fig.5, it is seen that the maximum temperature reached by our model is approaches to the previously developed model [3].



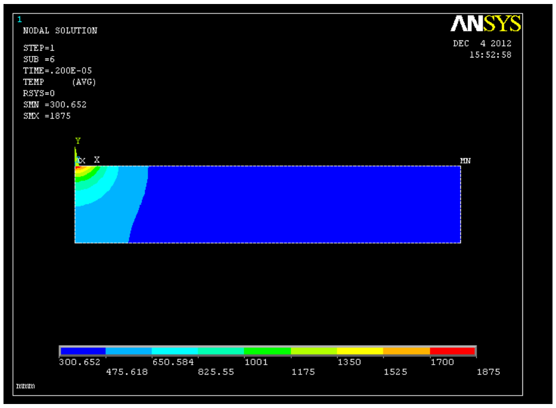
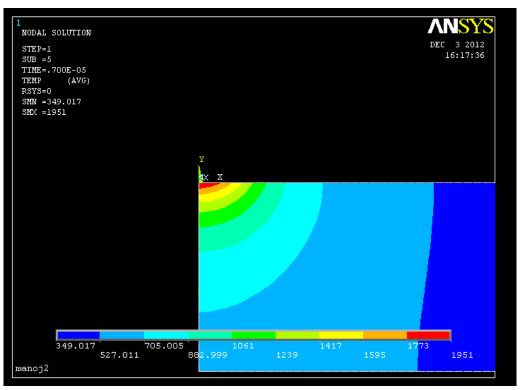



Fig.7 Temp. distribution (Al) V=22V,I=1A,P=0.08 Fjg.8 Temp. (Al) V=22V, I=2A, P=0.2



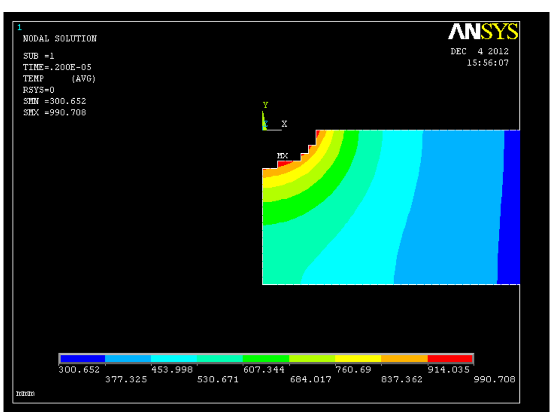




Fig.9 Temp. distribution (Al) after material removal V=22V, I=1A, P=0.08

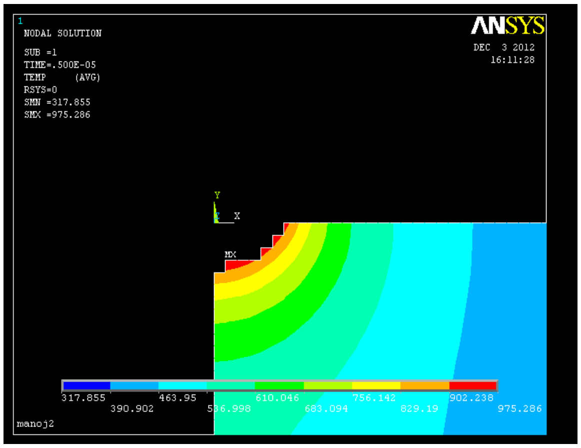



Fig.10 Temp. distribution (Al) after material removal V=22V. I=1.5A, P=0.15

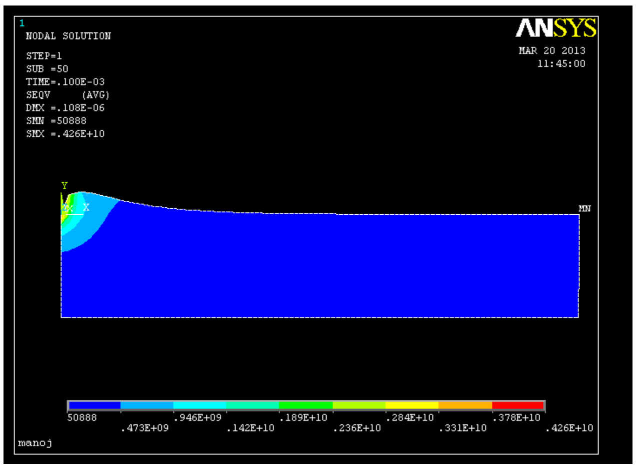



Fig.11 Residual stress(Al) V=22V, I=1A, P=0.08

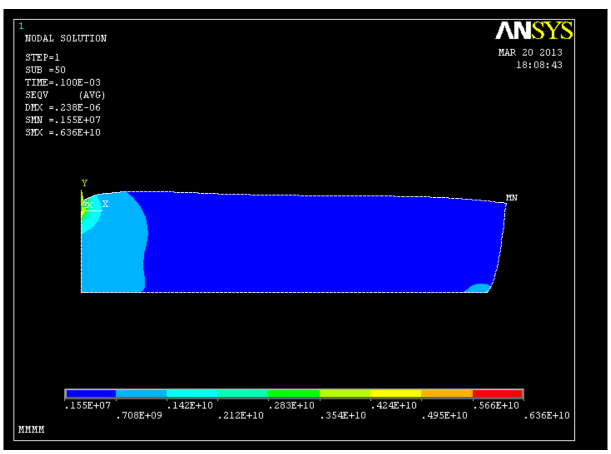



Fig.12 Residual stress of Al, V=22V, I=1.5A and P=0.15

## Results and discussion

Temperature distribution in Inconel 718 has been carried out using ANCYS modeling as shown in Fig.5. The modeling has been validated with an earlier model as shown in Fig.4 which has been carried out under identical conditions. It appears that the results are identical. The modeling of temperature distribution has been carried out for Al under different operating conditions. Some cases have been described below. Fig.6 is the temperature distribution of Al work piece. Maximum temperature reached is located at the Centre, where the intensity of heat flux is maximum. The magnitude of temperature decreases as the distance increases from the Centre line. Study from the above Fig.6 reveals that the distribution of temperature is divided in to four distinct regions. They are

i. Boiling region (red region)

ii. Liquid region (up to light green colour)

iii. HAZ (up to light blue colour)

iv. Solid metal (blue colour)

The temperature distribution corresponding to V=22V, I=1A, P=0.08 for aluminium is shown in Fig.7. Similarly four distinct regions are visible, though there is change in temperature. A similar case is represented corresponding to V=22V, I=2A, P=0.2 in Fig.8. The temperature distribution after material removal in aluminum corresponding to process parameter V=22V, I=1A, P=0.08 is shown in Fig.9. The region in the work-piece where temperature reaches boiling point, the material is removed because of melting. MRR is calculated from the volume of the cavity produced. The temperature distribution after material removal in Al corresponding to process parameters V=22V, I=1.5A, P =0.15 is shown in Fig.10.

The distribution of residual stress has also been computed from ANCYS modeling. The distribution of residual stress has been shown in Fig.11 corresponding to process parameters V =22V, I=1A, P=0.08. Similarly the distribution of residual stress is shown in Fig.12 corresponding to process parameters V=22V, I=1.5A, P=0.15.

Residual stress and MRR for Aluminium (Al) workpiece are theoretically estimated from ANCYS modeling. The optimization of the process parameters has been carried out using Taguchi Method. Three process parameters i.e. voltage, current and pulse on time($T_{on}$) with each having three levels were set at L9 orthogonal array as shown in Table-4.

Table.4 L9 orthogonal array

| No of runs | Voltage(V) | Current(A) | $T_{on}$(μs) |
|---|---|---|---|
| 1 | 22 | 1 | 2 |
| 2 | 22 | 1.5 | 5 |
| 3 | 22 | 2 | 7 |
| 4 | 24 | 1 | 5 |
| 5 | 24 | 1.5 | 7 |
| 6 | 24 | 2 | 2 |
| 7 | 26 | 1 | 7 |
| 8 | 26 | 1.5 | 2 |
| 9 | 26 | 2 | 5 |

The values of MRR and residual stress obtained theoretically from ANCYS model for different combination of process parameters is given in Table 5.

Table5: Theoretical values of MRR and Residual Stress obtained from AMCYS modeling

| Sl No. | MRR($mm^3$/min) | Residual stress(Gpa) |
|---|---|---|
| 1 | 0.251 | 4.26 |
| 2 | 0.1372 | 6.36 |
| 3 | 0.3653 | 7.11 |
| 4 | 0.01628 | 4.99 |
| 5 | 0.0562 | 5.02 |
| 6 | 0.0562 | 10.1 |
| 7 | 0.0661 | 6.94 |
| 8 | 0.2410 | 9.28 |
| 9 | 0.1314 | 8.2 |

The comparison has been done between theoretical and experimental material removal rate(MRR) as shown in Table6.

Table 6. Comparison of theoretical and experimental MRR

| Sl No | Voltage (V) | Current (I)A | $T_{on}$(µs) | P | Theoretical MRR($mm^3$/min) | Experimental MRR($mm^3$/min) | % error |
|---|---|---|---|---|---|---|---|
| 1 | 22 | 1.0 | 2 | 0.2 | 0.251 | 0.201 | 24.8 |
| 2 | 22 | 1.5 | 5 | 0.13 | 0.137 | 0.169 | -18.82 |
| 3 | 22 | 2.0 | 7 | 0.11 | 0.365 | 0.308 | 18.25 |
| 4 | 24 | 1.0 | 5 | 0.13 | 0.016 | 0.017 | 6.97 |
| 5 | 24 | 1.5 | 7 | 0.08 | 0.056 | 0.047 | 17.82 |
| 6 | 24 | 2.0 | 2 | 0.18 | 0.056 | 0.07 | -19.71 |
| 7 | 26 | 1.0 | 7 | 0.18 | 0.096 | 0.078 | 23.24 |
| 8 | 26 | 1.5 | 2 | 0.2 | 0.241 | 0.214 | 12.19 |
| 9 | 26 | 2.0 | 5 | 0.08 | 0.131 | 0.146 | -10.42 |

Grey relational analysis coupled with PCA has been carried out to determine the combined multi-response analysis. In Grey relational coupled with PCA, the optimum cutting parameters are: voltage 22V, Current 2.0A and $T_{on}$ is 2µs.

**Conclusions**

In the present paper, a two- dimensional axisymmetric model has been developed to predict several aspects of micro wire EDM operations. Finite element method (FEM) has been developed to analyze the temperature profile in the Al work piece material due to high temperature and transient operation. MRR has been predicted from ANCYS modeling. The temperature distribution in aluminium work-piece has been predicted after material removal for different operating conditions. The residual stress distributions have also been predicted for different operating conditions. The multi-response optimization has been carried out with Grey relational analysis combined with PCA. The experimental values of MRR and residual stress are compared with theoretical values.

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