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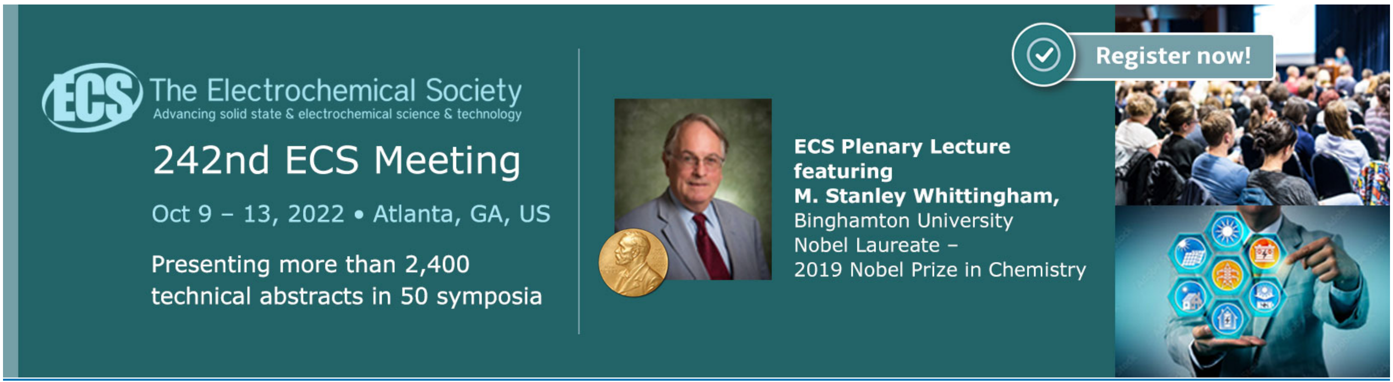

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Analysis and Simulation of Temperature Distribution and Stress Development in Wire EDM of Tungsten Carbide

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Abstract. The main objectives of this research are to investigate the performance of temperature distribution and equivalent Von- Mises stress development on tungsten carbide, determine the effect of different machining parameters on the tungsten carbide workpiece, prepare a set of parameters, temperature distribution and stress development that can be compared with the experimental result and to optimize the machining parameters for machining tungsten carbide using wire EDM. However, wire EDM is a complicated stochastic nature process mechanism and it has a very large number of parameters that should be considered. It is quite hard to select the best set of parameters in experimenting. In this research, the Ansys software was used to simulate the maximum temperature and maximum equivalent (Von-Mises) stress result of machining the tungsten carbide by wire EDM. The input parameters selected in conducting the simulation are pulse- on time and servo voltage. The wire diameter, convective coefficient, thermal expansion coefficient, current, thickness of the workpiece and wire material is taken as fixed parameters. By using Taguchi's L9 orthogonal array, the optimal value is obtained for maximum temperature and maximum equivalent (Von-Mises) stress. Additionally, the analysis of variance (ANOVA) is a useful technique to identify the most important factor that affecting the output response.

1. Introduction

Electrical Discharge Machining (EDM) is a non-contact machining between cutting tool and electrical conductive workpiece. The EDM machining operation depends on discharge of spark from the cutting tool towards workpiece. This operation can be categorised as precision manufacturing process which will result good machined surface quality and great accuracy [1]. One of the processes in EDM is wire EDM. Wire EDM is using wire as cutting tool and cut the material by the use of heat from electrical sparks. This electro thermal process is executed along with de-ionised water (used to conduct electricity) and resulting accurate and precise parts or component. Tungsten carbide (WC), example of the workpiece material, is a chemical compound composed of equal amounts of carbon and tungsten. It has an extremely tough substance that is twice as hard as steel and has a higher density [2]. Due to the force applied at the workpiece near the cutting region during the wire EDM process, stress is developed at the workpiece [3].

The stress is responded to the originality characteristic and properties of the workpiece during its manufacturing. Thus, in wire EDM, the study on stress development is required to obtain the most important working parameters affecting the response output. The most significant working parameters affecting stress development and temperature distribution are pulse- on time and pulse- off time. This is justified by Mohapatra [4] in the research conducted on the study of thermal and structural analysis in wire EDM by investigating the 3-dimensional model of a copper material as the workpiece. Avinash Shilpi et al [5] propose the 3D finite element model by using ANSYS software to determine the stress development and thermal distribution at different pulse times. The distribution of temperature and stress was investigated using a preliminary thermal analysis based on a Gaussian distribution heat source with temperature-dependent material properties. After the spark ended, thermal tension produced, and residual stress formed after cooling. The effect on a large pulse-on-time was explored, and the peak temperature increased dramatically when the parameter was increased.

Mohapatra [4] provided evidence to support his claim that the ANSYS software had been used to construct the model and complete the simulation. According to the results of the experiment, the temperature is higher near the cutting area than it is in any other area in the upper part of the region. The highest temperature recorded is 886.5°C when the probe is placed close to the point of contact between the wire and the workpiece, which is where the sparking occurs. As the water flows through the wire and falls on the workpiece, the dielectric fluid lowers the temperature between the contacts of the circuit. Additionally, Mohapatra [4] looked at the comparable stress that occurs after the required temperature distribution has been achieved. The static structural analysis in ANSYS is used to determine the amount of stress in the material being studied. The temperature analysis produced from the steadystate thermal is used to establish the boundary condition for estimating the tension in the workpiece. After investigating, it was discovered that the cutting area where the sparks developed was responsible for the greatest amount of strain. When the metallurgy varies, the stress variations are proportional to the volumetric variation.

In conclusion, the wire EDM field can be explored in a variety of ways, including the machining parameters, the workpiece to be cut, the machine, and the products. The most critical area of investigation for achieving the intended result is the working parameter, since it has an effect on stress development and temperature distribution. Based on the information obtained from previous authors, the working parameters that have been selected are pulse- on time, servo voltage and the output response of the parameters was studied. As for the setup of the experiment, Taguchi's L9 orthogonal array method was chosen as it gives the minimum number of the experiment while providing the optimal values of the objective function in a process [6]. The best-suited software that can be used is Minitab, Design expert and Microsoft Excel. As for the simulation, ANSYS software is used to simulate the wire EDM for machining the tungsten carbide and analyses the result obtained from the experiment conducted.

2. Material and Methods

2.1. Workpiece and Cutting Tool

In this experiment, the material used is tungsten carbide with a hardness of 85 HRC and chemical composition of the tungsten carbide is listed in Table 1, and Figure 1 below illustrates the design of the workpiece used in this research. The workpiece is 3 mm thick.

Table 1. Chemical composition of tungsten carbide.

Element	W	C	Co	Ni	Fe	Ti
Weight (%)	87.6	5	6.5	0.18	0.06	0.6

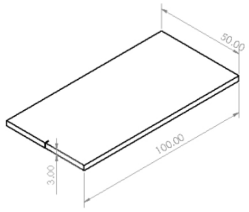

Figure 1. Design of the workpiece

The cutting tool that will be used in this experiment is brass wire which the diameter of the brass wire is 0.15 mm. The properties of the brass wire are shown in Table 2 below: -

Table 2. Brass wire properties.

Electrode Material	Thermal conductivity (W/m*K)	Melting point (K)	Electrical Resistivity (Ω cm)	Specific Heat Capacity (J/g °C)
Brass	159	990	4.7	0.38

2.2. Simulation

In this experiment, the wire material and wire diameter are the cutting tool parameters that must be taken into consideration before the operation can be completed successfully. The values of the parameters are listed in Table 3. The cutting or machining parameters that are involved in this experiment are the servo voltage and the pulse-on frequency. The values of the parameters are stated in Table 4, which has a three-level of variables.

Table 3. Cutting tool parameters.

Parameter	Description
Wire material	Brass CuZn37
Wire diameter (mm)	0.15

Table 4. Cutting or machining parameters

No.	Parameter	Symbol	Unit	Level 1	Level 2	Level 3
1	Servo Voltage	SV	V	45	50	55
2	Pulse- on time	ON	μsec	120	124	128

3. Thermal Modelling and Optimization

A thermal model was created to determine the total heat flux and temperature of the workpiece. In this research, thermal analysis is only conducted on the workpiece while the wire electrode is neglected. For heating the workpiece, the Gaussian type of heat generation is used. As for heat transfer to the solid, it is usually mainly due to conduction. According to Mohapatra [4], the steady-state temperature distribution is described by the governing Equation (1) given below: -

$$\rho C_p \left[\frac{\partial T}{\partial t}\right] = \left[\frac{1}{r}\frac{\partial}{\partial r}\left(K_r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(K_r \frac{\partial T}{\partial z}\right)\right] \quad (1)$$

Where ρ is the density, Kr is the thermal conductivity of workpiece, Cp is specific heat, t is time, r and z are coordinates of workpiece and T is the temperature.

Model Assumption- Few assumptions were taken into consideration that describes the temperature variation along the material axis. The assumptions of the model are shown in the Table 5 below: -

Table 5. Model assumption

Types	Assumption
Model	Single sparks
Heat source	Gaussian distribution of heat flux
Work domain	Axi- symmetric
Wire	Neglected
Material properties	Temperature-dependent
Temperature analysis	Steady-state thermal type
Stress analysis	Static structural type

For the temperature analysis, it is considered as steady-state thermal type as the wire is considered as constant at a particular time and for the stress analysis, it is assumed to be static structural type as the given load is considered to be constant at that particular time.

Thermal analysis- total heat flux, Q is used as the boundary condition for the steady-state thermal analysis. The total heat flux, Q as a function of radius, r is given by Equation (2) [4].

$$\text{Heat flux}, Q_w = \frac{4.45PVI}{\pi R^2}\, e^{-4.5\left[\left\{\frac{r^2}{R^2}\right\}\right]} \quad (2)$$

Where P is the energy distribution coefficient, V is the servo voltage (voltage between anode and cathode), I is the peak current, R is the spark radius, r is the diameter of the wire.
Spark radius, R is the most crucial parameters in modelling the thermal distribution and it can be calculated by the given Equation (3) [4].

$$\text{Spark radius}, R = (2.04\, e^{-3} I^{0.43} {T_{on}}^{0.44}) \quad (3)$$

Where "I" is the peak current and Ton is the Pulse- on time.

Stress analysis- After the required temperature from the steady-state thermal analysis is obtained, the temperature is used as a new boundary condition for the static structural analysis for calculating the stress development on the workpiece. Fixed support is applied at the end of the workpiece to prevent relative motion during the cutting process.

3.1. Parameters used for simulation input

Before the simulation operation commencement, the input parameters and material properties should be specified. These data will be used in the Ansys Workbench 20R2 (ANSYS Inc., USA) software to set the boundary condition for the temperature distribution and stress development analysis. Table 6 show the parameters used for the analysis of the workpiece and Table 7 show the thermo-mechanical properties of the tungsten carbide material.

Table 6. Parameters used for workpiece analysis

Parameters	Value
Convective coefficient (W/mm² °C)	0.000034
Energy distribution coefficient	0.38
Heat flux (W/mm²)	9 values
Servo Voltage (V)	45,50,55
Current (A)	2A
Spark radius (mm)	1.125, 1.141, 1.157
Diameter of wire (m)	0.15, 0.25
Thickness of workpiece (mm)	3

Table 7. Thermo-mechanical properties of tungsten carbide

Thermomechanical properties of tungsten carbide	Value
Thermal conductivity, K (W mK)	100
Specific heat, C (J kgK)	292
Melting temperature, T (°C	2000
Density. P (kg m³)	15880
Young's Modulus. E (GPa)	630
Poisson's Ratio	0.22
Bulk Modulus, B (GPa)	400

3.2. Taguchi's Method

Taguchi's statistically designed orthogonal array method was used to obtain best results within a minimum number of experiments, thereby reducing experimentation time and cost. The S/n ratio has been obtained for determination of quality characteristics. Smaller is better approach was used for determination of maximum temperature and maximum equivalent stress as per Equation (4).

$$S/N_{LB} = -10 \times \log\left(\frac{1}{r}\sum_{i=1}^{r} y_i^2\right) \tag{4}$$

Where 'r' represents the number of repeated and 'yi' represents the machining parameters.

3.3. ANOVA

Obtaining an optimum machining parameter is the primary goal. Therefore, identifying the most significant parameters that can contribute to achieving the optimum temperature and stress developed is essential. The obtained results are analyzed using Design Expert V11, statistical analysis software which is widely used in many engineering applications. Hence, an analysis of variance (ANOVA) was used to identify either the previously mentioned parameter is significant or not by comparing its p-value. The significance of the models is evaluated by the P-values of ANOVA.

4. Results and analysis

This section discussed about the results obtained from the simulation and optimization of the process parameters in machining the tungsten carbide by wire EDM using Ansys Workbench, Design Expert V11 and Minitab 17. The effect of the process parameters on the maximum temperature and maximum equivalent (Von- Mises) stress developed on the tungsten carbide material is studied. The results based on the simulation are recorded in the Table 8.

Table 8. Results from simulation using Ansys Workbench

Exp No.	Parameters		Output response	
	SV (V)	ON (µsec)	Maximum temperature (°C)	Maximum (von-Mises) stress (Mpa)
1	45	120	1584.3	291.03
2	45	124	1543.6	283.45
3	45	128	1504.7	276.21
4	50	120	1757.6	323.31
5	50	124	1712.5	314.91
6	50	128	1669.6	306.93
7	55	120	1930.9	355.6
8	55	124	1881.8	346.45
9	55	128	1834.1	337.56

Steady state analysis- The temperature trend was increasing along with increasing heat flux value. These findings were similar to Fourier's Law where the heat flux moves from a higher temperature to the lower temperature region. The workpiece that is exposed to the higher heat flux value has a higher tendency to distribute or generate higher temperature toward the tungsten carbide material during the cutting operation.

Static structural analysis- The equivalent stress trend increasing with the temperature increases. The tungsten carbide changes in temperature result in volumetric change. These findings were similar to Charles' Law where the volume is directly proportional to temperature. The molecule's kinetic energy increases with the increase in temperature and they begin to vibrate faster to move away from each other. The increase in temperature results in the expansion of the material structure causing the increase of stress development on the material

4.1. Taguchi's L9 Orthogonal Array

Taguchi L9 orthogonal array results are illustrated in the Table 9. Based on the response for the signal to noise in Table 10 and Table 11, servo voltage shows lower delta value compared to pulse- on time. So, according to Sathiyaraj [7], the factor that obtained the greater value of delta will have a larger effect on the output response. It can be concluded that servo voltage has a larger effect on the maximum temperature and maximum equivalent (von-Mises) stress compared to pulse- on time. Main effect plot and S/N ratio plot obtained for maximum temperature and maximum equivalent stress are depicted in Figure 2 and Figure 3. Based on the result obtained, it clearly can be concluded that the most optimal process parameters are at running 7 where the servo voltage is 55 volt and the pulse-on time is 120 µsec for both output response. These parameters will provide an optimum temperature during machining.

Table 9. S/N ratio of the output response

Run	Maximum temperature, (°C)	Maximum stress, (MPa)	S/N ratio for maximum temperature (dB)	S/N ratio for equivalent von mises stress (dB)
1	1584.3	291.03	-63.9967	-49.2788
2	1543.6	283.45	-63.7707	-49.0495
3	1504.7	276.21	-63.5490	-48.8248
4	1757.6	323.31	-64.8984	-50.1924
5	1712.5	314.91	-64.6726	-49.9637
6	1669.6	306.93	-64.4522	-49.7408
7	1930.9	355.6	-65.7152	-51.0192
8	1881.8	346.45	-65.4915	-50.7928
9	1834.1	337.56	-65.2685	-50.5670

Table 10. Table for Signal to Noise Ratios (Maximum temperature)

Level	**Servo voltage**	**Pulse-on time**
1	-63.77	-64.87
2	-64.67	-64.64
3	-65.49	-64.42
Delta	1.72	0.45
Rank	1	2

Table 11. Table for Signal to Noise Ratios (Maximum equivalent von- Mises stress)

Level	**Servo voltage**	**Pulse-on time**
1	-49.05	-50.16
2	-49.97	-49.94
3	-50.79	-49.71
Delta	1.74	0.45
Rank	1	2

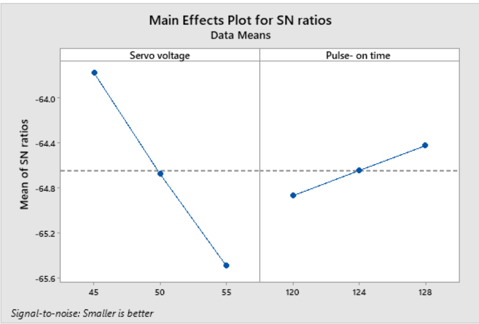

Figure 2. Main effect plot for S/N ratios (Maximum temperature)

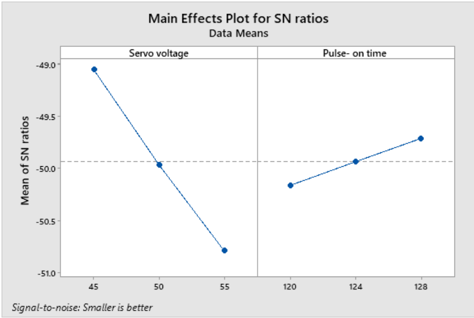

Figure 3. Main effect plot for S/N ratios (Maximum equivalent Von-Mises stress)

4.2. Analysis of variances (ANOVA)

The output response of maximum temperature is having a Model F- a value of 100.69 (Table 12) which indicates that the model is significant. As for the P-value, it shows that the value is less than 0.05 which implies that the model terms are significant. Both servo voltage and pulse- on time are significant as the P- values are less than 0.0001 and 0.0117 respectively.

The Model F- value (100.67) indicates that the model is significant. Overall, both parameters, servo voltage (p<0.0001) and pulse- on time (p=0.0001) are significant in affecting the maximum temperature output response as its p-value not exceeding 0.0500 (Table 13).

Table 12. ANOVA for maximum temperature

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.779E+05	2	88930.61	100.69	< 0.0001	significant
A-Servo volt	1.665E+05	1	1.665E+05	188.57	< 0.0001	
B-Pulse on time	11313.90	1	11313.90	12.81	0.0117	
Residual	5299.26	6	883.21			
Cor Total	1.832E+05	8				

Table 13. ANOVA for maximum equivalent (Von-Mises) stress

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	6171.30	2	3085.65	100.67	< 0.0001	significant
A-Servo volt	5778.96	1	5778.96	188.54	< 0.0001	
B-Pulse on time	392.35	1	392.35	12.80	0.0117	
Residual	183.91	6	30.65			
Cor Total	6355.21	8				

4.3. 3D Model response surface

Two response surfaces were created to study the interaction between the process parameters with the output response. As visualized in figure 4, it can be observed that the maximum temperature is low when the pulse- on time increases with the decrement of servo voltage value. The higher the value of pulse on time, the lower the value of heat flux generated. This will be resulting in decreasing value of temperature developed on the workpiece during the cutting operation. The value of heat flux will decrease with the decrease in the value of the servo voltage. Therefore, the temperature of the machined workpiece will decrease where it will be resulting in the decreasing value of equivalent (Von-Mises) stress (Figure 5).

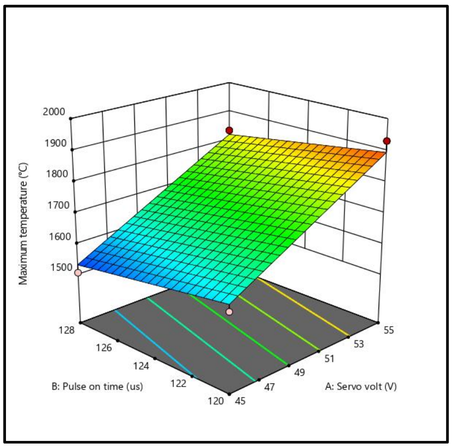

Figure 4. Surface plot for maximum temperature

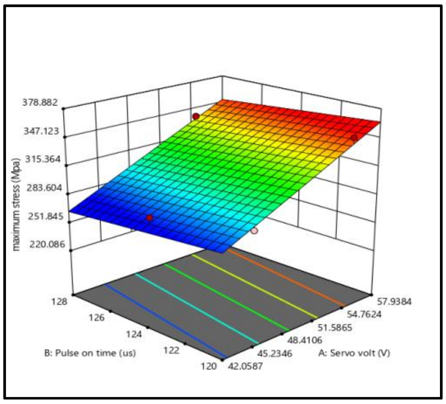

Figure 5. Surface plot for maximum equivalent (von- Mises) stress

4.4. Optimization of the response

The optimization process is required to enhance the wire EDM machining performance. In this research, the goal is to minimize the maximum temperature and maximum equivalent (Von-Mises) stress development on the tungsten carbide. Hence, the desirability function approach has been employed for the process parameters optimization. Table 14 shows the desirability result from the optimization process and the first run was selected as the desirability is the nearest to 1.

From Figure 6, the dot on each ramp graph represents the optimal level of the parameter and the optimal output response in machining tungsten carbide. It can be concluded that 45 volts and 128 μsec are the optimal parameters to obtain 1531.34 °C of maximum temperature and 281.17 MPa of maximum equivalent von mises stress. The height at which the dot is located indicates the desirability of the parameters.

Table 14. Output response optimization in machining tungsten carbide by wire EDM

No.	Servo voltage (v)	Pulse-on time (µsec)	Max. temperature (°C)	Max. equivalent stress (MPa)	Desirability	
1	45.000	128.000	1531.341	281.170	0.938	Selected
2	45.000	127.935	1531.956	281.284	0.936	
3	45.042	128.000	1532.566	281.398	0.935	
4	45.082	128.000	1533.695	281.609	0.932	
5	45.000	127.496	1536.081	282.053	0.926	
6	45.000	127.400	1536.982	282.221	0.924	
7	45.000	126.861	1542.046	283.163	0.912	
8	45.000	126.828	1542.358	283.222	0.912	
9	45.000	126.273	1547.580	284.194	0.899	
10	45.000	122.356	1584.408	291.052	0.813	

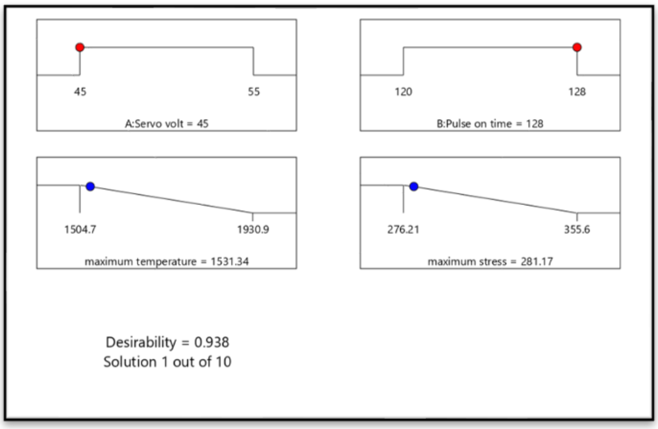

Figure 6. Ram function graph of the parameter's optimization

5. Conclusion

Heat flux is the most significant factor which effects the temperature development during simulation. From the result obtained from the steady-state thermal analysis, the maximum temperature obtained was 1504.7 °C with the 33.54 W/mm² value of heat flux while the maximum temperature obtained was 1930.9 °C with the 43.18 W/mm² value of heat flux. It can be concluded that the higher the value of the heat flux, the higher the value of maximum temperature obtained. This is due to the workpiece that is exposed to the higher heat flux value has a higher tendency to distribute or generate higher temperature toward the tungsten carbide material during the cutting operation.

The equivalent (Von-Mises) stress trend increasing with the temperature increases. An increase in temperature results in the expansion of the material structure causing the increase of stress development on the material. The molecule's kinetic energy increases with the increase in temperature and they begin to vibrate faster to move away from each other. Both temperature and stress development are at a maximum near the cutting potion where the sparking occurs. This is due to the heat flux was applied at the surface of the tungsten carbide during the simulation operation.

Based on the optimization results by Taguchi's method, servo voltage has a larger effect on the maximum temperature compared to pulse- on time based on the delta value rank. The optimal parameters for machining the tungsten carbide are found to be 55 volts of servo voltage and 120 µsec of pulse- on time. This value is obtained by observing the trend of the main effect plot for the signal-to-noise ratio graph. From the analysis by ANOVA, the parameters can be determined whether it is significant or not significant to be used in the next process to create the model. The desirability to optimize parameters can be reached up to 0.938. However, the optimal parameters for machining the tungsten carbide are found to be 45 volts for the servo voltage with 128 μsec.

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