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Fea for WEDM Process of Titanium Alloy

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Abstract:* Advance non-conventional machining processes are used in a modern manufacturing system. In Titanium alloy specimen condition machining process are require maximum energy. Wire electrical discharge machining (WEDM) is widely used in machining of conductive materials when precision is considered as a prime importance. This work proposes a three-dimensional finite element model (using ANSYS software) and a new approach to predict the temperature distribution at different pulse time as well as stress distribution in non-conventional machining for Titanium Alloy Specimen. A transient thermal analysis assuming a Gaussian distribution heat source with temperature-dependent material properties has been used to investigate the temperature distribution and stress distribution. Thermal stress developed after the end of the spark and residual stress developed after subsequent cooling. The effect on significant machining parameter pulse-on-time has been investigated and found that the peak temperature sharply increases with the parameter.

***Keywords:* FEA, ANSYS, WEDM, Thermal stress &Temperature Distribution in Titanium Alloy.**

I. INTRODUCTION

Titanium alloys are attractive materials in many engineering fields such as aerospace, biomedical, nuclear research, turbines, and sports. High temperatures are produced during conventional machining of Titanium alloys due to their poor thermal diffusivity is responsible for rapid tool wear and deterioration of the work piece surface condition.

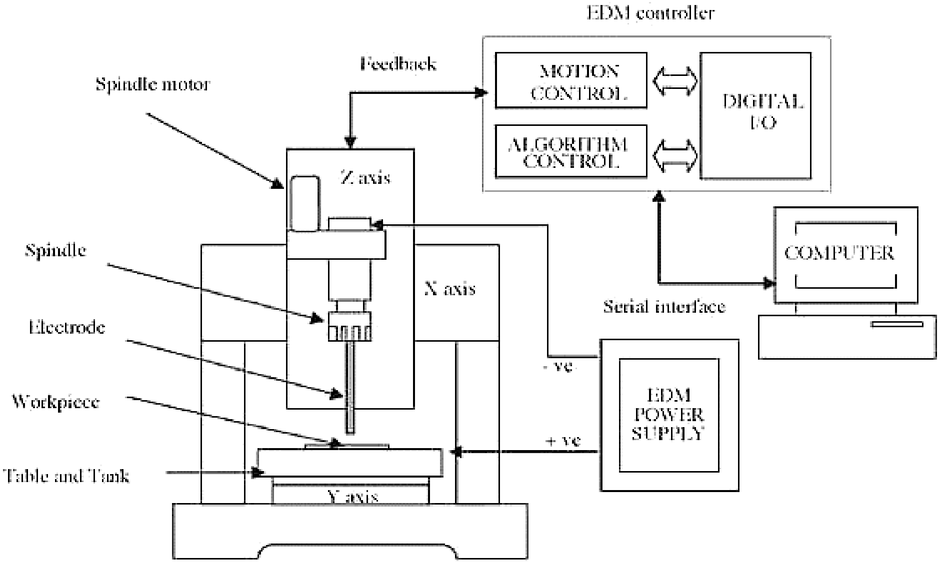
However electrical discharge machining is a thermal process that involves melting and vaporization of the work piece electrode. Wire EDM machining (Electrical Discharge Machining) is an electrothermal production process in which a thin single-strand metal wire in conjunction with de-ionized water (used to conduct electricity) allows the wire to cut through metal by the use of heat from electrical sparks. Due to the inherent properties of the process, wire EDM can easily machine complex parts and precision components out of hard conductive materials. It's widely using in the die casting, mold designing and aerospace industries for manufacturing. It's also using in plastics molds, forging dies made from hardened tool steels, together with engine components, such as compressor blades made from nickel-based superalloys and titanium alloys. The EDM process uses electrical discharges to remove material from the work piece, with each spark producing a high spark temperature up to 20,000°C. Consequently, the work piece is subjected to a heat generated stress due to HAZ the top layer of which comprises recast material. The composition, condition, and thickness of this layer depend on the discharge energy and the make-up of the work piece, dielectric fluid, and tool electrode, and both soft and hard surface layers can be produced resistance perceived wisdom that the recast layer is always hard. Also, it can be defined as the process of material removal by controlled erosion through a series of electric sparks. Electrical energy is used to generate an electrical spark and material removal mainly occurs due to the thermal energy of the spark. EDM can be used to machine difficult geometries in small batches or even on the job-shop basis. The frequencies of an original shape and modified shape should be within range. The process has, however, some limitations such as high specific energy consumption, longer lead times and lower productivity which limit its applications. Researchers worldwide are thus, focusing on process modeling and optimization of EDM to improve the productivity and finishing capability of the process.

There is a need to select the machining parameters for satisfying the customer requirements. Due to high investment and machining cost of nonconventional machines, there is an efficient need to operate the machines as efficiently as possible to get the required payback. The cost of machining is sensitive to the selection of machining variables. In wire electrical discharge machining process an always traveling wire electrode made of thin copper, brass or tungsten of diameter 0.05–0.3 mm is used, which is precisely controlled by a CNC system. Here the role of CNC is very important. The function of CNC is unwound the wire from a first spool, and feed throughout the work-piece, and takes it on a second spool. Generally, wire velocity varies from 0.1 to 10 m/min, and feed rate is 2 to 6 mm/min. A direct current is used for generating a high-frequency pulse to the wire and the work piece. The wire (electrode) is held in tensioning device for decreases the chance of producing inaccurate parts. In wire electrical machining process, the work piece and tool is eroded and there is no direct contact between the work piece and the electrode, and this reduces the stress during machining.

Alauddin et al (1995) developed the mathematical model of surface roughness for the end milling of 190 BHN steel considering only the center line average (CLA) roughness parameter (Ra) in terms of cutting speed, feed rate and depth of cut using response surface method (RSM).

(ANOVA) were employed to the study the performance characteristics in the turning of commercial Ti-6Al-4V alloy using CNMG 120408-883 insert cutting tools. The conclusions revealed that the feed rate and cutting speed were the most influential factors on the surface roughness and tool life, respectively. The surface roughness was chiefly related to the cutting speed, whereas the axial depth of cut had the greatest effect on tool life.

Horacio et al (2011) used ANOVA and regression models were used to predict the EDM output performance characteristics, such as MRR, EWR, and SR in the EDM process for AISI 1045 steel with respect to a set of EDM input parameters, In addition, it is



noted that this approach has only considered a limited number of parameters. The symmetric diagram of WEDM is as shown

Fig 1. Schematic diagram of WEDM

A. Features of Micro Wire EDM process

1. A forming electrode adapted to product shape is not required.
2. Electrode wear is negligible.
3. Machined surfaces are smooth.
4. Geometrical & dimensional tolerances are tight.
5. Relative tolerance between punch & die is extremely high & die life is extended.
6. Straight holes can be produced to close tolerances.
7. EDM machine can be operated unattended for a long time at the high operating rate.
8. Machining is done without requiring any skills.
9. Any electrically conductive material can be machined irrespective of its hardness & strength.
10. EDM allows the shaping of complex structures with high machining accuracy in the
11. Figure 1.2: WEDM process
12. Order of several micrometers and achievable surface roughness Rz=0.µm.
13. It proves to be a competitive method for ceramic processing because of the abilities to provide accurate, cost-effective and flexible products.

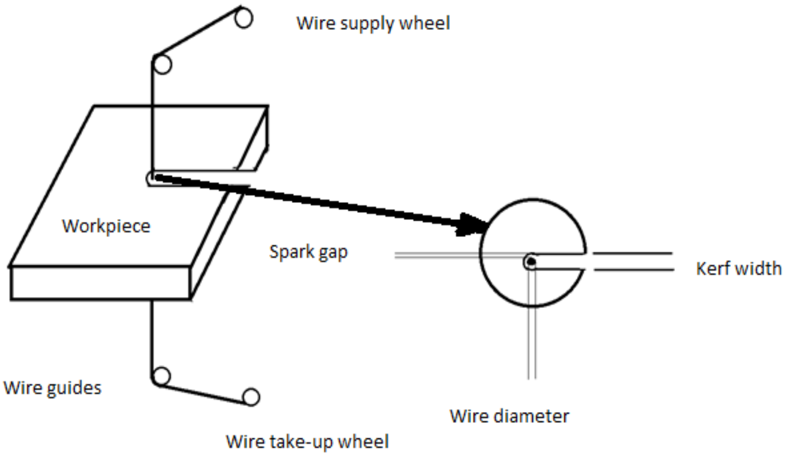


Fig 2. WEDM process

B. Wire-EDM process

Wire electrical discharge machining (EDM) is a non-traditional machining process that uses electricity to cut any conductive material precisely and accurately with a thin, electrically charged copper or Titanium Alloy as an electrode. During the wire EDM process, the wire carries one side of an electrical charge and the work piece carries the other side of the charge. The wire electrical discharge machining process generally use of electrical energy generate the plasma channel between the cathode and anode and create thermal energy at a temperature in the range between 8,0000C to 12,0000C or as higher as 20,0000C and create a considerable amount of heat and melting of the materials on the surfaces of each pole. When the pulsating direct current power supplying occurs between 20,000 and 30,000 Hz is turned off, the plasma channel breaks down. This cause sudden decrease in the temperature, allow circulating dielectric liquid to implore the plasma channel and flushing the molten particle from the each pole surface in the form of microscopic debris. The WEDM machining process is as shown in Fig.

C. Principle of spark erosion

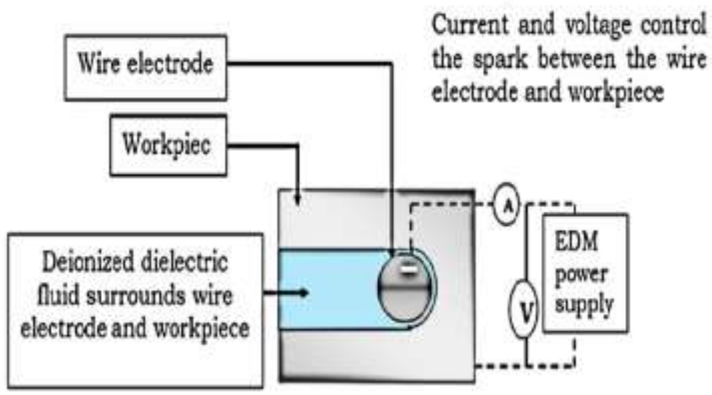


Fig 3. Sparking phenomena in WEDM process

The principle of spark erosion is simple. The work piece and tool are placed such a way that these don't touch each other. These are separate through a gap which is filling with dielectric fluid. The cutting mechanism, therefore, takes place in a container. The work piece and tool are connected to a direct current source. There is a switch in one lead. When this is closed, an electrical potential is applied between the work piece and tool. At initially no current flows since the dielectric between the work piece and tool is an insulator. If the gap is decreasing then a spark jumps across it when it reaches a certain very small size. In this process, current is converted into heat and form plasma channel. The surface of the materials is very powerfully heated in the area of the discharge channel. If the flow of current is sporadic the discharge channel collapses very quickly. Therefore the molten metal on the surface of the material evaporated explosively and takes liquid material with it down to a certain depth. A small crater is formed. If one discharge is followed by another, new craters are for med next to the previous ones and the work piece surface is constantly eroded.

D. Taguchi Loss Function

The heart of Taguchi Method is the definition of the nebulous and elusive term „Quality‟ as the characteristic that avoids a loss to the society form the time the product is shipped. The loss is measured in terms of monetary units and is related to quantifiable product characteristics. Taguchi defines quality loss via „Loss function‟ He unites financial loss with the functional characteristics specifying through a quadratic relationship that comes from a Taylor series expansion. The quadratic takes the form of a parabola. Taguchi defines the loss function as a quantity proportional to the square of deviation from the nominal quality characteristics. The representation of the Taguchi loss function is graphically shown in fig. He found the following quadratic

From to be a practical workable function.

$$L(y) = K\,(y - m)^2$$

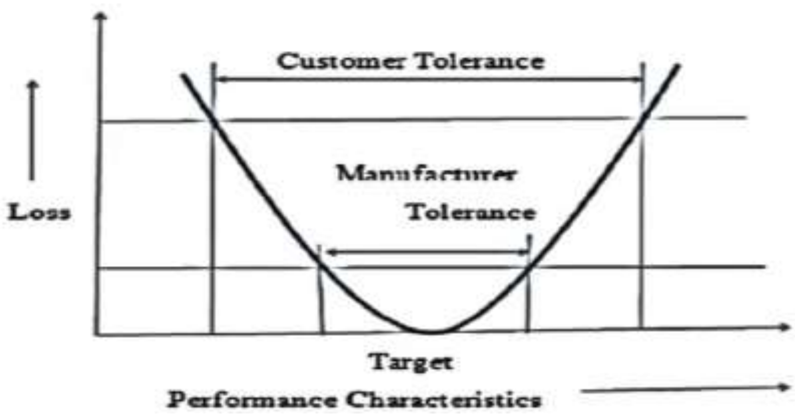


Fig 4. Sparking phenomena in WEDM process

E. Terms used in WEDM process

- **Spark Gap**

Space between electrode and work piece is called spark gap. Here voltage is applied. The electric field created throughout the space between these electrodes.

- **Kerf width**

It is the sum of the wire diameter and twice of the spark gap. The kerf width is generally measured using the Infinite Focus Alicona Machine.

F. The use of Dielectric in WEDM Process

- **Insulation**

One significant purpose of the dielectric is to insulate the work piece from the electrode.

- **Cooling**

Due to high temperature, overheating of the electrode and wear can generate. So avoid this wear, dielectric must cool the both the electrode and work piece.

- **Removal of waste particles**

Particles which are creating during the machining must be removed from the area of erosion by the dielectric to avoid disruptions in the process.

G. WEDM applications in industry

- Dies and punches for Electronic and hierological components.
- Microsurgical tools and biomedical devices.
- Precision flexures for micro positioning systems.
- Miniature spool valves.
- Thin-walled structural parts for aerospace industries.
- Precision form gauges for different profiles
- WEDM developments

H. Objective of the Present Work

- To determine the temperature distribution, displacement and stress distribution in work piece using FEM analysis.
- To develop a thermo-structural analyzing of work piece for analyzing the effect of built-in temperature to the machining performance.

II. TITANIUM ALLOYS AND ITS PROPERTIES

Titanium Alloys

In 1791 William Gregor the British reverend, mineralogist, and chemist discovered Titanium. He named it “mechanite”, after the location. Four years later, the Berlin chemist Martin Heinrich Klaproth independently isolated titanium oxide from a rutile. Greek mythology provided him a new name from the children of Uranos and Gaia, the titans. The titans were utterly hated by their father and so detained in captivity by him in the earth’s crust, similar to the hard to extract ore – hence he named it Titanium. It took more than 100 years before Matthew Albert Hunter from Rensselaer Polytechnic Institute in Troy, N.Y., was able to isolate the metal in 1910 by heating titanium tetrachloride ($TiCl_4$) with sodium in a steel bomb. Finally, Wilhelm Justin Kroll from Luxembourg is recognized as the father of the titanium industry. In 1932 he produced significant quantities of titanium by combining $TiCl_4$ with calcium. At the beginning of World War II, he fled to the United States. At the U.S. Bureau of Mines, he demonstrated that titanium could be extracted commercially by reducing $TiCl_4$ by changing the reducing agent from calcium to magnesium. Today this is still the most widely used method and is known as the “Kroll process”. After the Second World War, titanium-based alloys were soon considered key materials for aircraft engines. In 1948 the DuPont Company was the first to produce titanium commercially. Today aerospace is still the prime consumer of titanium and its alloys, but other markets such as architecture, chemical processing, medicine, power generation, marine and offshore, sports and leisure, and transportation are gaining increased acceptance.

Titanium is not actually a rare substance as it ranks as the ninth most plentiful element and the fourth most abundant structural metal in the Earth's crust exceeded only by aluminum, iron, and magnesium. Unfortunately, it is seldom found in high concentrations and never found in a pure state. Thus, the difficulty in processing the metal makes it expensive. Even today it is produced only in a batch process, and no continuous process exists as for other structural metals.

Structure prototype Mg
Pearson symbol hP2
Space group P63/mmc (194)
b -transus temperature 882 ºC
Lattice parameters a=0.295 nm
c=0.468 nm
c/a=1.587
Thermal expansion coefficient [10–6 K–1] 8.36
Thermal conductivity [W/mK] 14.99
Specific heat capacity [J/kgK] 523
Electrical resistance [10–9 Wm] 564.9
Elastic modulus [GPa] 115
Shear modulus [GPa] 44
Poisson's ratio 0.33ysical properties

Table 1. Physical properties of high-purity polycrystalline

Titanium (> 99.9%) at 25ºC.

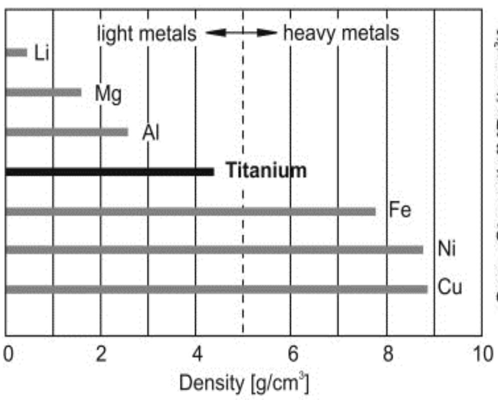


Fig 5. The density of selected metals.

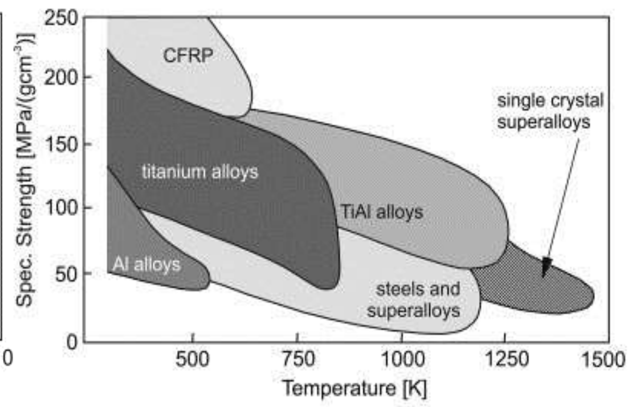


Fig 6. Specific strength versus use temperature of selected structural Materials compared with titanium alloys and aluminized.

The Alloying Elements of Titanium

The properties of titanium alloys are essentially determined by two factors: the chemical composition and the microstructure. The chemical composition of the titanium alloys primarily determines the properties and volume fraction of the phases, α, and β. Due to the limited deformation capability of hexagonal dense packed crystal structures, α is less ductile compared with the body-centered cubic α.

Therefore, the resistance to creep and oxidation increases with increasing aluminum content, while simultaneously the ductility and the deformation capability deteriorate. Therefore, care had to be taken when new alloys were developed so as to not exceed 9 wt. % of the so-called aluminum-equivalent

Al eq. =wt. %Al+1/3 wt. %Sn+1/6 wt. %Zr+10 wt. %O <9 wt. %

III. METHODOLOGY

Thermal analysis of EDM Workpiece

The general finite element modeling procedure consists of the following steps:

- Create geometry by design modeler on ANSYS or import geometry.
- Define material properties from Engineering DATA of ANSYS.
- Mesh generation by auto meshing tool of ANSYS.
- Application of loadings and boundary condition.
- ANSYS- Solving Wizard for fatigue analysis type of strain life and stress Results for fatigue life and optimization with fatigue.

A. Design Criteria

The high-strength Titanium Alloys has been subjected to extensive fatigue research. So-called damage tolerant design is used in fatigue life assessment, where a certain amount of crack growth is allowed before they need to be replaced.

For safety-critical components, such as a suspension arm, fatigue life is defined as the time to initiate a small crack, although fracture mechanics can be used to assess the component's integrity in case of a special event loading. Compared to nuclear reactors, there is more uncertainty as to what loads to expect for a given car component due to individual driving styles and varying geographic road conditions. Furthermore, the prediction of fatigue crack initiation is associated with less accuracy than crack growth predictions, leading to a considerable uncertainty with regard to fatigue strength even under controlled laboratory conditions. In order to account for uncertainties, various empirical safety factors are used, in effect increasing the size of the components so that fatigue failure would be highly unlikely from the expected use. Prediction uncertainty is, therefore, a competing factor in the aforementioned trend towards reducing vehicle weight – improving life prediction accuracy allows lighter designs to be used.

Process of WEDM

To obtain the relationship between pulse conditions and material removal rate, many attempts have been made to calculate temperature distribution in the electrodes caused by a single pulse discharge by solving time-dependent heat transfer equations assuming various heat source models. Based on the mathematical models, the temperature profile due to the passage of an individual pulse can be created. However, the scope of such analysis is limited; a more comprehensive approach is needed. So it can be considered as best available, realistic and reliable thermal model for the further work of development in EDM process. Thus this model is the taken as a benchmark for the present work of stress analysis.

During the process, spark discharges may occur over work surface at locations where the inter-electrode gap is minimum. Figs show the two-dimensional axisymmetric process continuum and the associated boundary conditions taken for the analysis. Following assumptions have been made during the thermal Analysis.

- Titanium alloy and tool materials are isotropic and homogeneous.
- The properties of the Titanium alloy and tool's material are temperature dependent.
- The wedm operation, heat is transferred from plasma to electrodes by radiation and conduction, while from plasma to dielectric by convection and radiation.
- WEDM spark channel is considered as a cylindrical wire and the spark radius is assumed to be a function of discharge current and time.
- Gaussian distribution is taken for heat flux. The influence of the spark zone is taken to be axisymmetric in nature.
- Out of total spark, some of the total spark energy is dissipated as heat into the work piece, the rest is lost into the dielectric convection and radiation.
- Flushing efficiency is considered as 100%. On the machined surfaces there is no deposition of recast layer.

B. Heat distribution equation

Heat distribution equation used for calculation of transient temperature distribution in work piece. The differential governing equation of thermal diffusion differential equation in a model is governed by the following.

$$\frac{\partial}{\partial r}\left(kw\frac{\partial T}{\partial \theta}\right)+\frac{1}{r^2}\frac{\partial}{\partial \theta}\left(kw\frac{\partial T}{\partial \theta}\right)+\frac{\partial}{\partial z}\left(kw\frac{\partial T}{\partial z}\right)+q^{'''}=\rho c\frac{\partial T}{\partial t}$$

Where r and θ are the radial and angle coordinates respectively, z is the axial coordinate, ρ and c are the density and the specific heat of the wire material, kw thermal conductivity of the wire material and T is the temperature of the micro element in the wire.

C. Heat generation

Consideration of average thermo-physical material properties and constant EDM spark radius make the available models simplistic and less accurate in predictions. The Gaussian distribution of heat flux input has been used to approximate the heat from the plasma. Due to EDM spark is given by the heat q entering the work piece,

$$q(r)=q_0\exp\left\{-4.5\left(\frac{r}{R_{pc}}\right)^2\right\}$$

Using this equation, the maximum heat flux can be calculated as under.

$$q_0=\frac{4.57F_{CVI}}{\pi R_{PC}^2}$$

where$Fc$is fraction of total EDM spark power going to the cathode; V is discharge voltage; I is discharge current and Rpc is spark radius at the work surface.

D. Boundary conditions of Spark Radius

Spark radius is an important factor in the thermal modeling of the WEDM process. In practical, it's extremely difficult to experimentally measure spark radius due to the single short pulse duration of the order of microseconds. The equations proposed by these researchers are not realistic in nature as the WEDM spark is controlled both by discharge energy and discharge on-time 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) Eq. . It is more realistic when compared with the other approaches.

$$R_{pc} = (2.04e - 3)I^{0.43}I_{on}^{0.44}(\mu m)$$

$$q(t) = \frac{3.4875 \times 10^5 F_c V I^{0.14}}{t_{on}^{0.88}} exp\left\{-4.5\left(\frac{t}{t_{on}}\right)^{0.88}\right\}$$

WhereFc is the fraction of total power going to the cathode; V is the discharge voltage; I is the discharge current; t is the time μs and ton is time μs at the end of electric discharge. Eq. (5) controls the amount of heat which is applied on the cathode which in turn, causes removal of material from cathode during operation.

The boundary between area 1 and area 2 can be mathematically determined by the following equations:

$$r = r_w$$
$$(r_w \ sin\,\theta)^2 + z^2 = r_d^2$$

Where rd is defined as the radius of the discharge channel, rw is the wire radius and r
Represents the cylindrical boundary between the wire and the dielectric.

From fig. 4: in inside area 2, the thermal equilibrium can be described by the following equations:

If $r = r_w$ $\qquad (r_w \ sin\,\theta)^2 + z^2 > r_d^2$

Then $k_w \frac{\partial T}{\partial r} = h(T - T_0)$

Where h is the heat transfer coefficient, T_0 is the initial temperature of wire electrode and T Temperature.

E. Heat Flux due to the wire electrode in a single spark

In this paper, a Gaussian heat distribution is assumed. If it is assumed that total power of the power of each pulse is to be used only single spark can be written as follows:

$$q^r = \frac{k}{\pi R^2(t)} PVI\ exp.\left(-\frac{kr^2}{R^2(t)}\right)$$

Where q(r) is the heat flux at the radius of r, k is the heat concentration coefficient (k=4.5, Kunieda et al. case), R (t) is the radius of arc plasma at the moment of t, P is the energy distribution coefficient (= 0.38, Kunieda et al.), V is the voltage between anode and cathode during discharge occur, I is the peak current and r is the distance from the center of arc plasma.

F. 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.

$$\text{Spark Radius } (R) = (2.04e^{-3})I^{0.43}t_{0n}^{0.44})\ (\mu m)$$

Modelling of WEDM

- Modeling procedure using ANSYS
- Process of Thermal Modeling using ANSYS software
- Process of structural Modeling using ANSYS software
- Process of Thermo-structure Modeling using ANSYS software

Thermal model of Wire EDM using ANSYS

The working principle of WEDM is as same EDM process, when the distance between the two electrodes (wire and the workpiece) is reduced the intensity of electric field in the volume between the electrodes (wire and the workpiece), become greater than the strength of the dielectric, which breaks, allowing current to flow between the two electrodes. For this reason, the spark will be generated.

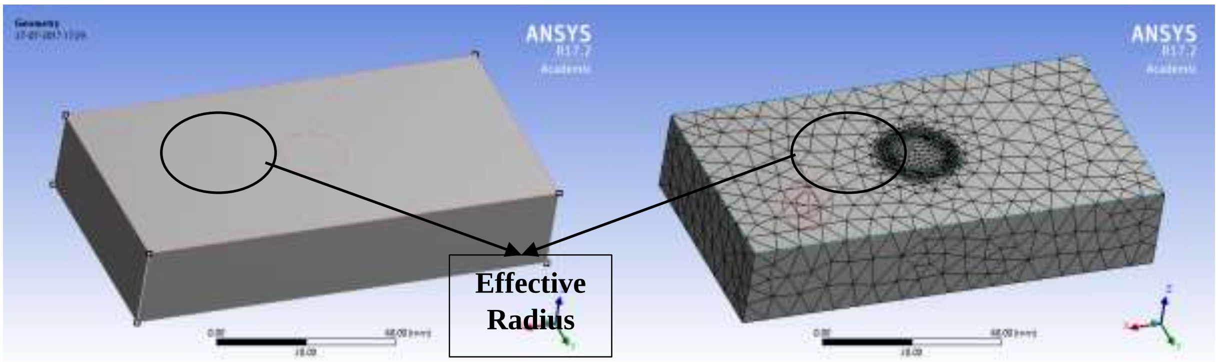


Fig 8. 3D Model and Mesh view of work piec

Assumption

The mathematical statement that describes the temperature variation along the wire axis in the wire-EDM process is formulated under the following:

Assumptions:

- The model is developed for a single spark.
- The thermal properties of work piece material are considered as a function of temperature. It is assumed that due to thermal expansion, density and element shape are not affected.
- Temperature analysis is considered to be of a transient type.
- The material of the wire is homogeneous, isotropic and has constant properties.
- The heat source is assumed to have a Gaussian distribution of heat flux on the surface of the work piece.
- The composition of the material of work piece is assumed to be homogeneous and isotropic
- Thermal meshed model
- The discharge phenomenon in wire EDM can be modeled as the heating of the work piece by the incident plasma channel. The mode of heat transfer in solid is conduction.

IV. RESULT ANALYSIS AND DISCUSSION

Most of the products which are subjected to repeated cyclic loadings will fail eventually. This type of failure is termed as fatigue failure. A major cause of the failure of a product is fatigue failure which can result in substantial injuries and damage sometimes. Varying or repeated loads on repetitive stress for a long time duration changes the microscopic structure of component which resulted in a crack formation that origins the breakdown. Initially, many components work properly but due to fatigue failure, they often fail due to repeated cyclic loadings in their service. Basically, we use to do fatigue simulation for following factors:

•Desired product life.
•Optimization of shape and size.
•Optimization of material consumption.

Ansys is a tool containing non-destructive simulation process to simulate fatigue life which is governed by the equation of fatigue. Ansys empowers the engineers to calculate the product life with the complete simulation process of fatigue. We can use ansys very efficiently for fatigue life estimation due to its huge material library, convenient way to apply boundary conditions and loads, automatic meshing and much more advantageous information. Ansys is also connected with CAD geometry so that we can import a complicated geometry in ANSYS. Optimization can also be done by ansys.

Thermal analysis is analyzed by two methods in ansys:
Finite Element Analysis Procedure using ANSYS software

FEM analysis

Thermal modeling of wire EDM for single spark in Titanium Alloy
Main parameters of the thermal analysis (analysis parameters)
Parameters used for thermal analysis in WEDM process
Parameter >Unit>Value

Peak current of electro- discharge A 24
Voltage of electro discharge, V 45
Duration of single pulse µs 0.10, 0.15, 0.25, 0.48, 0.55, 0.8, 1.5
Wire radius Mm 5
Convective coefficient W/m2 0C 3028
Temperature of the dielectric 0C 27
Poisson' ratio .34
Coefficient of linear thermal expansion K1 1.9×10^-5

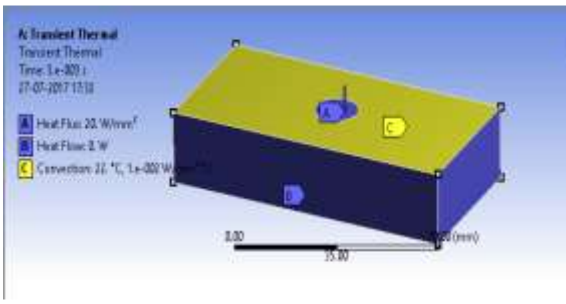


Fig 9. Boundary condition of Titanium Alloy work piece

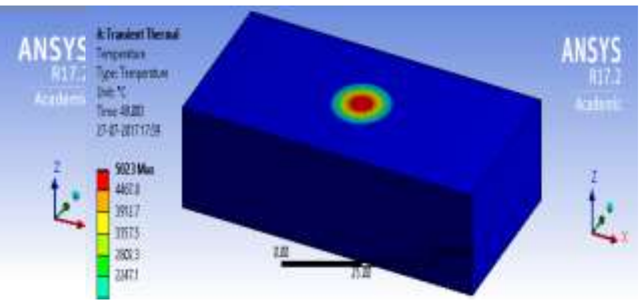


Fig 10. Temperature distribution in Titanium Alloy with V=45V, I=24 A, P=0.48 and ton=0.10µs

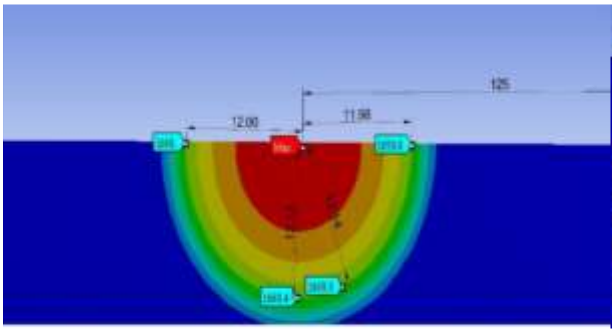


Fig 11. Temperature distribution in mm at top view of Titanium Alloy work piece with V=45V, I=24 A, P=0.48 and ton=0.10µs

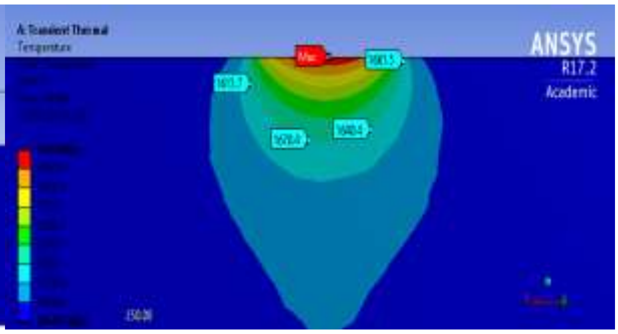


Fig 12. Temperature distribution in mm in section view of Titanium Alloy work piece with V=45V, I=24 A, P=0.48 and ton=0.10µs

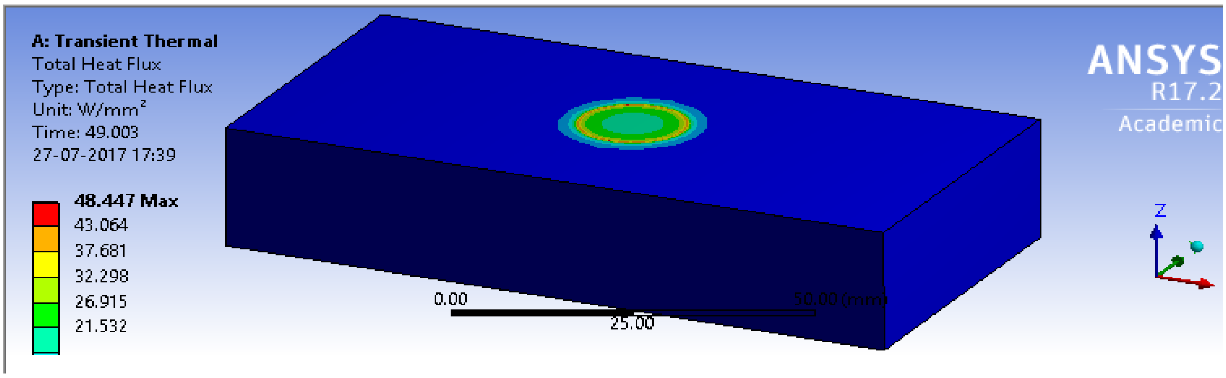


Fig 6. Total heat flux distribution of Titanium Alloy work piece with V=45V, I=24 A, P=0.48 and ton=0.10µs

CONCLUSIONS

This experimental work reveals the following conclusions on WEDM operations on Titanium Alloy work piece material. The main objective of this work is to develop the empirical model using ANSYS software. The genetic algorithm methodology is one of the best technique to identify the effects of machining parameter on the WEDM process. The voltage and pulse off time have the significant effect on machining time, the higher level of current produce lower machining time. In this dissertation, a robust three-dimensional finite element model has been developed using ANSYS software to predict the temperature distribution at different pulse time as well as stress distribution in the wire of WEDM. A transient thermal analysis assuming a Gaussian distribution heat source with temperature-dependent material properties has been used to investigate the temperature distribution and stress distribution. Thermal stress was developed after the end of the spark and also residual stress was developed after subsequent cooling. Finite element modeling was carried out for a single spark with temperature-dependent material properties. Certain parameters such as spark radius, discharge current and discharge duration, the latent heat, the plasma channel radius and Gaussian distribution of heat flux, the percentage of discharge energy transferred to the tool electrode have made this study nearer to real process conditions. The FE model shows that, at pulse time = 0.12 µs, corresponding temperature is 86.75^{0}C and maximum Temperature is 4525. At pulse time = 0.26 µs, corresponding temperature is 247.7^{0}C and .At pulse time = 0.36 µs, corresponding temperature is 318.6^{0}C. At pulse time = 0.52 µs, the corresponding temperature is 446.9^{0}C and the maximum compressive stress is 288Mpa in Z-component, and maximum Temperature is 4525. At pulse time = 0.58 µs, corresponding temperature is 578.335^{0}C. At pulse time = 1.2 µs, corresponding temperature is 854.8^{0}C. At pulse time = 1.82 µs, corresponding temperature is 1144^{0}C and the maximum Temperature is 4525 for ton=1.82µs in Z-component, and maximum residual Temperature is 4525.

Further increasing the pulse time is not possible because, at temperature 1683^{0}C, the Titanium Alloy melt.

Possible to make a drill or machining in Titanium Alloy work piece using the WEDM method with less HAZ.

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