

STUDY AND ANALYSIS OF RESIDUAL STRESSES IN ELECTRO-DISCHARGE MACHINING (EDM)

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR DEGREE OF

**Bachelor of Technology
in
Mechanical Engineering**



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National Institute of Technology
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Under the Guidance of

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2007



**National Institute of Technology
ROURKELA**

CERTIFICATE

This is to certify that the thesis entitled , “**STUDY AND ANALYSIS OF RESIDUAL STRESSES IN ELECTRO-DISCHARGE MACHINING (EDM)**” submitted by **Sri Pankaj Kumar Soni** and **Sri Raju Gholley** in partial fulfillment of the requirements for the award of Bachelor of Technology in Mechanical Engineering at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any Degree or Diploma.

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ABSTRACT

Technological advances have led to an increasing use of high strength, high hardness materials in manufacturing industries. In machining of these materials, traditional manufacturing processes are increasingly being replaced by more advanced techniques such as electro-discharge machining (EDM), ultrasonic machining (USM), electric chemical machining (ECM) and laser machining. EDM has found widespread application in MEMS, tool and mould industries and aerospace industries. Therefore, promoting the quality of the EDM process by developing a thorough understanding of the relationship between the EDM parameters and the machined surface integrity has become a major research concern. Electric discharge machining removes materials by melting and vaporizing caused by the high heat within the discharge column. Furthermore, EDM can easily fabricate the precision and complicated parts by choosing the appropriate machining conditions to effectively control the amount of removed materials. Although EDM can obtain fine surface integrity and precise dimensions under finishing condition, the rough machining condition produces larger and deeper discharge craters since the great quantity of the melted material is removed. Furthermore, the melted material is not removed completely because the impulse force is insufficient to flush away the melted material at the end of discharge interval. The remaining melted material is solidified to form a recast layer that distributes micropores and cracks due to the effect of thermal stress during cooling. Thus, the microscopic feature of machined surface is severely coarse that significantly deteriorates the usage life and precision of machinery parts.

EDM involves the complex interaction of many physical phenomena. The electric spark between the anode and the cathode generates a large amount of heat over a small area of the work-piece. A portion of this heat is conducted through the cathode, a fraction is conducted through the anode, and the rest is dissipated by the dielectric. The duration of the spark is of the order of microseconds and during this time, a plasma channel is formed between the tool and the work-piece. Electrons and ions travel through this plasma channel. The plasma channel induces a large amount of pressure on the work-piece surface as well. This pressure holds back the molten material in its place. As the plasma starts forming it displaces the dielectric fluid and a shock wave passes through the fluid. As soon as the spark duration time is over and the spark collapses, the dielectric gushes back to fill the void. This sudden removal of pressure results in a violent ejection of the molten and vaporized material from the work-piece surface. Ejected molten particles quickly solidify in contact with the colder fluid and are

eventually flushed out by the dielectric. Small craters are formed at locations where material has been removed. Multiple craters overlap each other and the machined surface that is finally produced consists of numerous overlapping craters. Although molten material ejection is not the only means of material removal in EDM, it is, however, the dominant mode of material removal in case of metals. During machining the local temperature in the workpiece gets close to the vaporization temperature of the material. Thus, phase transformation from solid to liquid as well as liquid to vapor occurs during the heating cycle. Part of the transformed material is removed but the rest re-solidifies on the surface of the workpiece. This re-solidified layer is usually called the white layer, as it is not easily etchable. EDM processes carried out in hydrocarbon dielectrics lead to the partial breakdown of dielectrics and this further leads to some diffusion of carbon. Below the re-solidified white layer lies a second layer that does not melt but is still affected by heat. For steels, during the cool-down cycle, solid-state transformations occur in this heat-affected zone because the highest temperature reaches beyond the austenite transformation temperature. Finally, all the non-uniform heating and cooling give rise to transient and residual stresses in the workpiece. As a result of these residual stresses surface cracks may be formed in the white layers. Usually, residual stresses are not high enough to cause sub-surface cracks in the parent material but may lead to detrimental effects when the machined work-piece is used in applications.

This work is intended on analyzing the cause of residual stress in EDM process. It is also showing how current variation brings about a change in the surface characteristics and how the microstructure variation occurs because of subsequent sparks with constant magnitude. This is studied to draw a relationship between the micro structural change and the generation of residual stresses. Scanning Electron Microscope (SEM) images taken from the samples show the surface variation at different currents. A comparative study shows current variation is a factor for the craters developed at the EDMed surface, and that higher magnitude of current changes the grain structure of the sample drastically and intensifies the magnitude of residual stresses generated in EDMed sample. The solid-solid transformation is brought about at a higher temperature (at higher current) and sample EDMed at higher current is seen to have greater surface roughness.

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CHAPTER 1

General Introduction

1.1 INTRODUCTION OF EDM :

Electrical discharge machining is a non-traditional manufacturing process based on removing material from a part by means of a series of recurring electrical discharges (created by electric pulse generators at short intervals) between a tool called electrode and the work piece in the presence of a dielectric fluid. This fluid makes it possible to flush eroded particles (mainly in the form of hollow spheres) from the gap and it is really important to maintain this flushing continuously.

The first EDM application was carried out by Mr. and Mrs. Lazarenko in the Technical Institute of Moscow during the Second World War . The first of the two important improvements, also carried out by these Soviet scientists, which make it feasible to elevate this electrical technique to the category of manufacturing process was the RC relaxation circuit, which provided the first consistent dependable control of pulse times. The second innovation consisted of adding a simple servo control circuit in order to find and hold a given gap automatically. In spite of these first trials and innovations, EDM technology got nearly unknown until the 1950s. At this time, this technique began to be interesting for the industrial marketing mainly in the USA. Some of the causes that eased a much more widespread use of the EDM process were the vacuum tubes, its combination with the basic RC relaxation circuit and finally, the development of the transistor. These solid state devices were able to provide high currents and a really much faster switch on and off than the previous vacuum tubes. Nowadays, EDM is widely used both in the European market and in the American market.

Therefore, EDM is the technique used in industry for high-precision machining of all types of conductive materials such as metals, metallic alloys, graphite, ceramics, etc., of any hardness.

1.2 BASIC PRINCIPLE OF EDM PROCESS:

EDM machining is carried out by means of electric sparks that jump between two electrodes subjected to a voltage and submerged in a dielectric fluid. Thus, the voltage applied to them must be enough to create an electric field higher than the dielectric rigidity of the fluid used in the process. As a consequence of this electric field, positive ions and electrons are accelerated, producing a discharge channel that becomes conductive. It is just at this point when the spark jumps causing collisions between ions and electrons and creating a channel of plasma. A sudden drop of the electric resistance of the previous channel allows that current density reaches very high values producing an increase of ionization and the creation of a powerful magnetic field.

These effects make a little part of metal volume melt or even vaporise. In these conditions, that is, ions and electrons crashing among them and therefore creating high temperatures in both poles, a gas ball or bubble is formed around the plasma channel and then begins to grow providing just at the end of the discharge a large ball of gas. In this situation, electric current is shut off and the plasma channel collapses

producing the spark to disappear. Due to the sudden decrease of internal pressure of the gas ball, the dielectric fluid breaks it making the ball implode, that is, explode inwards. As a consequence of this implosion, an ejection of molten metal is carried out and, afterwards, this ejected molten material solidifies in the form of little balls formed the so called EDM splinter or debris.

Basically, there are two different types of EDM:

- 1) Die-sinking
- 2) wire-cut.

Die-sinking EDM reproduces the shape of the tool used (electrode) in the part wire-cut EDM a metal wire (electrode) is used to cut a programmed outline into the piece. In spite of the advantages that present EDM processes, one of the most important drawbacks is the high manufacturing time. This is really important when obtaining low values of surface roughness is pretended. In such case, an inadequate selection of operation conditions may cause quite high process times without achieving an improvement on the surface roughness properties.

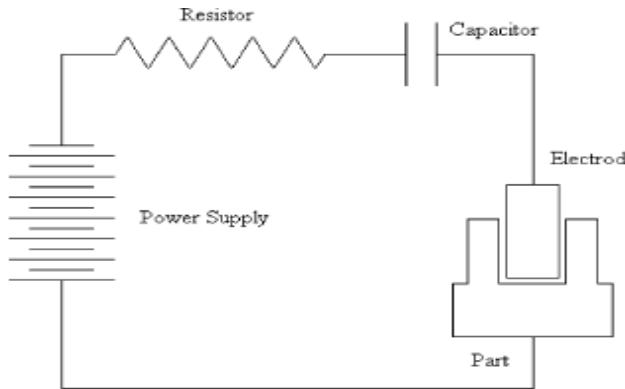


Fig. 1. The basic RC relaxation circuit.

1.3 Some of the most important parameters implicated in the EDM manufacturing process are the following ones:

- On-time (pulse time or t_i): is the duration of time (s) the current is allowed to flow per cycle. Material removal is directly proportional to the amount of energy applied during this on-time. This energy is really controlled by the peak current and the length of the on-time.
- Off-time (pause time or t_0): is the duration of time (s) between the sparks (that is to say, on-time). This time allows the molten material to solidify and to be wash out of the arc gap. This parameter is to affect the speed and the stability of the cut. Thus, if the off-time is too short, it will cause sparks to be unstable.
- Arc gap (or gap): is the distance between the electrode and the part during the process of EDM. It may be called as spark gap.
- Duty cycle: is a percentage of the on-time relative to the total cycle time. This parameter is calculated by dividing the on-time by the total cycle time (on-time pulse off-time).

1.4 APPLICATIONS OF EDM:

1. It is used to machine extremely hard materials that are difficult to machine like alloys, tool steels, tungsten carbides etc.
2. It is used for forging, extrusion, wire drawing, thread cutting.
3. It is used for drilling of curved holes.
4. It is used for internal thread cutting and helical gear cutting.
5. It is used for machining sharp edges and corners that cannot be machined effectively by other machining processes.
6. Higher Tolerance limits can be obtained in EDM machining. Hence areas that require higher surface accuracy use the EDM machining process.
7. Ceramic materials that are difficult to machine can be machined by the EDM machining process.

CHAPTER 2

BRIEF INTRODUCTION OF THE PROJECT

2.1 CAUSE OF RESIDUAL STRESSES IN EDM PROCESS:

EDM generates residual stresses mainly due to the non homogeneity of heat flow and metallurgical transformations. Investigation of the residual stresses of electric discharge machined components revealed their tensile nature, the extremely narrow superficial zone where they appear, their high magnitude at the surface layers, and their increase with increasing pulse energy. Earlier attempts to measure residual stresses due to EDM conducted by several authors have shown that high tensile residual stresses are developed. These stresses were found to approach the upper tensile strength of the material at the immediate surface, and then fall rapidly to a relatively low value before giving way to small residual compressive stresses in the core of the material. The stresses were deemed to arise mainly as a result of the thermal contraction of the resolidified metal, which was not expelled from the craters, onto the relatively unaffected parent metal, inducing plastic deformation and biaxial tensile stress.

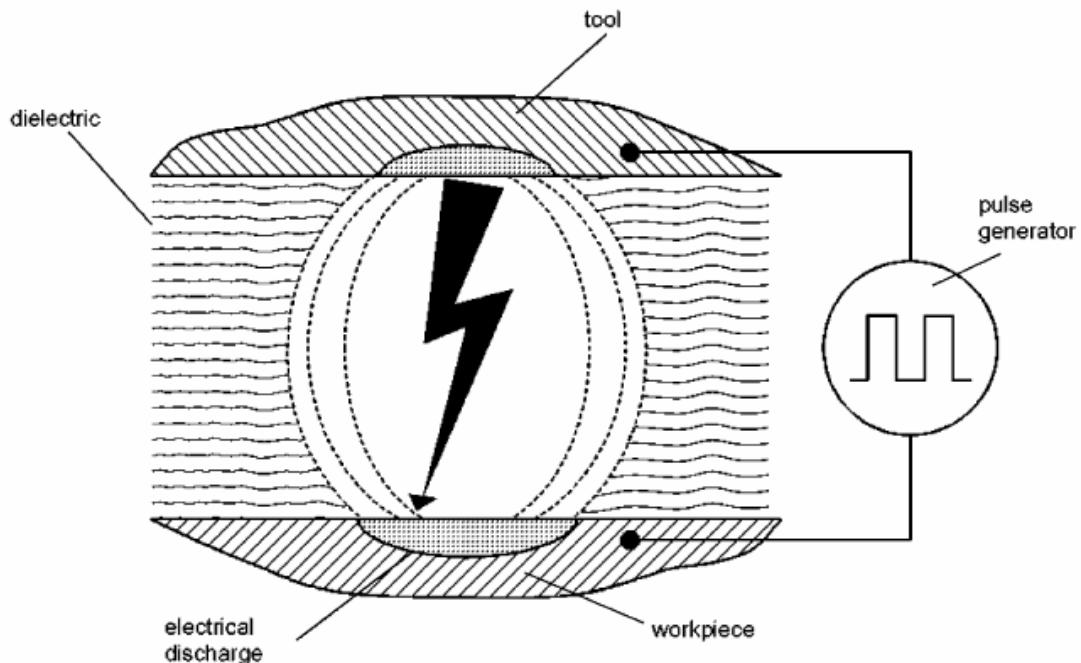


Fig. 1. Close-up of the EDM machining region.

2.2 DIFFERENT METHODS OF MEASURING RESIDUAL STRESSES:

2.2.1 EDM-HOLE DRILLING METHOD:

In this study the EDM drilling process is used to measure the residual stresses of high-performance materials, whose stress state is difficult to obtain by a widely used technology called high-speed (HS) hole-drilling method (ASTM Standard E837). . The experimental results in this method reveal that the stress measurement curves of both EDM conditions, which have the same EDM energy, are parallel with the ideal curve. Therefore the results of EDM hole-drilling method can be positively calibrated by a constant, and it depicts the feasibility of residual measurement on materials with high hardness and wear resistance.

2.2.2 FINITE ELEMENT METHOD:

A finite element-based model for the electric discharge machining (EDM) process is presented. IN this method we use process parameters such as power input, pulse duration, etc., to predict the transient temperature distribution, liquid- and solid-state material transformation, and residual stresses that are induced in the workpiece as a result of a single-pulse discharge. An attractive feature of this method is its ability to predict the shape of the crater that is formed as a result of the material removal. But in this method ,improvements to simulate the effects of multiple pulses hasn't been undertaken in the near future.

2.2.3 X-RAY DIFFRACTION METHOD :

In this method parallel beam modification to determine the residual stress profile of electric discharge machined micro alloyed steel. Considerable amount of residual stresses is observed at the sub-surface layer and that the peak stresses were almost independent of the discharge energy and approaches the ultimate tensile strength of the material. The effect of increase in discharge energy was described as increase in depth where the peak residual stress occurs. This was related

to the intensification of the surface cracking with energy. They observed lower stresses for dual phase samples compared to micro alloyed one, although the difference in strength between these steels is not significant. They have concluded this situation as the influence of transformation stresses due to phase changes. The residual stress values increase from the bulk material to a maximum and then decrease again near to the surface. This decrease is related to crack formation since the residual stresses exceed the fracture strength of the material. It is noticed that the depth of the maximum stress value corresponds to the average depth of the thermal cracks network induced by EDM.

2.2.4 BENDING DEFLECTION METHOD:

The bending deflection method is based on continuous material removal. It is observed that the peak stress is not located at the surface, but somewhat below for roughing. They explained this situation by the fact that the white layer has a lot of cavities and micro-cracks, which cause relaxation of the residual stresses. After reaching the peak value, the tensile stresses decrease and switch to small compressive values at a certain penetration depth below the surface. The maximum stress value decreases considerably whereas the depth of maximum stress and the penetration depth of the tensile stress are unchanged.

2.2.5 THE PRINCIPLE OF LAYER REMOVAL METHOD:

The principle of layer removal method depends on the balance of internal stresses and moments when residual stresses are gradually removed from the material in form of thin layers using chemical or electro-chemical machining. Stressed layers from a thin parallelepiped test specimen, which usually include residual stresses in one of their planes, are removed successively and resulting strains or deformations are measured. Since the resulting deformations of the analyzed part can be related to stresses in removed layer by equilibrium of forces and moments, residual stresses can be determined using simple elasticity theory. In this method, only

the principal stress component parallel to the axis of the test specimen can be calculated. An electric discharge machined surface is produced with applying consecutive spark discharges, which bring about overlapping craters that is randomly distributed over the entire surface. Supposing that each discharge is axisymmetric, a biaxial stress field with equal stress magnitudes can be assumed. The transverse stresses could be considered negligible due the thermal nature of the process. Therefore, only one directional measurement of the curvature is sufficient while knowing that a two dimensional stress is present. One of the most appropriate machining processes to remove stressed layers from an analyzed part is electrochemical machining since it does not add any additional stresses and it is possible to remove thin layers which is crucial for the measurements.

CHAPTER 3

LITERATURE REVIEW

3.1 EXPERIMENTAL STUDIES ON RESIDUAL STRESS:

EDM involves the complex interaction of many physical phenomena. The electric spark between the anode and the cathode generates a large amount of heat over a small area of the workpiece. A portion of this heat is conducted through the cathode, a fraction is conducted through the anode, and the rest is dissipated by the dielectric. The duration of the spark is of the order of microseconds and during this time a plasma channel is formed between the tool and the workpiece. Electrons and ions travel through this plasma channel.

The plasma channel induces a large amount of pressure on the workpiece surface as well. This pressure holds back the molten material in its place. As the plasma starts forming it displaces the dielectric fluid and a shock wave passes through the fluid. As soon as the spark duration time is over and the spark collapses, the dielectric gushes back to fill the void. This sudden removal of pressure results in a violent ejection of the molten and vaporized material from the workpiece surface. Ejected molten particles quickly solidify in contact with the colder fluid and are eventually flushed out by the dielectric. Small craters are formed at locations where material has been removed. Multiple craters overlap each other and the machined surface that is finally produced consists of numerous overlapping craters. During machining the local temperature in the workpiece gets close to the vaporization temperature of the material .Thus, phase transformation from solid to liquid as well as liquid to vapor occurs during the heating cycle. Part of the transformed material is removed but the rest re-solidifies on the surface of the workpiece. This re-solidified layer is usually called the white layer, as it is not easily etchable. EDM processes carried out in hydrocarbon dielectrics lead to the partial breakdown of dielectrics and this further leads to some diffusion of carbon into the white layer . It has been reported by many researchers that white layers formed in the presence of hydrocarbon dielectrics contain higher percentages of carbon than those machined in de-ionized water due to the diffusion of carbon into the surface layers. Below the re-solidified white layer lies a second layer that does not melt but is still affected by heat. For steels, during the cool-down cycle, solid-state transformations occur in this heat-affected zone because the highest temperature reaches beyond the austenite transformation temperature. Experimental data shows that this heat-affected layer transforms mostly to martensite along with some retained austenite for steel samples. Finally, all the non-uniform heating and cooling give rise to transient and residual stresses in the workpiece.

As a result of these residual stresses surface cracks may be formed in the white layers. Usually, residual stresses are not high enough to cause sub-surface cracks in the parent material but may lead to detrimental effects when the machined workpiece is used in applications.

3.2 Cracks Causes:

Crack formation can be attributed to the presence of thermal stress and tensile stress within the machined component. Thermal stress is produced when the electrode discharges bombard the surface of the sample during the machining process. Tensile stress within the sample is generated because not all of the material which melts during the machining process is swept away from the component's surface by the dielectric. Due to the ingress of carbon, the melted material contracts more than the unaffected parent part during the cooling process, and when the stress in the surface exceeds the material's ultimate tensile strength, cracks are formed. Since both tension cracks and voids form during the cooling stage, there would appear to be some relationship between the two. Although results from previous studies have indicated that cracking increases as the pulse energy increases, the exact relationship between cracking and EDM parameters has never been presented.

Observation of the machined surface, and the sample sections, reveals that the surface cracks are often micro-cracks. The high magnification microscope shows that cracks exist in the white layer; initiating at its surface, and traveling down perpendicularly towards the parent material. In the vast majority of cases the cracks terminate within the white layer, or just on the interface of the white layer and the parent material. Only rarely do the cracks penetrate the entire white layer thickness to extend into the parent material.

If one material sample is considered in isolation, surface deviation reveals that different EDM parameters cause different surface crack densities. However, since surface cracking is a potential source of component failure, it is necessary to qualify the degree of cracking by means of some objective standard. Since it is not easy to quantify the cracking in terms of an estimation of the width, length, or depth of the crack, or even by the amount of cracking, this study defines a "surface crack density", i.e. the total length of cracks (cm) in a unit area (cm^2) to evaluate the

severity of cracking.

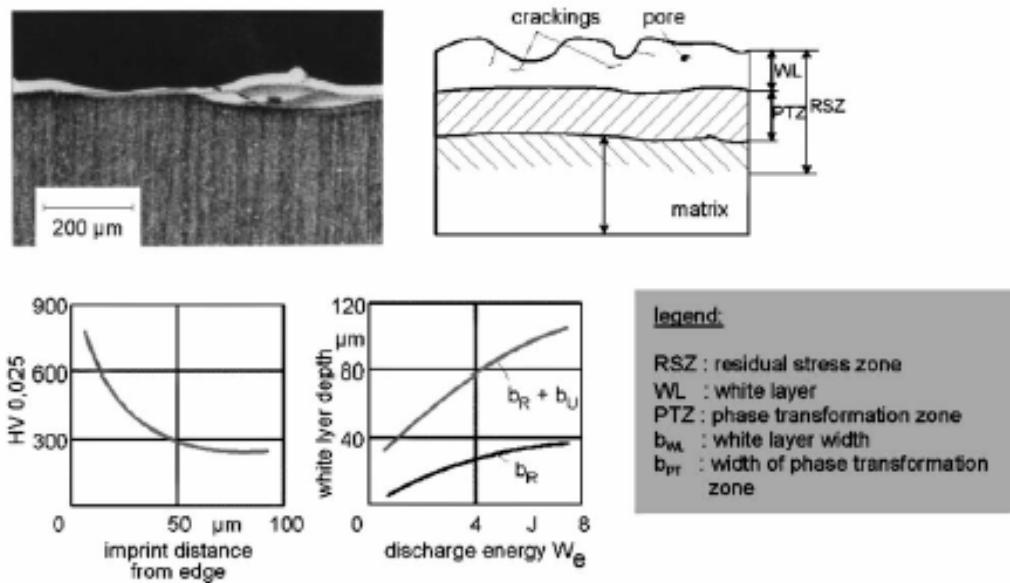


Fig. 3. EDMed surface with surface cracks and sketch of sub-surface regions.

3.2 OBJECTIVE OF THE PRESENT WORK:

The objective of the present work is to:

- 1) study the various causes of residual stresses induced during EDM process and analyse the different methods for measuring the residual stresses in EDM process.
- 2) study and analyse the phase transformation and the change of microstructure in an EDMed sample that causes residual stress development.
- 3) Analyse the cracks and the surface defects occurring at different currents in EDMed sample.

CHAPTER 4

EXPERIMENTAL WORK

4.1 Procedure:

En-19 alloy steel is used as the work piece in this experiment. The sample was cut into standard dimension using hacksaw at metallurgy lab. The diameter of the sample is 50 mm and the thickness is 13 mm. Three samples of same dimension were prepared. The three different samples were grinded and polished in the grinding machine. Grinding was done in order to level the work-piece. Then keeping the pulse rate constant and varying the current each sample was EDMed for 7-8 minutes. The first sample was machined at 5 amp current. The second sample was machined at a current of 25 amp. while The third sample was machined at a current of 45 amp. Each of the samples was then polished with diesel to clear the carbon deposits. All the three samples were then viewed under Scanning Electron Microscope. The surface characteristics of each sample EDMed at different current was studied. The phase transformation analysis was done which gives rise to residual stresses.

The formation of cracks and surface defects are studied from the images obtained from SEM images.

4.2.1 TABLE 1: Sample no 1

	Step	X	Y	Z	Ip	Ton	t	Vg	SEN	ASEN	Tw	Tp	Pol
S	1	0.0000	0.0000	-9.000	5	100	10	50	7	2	1.5	0.3	+ve
E	2	0.0000	0.0000	-9.000	5	100	10	50	7	2	1.5	0.5	+ve

4.2.2 TABLE 2: Sample no 2

	Step	X	Y	Z	Ip	Ton	t	Vg	SEN	ASEN	Tw	Tp	Pol
S	1	0.0000	0.0000	-9.000	25	100	10	50	7	2	1.5	0.3	+ve
E	2	0.0000	0.0000	-9.000	25	100	10	50	7	2	1.5	0.5	+ve

4.2.3 TABLE 3: Sample no 3

	Step	X	Y	Z	Ip	Ton	t	Vg	SEN	ASEN	Tw	Tp	Pol
S	1	0.0000	0.0000	-9.000	45	100	10	50	7	2	1.5	0.3	+ve
E	2	0.0000	0.0000	-9.000	45	100	10	50	7	2	1.5	0.5	+ve

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Phase transformation:

The dramatic temperature changes in the workpiece associated with EDM induce change of phase in the material. Regions that achieve the melting point are called fusion or molten region. For the molten areas the phase changes from solid to liquid (and perhaps to gas as well). The neighborhood of the fusion zone experiences similar rise and fall in temperature but the highest temperature does not necessarily reach the melting point of the workpiece. This region is called the heat-affected region. The temperature cycle observed near the machined area of the workpiece is in many ways similar to the temperature cycles involved in many welding processes. Like in welding, two distinct zones, a fusion zone and a heat-affected zone are observed after EDM machining. While the fusion zone experiences solid–liquid phase transformation, the heat-affected zone experiences solid–solid phase transformation. Solid–solid phase transformations in steel are initiated when the temperature is raised above austenite transformation or A₃ temperature. Once this temperature is crossed the parent material transforms to austenite. Subsequently, as the austenite cools several daughter phases, such as ferrite, pearlite or banite could be created. These solid-state transformations are controlled by the cooling rate of the transformed austenite and the composition of the parent material. TTT or the CCT diagrams for different steel compositions are excellent tools to predict the fractions of daughter phases that are created during a certain cool-down process. Mathematical representations of the TTT diagrams were used in the past along with process simulation tools to predict the fractions of daughter phases formed during welding and heat treatment [18–21]. These tools enable the user to track the formation of Ferrite, Pearlite and Banite during cool down. The untransformed austenite that remains after the martensite transformation temperature is reached promptly transforms to martensite.

For solid-state phase transformation, the cooling rate is an important factor. The faster the cooling rates the more propensities there is for the formation of martensite. In the case of EDM, cooling rate is extremely high. It is much higher than water quenching (which shows one of the highest cooling rates among the traditional processes). Thus, it is expected that most of the heat-affected zone area will have transformed to martensite. After a portion of the molten layer is removed when the discharge collapses, the remaining material solidifies very quickly to form a thin layer of re-solidified material on the surface of the work-piece. Single spark experiments show the formation of craters on work-piece surfaces. The thin re-solidified layer observed on

the machined surface is really a result of overlapping craters formed due to numerous overlapping sparks. The thin re-solidified layer is generally called the white layer because it is difficult to etch using standard etching agents like nitol, etc. We observe several features within the white layer by employing non-traditional etching techniques. We described three sub-layers within the white layer. Two of these were formed due to simultaneous cooling from the outer surface inwards and from the inner surface outwards. These two layers are characterized by long dendritic structures. A third layer was observed sandwiched in between these two layers. In this current model it is possible to predict the extent of the fusion zone (i.e. the re-solidified molten layer) and the heat-affected zone that mostly contains martensitic material. Heat transfer results provide transient temperatures at all nodes. Nodal temperature data determines the region that melts and the region that experiences temperature above the A₃ temperature but stays below the fusion temperature. The fusion region loses some elements to simulate material removal. The rest solidifies to form the fusion zone. Due to the high cooling rate the solid-state transformation produces predominantly martensite. So all the heat-affected zone is shown to transform into martensite.

5.2 Crater Shape:

The final shape of the crater as a result of a single pulse is quite well known to researchers. It is a depression in the middle with edges that are raised above the surface (photographs are included in this document). This shape is formed as a result of two effects. During the plasma-on time the plasma pressure holds the liquid metal in place under pressure. This may force some of the fluid to be pushed towards the side and try and escape the pressure. It is assumed these liquids re-solidify to form the protruding edges around the hole. When the plasma pressure is released violently ejected liquid metal splatters and this leaves splashy re-solidified material all over the crater. In the simulation the depression within the crater is automatically simulated when the molten material is removed. To simulate the protruding edges a pressure boundary condition is applied on the molten pool and the pressure is kept on until the pulse-on time. This forces some of the molten material to severely shear and form the edge around the pool.

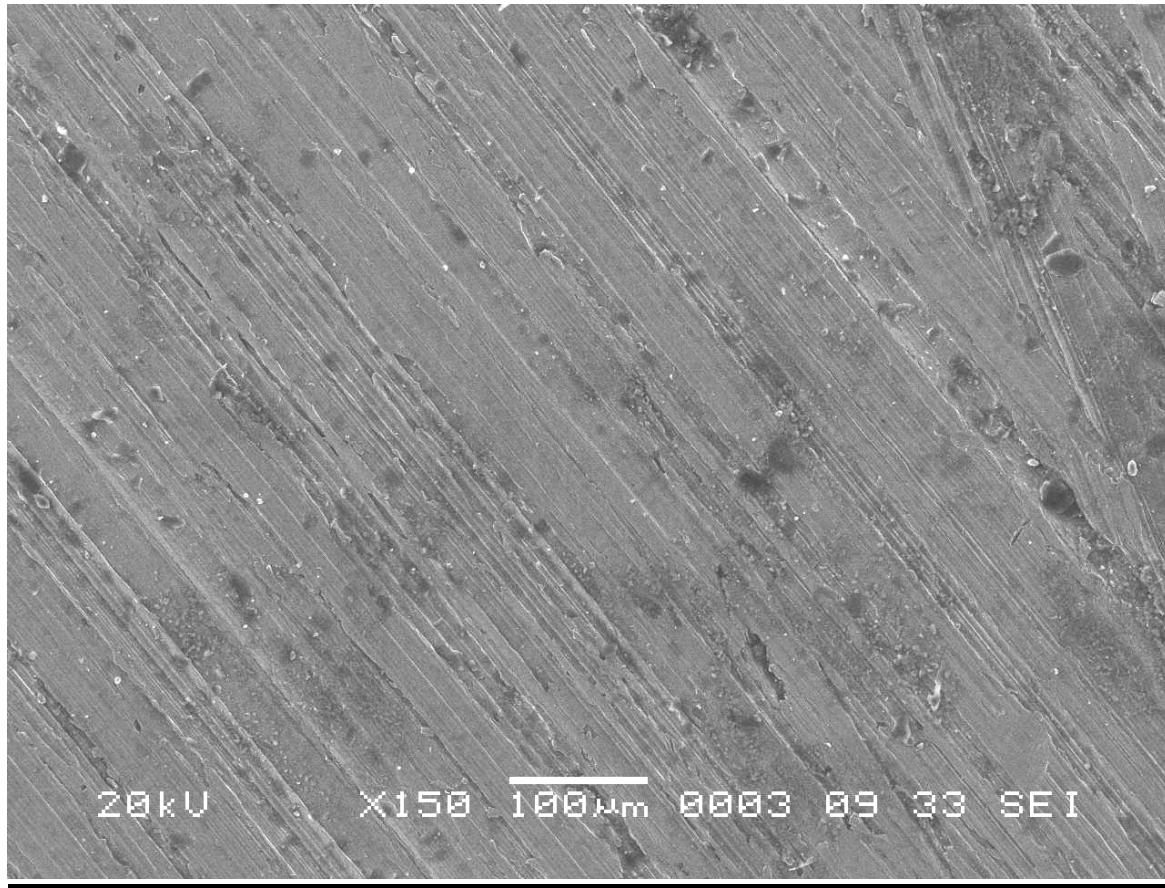


Fig 5.1 UnEDMed surface of En-19

Fig 5.1 shows the UnEDMed surface of Sample 1 which is of material En-19 at 150 magnification on SEM screen.

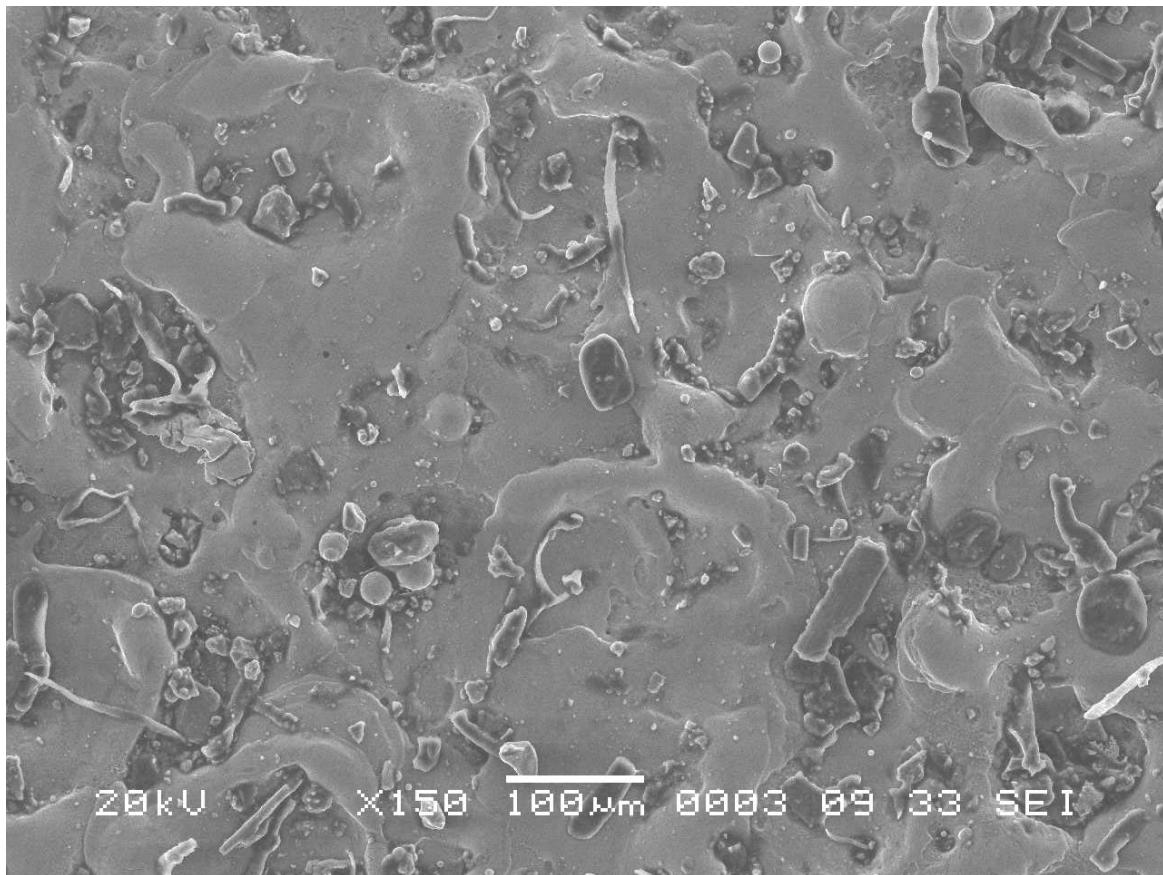


Fig 5.2 SEM photograph of EDMed surface of En-19 at 5 amp current

Sample 1:

SEM photograph of Sample 1 EDMed with current of 5 ampere (A) is shown in Fig. 5.2. From the figure it is evident that the surface roughness is better because of the less intensity of current. As seen from the figure, there is little distortion in the microstructure and almost no cracks develop. The phase transformed in this case is hence less because the thickness of white layer formed would be less, hence it is seen that the sample undergoes little transformation of phase and subsequently less residual stresses develop in sample no 1.

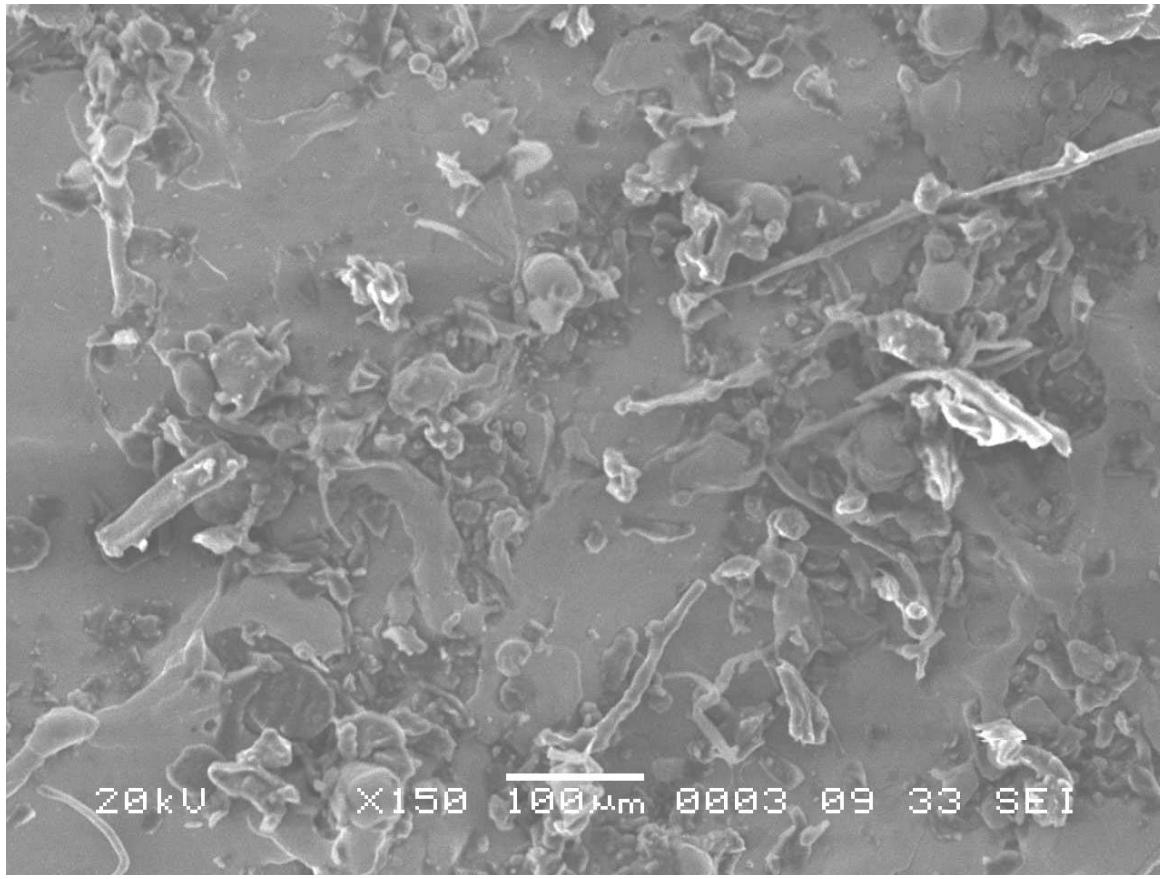


Fig 5.3 SEM photograph of EDMed surface of En-19 at 25 amp current

Sample 2:

Sample 2 EDMed at a current of 25 amp shows slight development of craters which would initiate cracks later (ref Fig 5.3). This sample undergoes constant overlapping of subsequent sparks which results in solid-solid transformation because of higher heat generation in the fusion zone at higher current of 25 amp. Hence solid transformation results in the development or generation of stresses below the solidified layer which is the residual stresses in the sample. The SEM pictures depict that there is higher surface roughness in this sample machined at a higher current and the microstructure is seen to vary largely from the unEDMed surface (ref. Fig. 5.1), hence giving rise to residual stresses in the sample, whose magnitude is higher than that of sample 1.

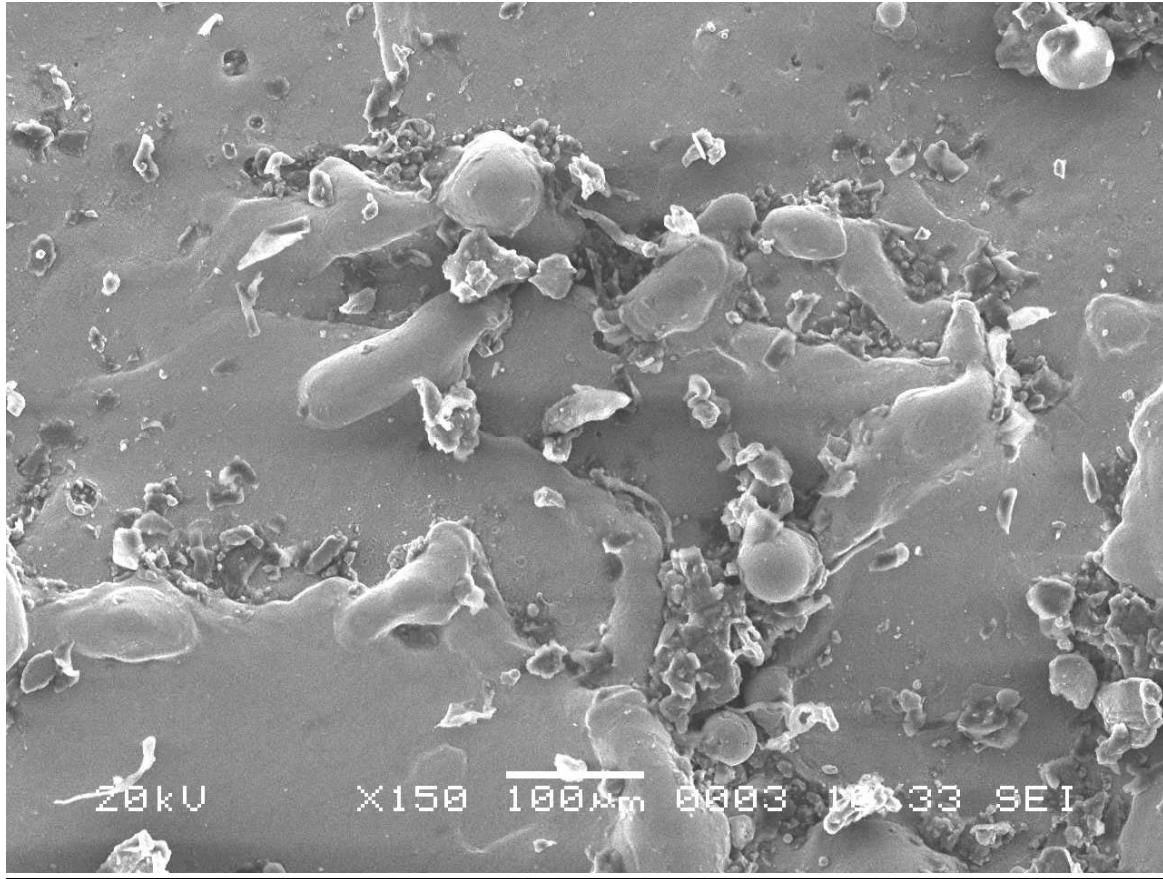


Fig 5.4 SEM photograph of and EDMed surface of En-19 at 45 amp current

Sample 3:

Sample No 3 EDMed at a current of 45 amp is the most interesting of the other two samples. In this sample we observe a drastic change in the microstructure of the sample being EDMed at such a high current. Craters are visible in the microstructure of this sample machined at 45 amp. The formation of craters clearly indicate the intensity of stress generated because of the phase transformed in this sample. At this current the sample while being EDMed bears violent and subsequent sparks at a short interval. These sparks generate a high heat zone in the fusion region, transforming the phase of the material from solid to liquid (and even to gas). The liquid metal quickly re-solidifies and a thin layer known to be white layer is formed because of high current the temperature developed is much higher which brings about drastic modification in the grain

structure of the material as seen from the SEM images. Hence the intensity of stress developed is much higher in the white layer just below the re-solidified layer, giving rise to residual stress which results in the formation of craters in the sample as seen from the SEM pictures.

5.3 CONCLUSION:

The present work deals with the analysis of residual stresses in EDMed samples which has been subjected to machining at different currents. The surface characteristics have been studied and the microstructures observed to conclude the impact of current and pulse on the sample. The significant findings of the present work are as follows:

- 1) At low current the surface tends to change less microstructurally. There is little distortion in the grain structure of the material. Intensity of residual stress developed is less as seen from the microstructural changes in the sample. At higher current, the surface roughness is more because of subsequent sparks. The material undergoes a phase transformation from solid to liquid and re-solidifies very quickly changing the grain structure drastically. Hence it is clear that the magnitude of stress generated is more at higher current than at lower current.
- 2) It is seen that the molten material and material that reached high temperatures tends to expand. This expansion is impeded by adjacent colder material resulting in significant rise in compressive stress in the region. Such high stresses lead to localized plastic deformation of the material. A significant component is the large tensile stress at the surface of the work-piece near where the plasma arc struck. When molten/heated material cools down it tries to contract but because it is in contact with the colder region its tendency to contract is impeded to a certain extent. This results in large tensile residual stresses.
- 2) Crack formation is related to the EDM parameters. An increased current will increase both the average white layer thickness and the induced residual stress. These two conditions tend to promote crack formation. When the pulse current is increased, the increase in material removal rate causes a high deviation of thickness of the white layer. Compared to a thin white layer, it is

true to say that a thick white layer has a tendency to crack more readily, however, the area occupied by the thick layer is less, so the density of surface cracking is broadly similar for both thin and thick layers.

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