Sophisticated industries like aeronautics, nuclear reactors, automobiles etc. have been demanding materials like high strength temperature resistance (HSTR) alloys having high “strength to weight” ratio. Researchers in material science are developing materials having higher strength, hardness, toughness, and other diverse properties. But, such materials are difficult to be machined by traditional machining methods. Because it is very difficult to find hard tool materials to cut materials like titanium, nimonics, tungsten carbide, fiber-reinforced composites, ceramics and other difficult to machine materials. It is, therefore, clear that some new methods of metal machining must be found out to deal with the problems created by the development and use of the hard-to-machine and high-strength-temperature-resistant alloys. Hence, intensive research have been carried out for many years to develop advanced machining processes which are unaffected by the hardness of the work piece and can machine easily and economically. Again, production of complex shape in hard to machine material by traditional method is still more difficult. Other higher level requirements are better finish, low values of tolerances, higher production rates, automated data transmission, miniaturization etc. To fulfill such demand, different classes of advanced machining processes have been
developed. Advanced machining processes can be broadly classified into three basic categories, i.e. mechanical, thermoelectric, and electromechanical & chemical machining processes (Jain, 2008). Wire Electric Discharge Machining (WEDM) is under the category of thermoelectric machining process. WEDM process is a widely accepted non-contact technique of material removal. Since the introduction of the process, WEDM has evolved from a simple means of making tools and dies to the best alternative of producing small parts with the good dimensional accuracy and surface finish quality. Thus the increased use of wire electrical discharge machining (WEDM) in manufacturing has kept growing at a highly accelerated rate. Its broad capabilities have allowed it to cover production of virtually all areas of conductive material machining. This is because wire EDM provides the best alternative, or sometimes the only alternative, for machining conductive, exotic and HSTR material with the scope of generating intricate shapes and profiles. Also, WEDM has proved to have huge potential in its applicability in the present day metal cutting industry for achieving a considerable dimensional accuracy, surface finish and intricate contour generation feature of products or parts.

The cutting speed, surface finish and taper angle are improving remarkably day by day since the inception of wire EDM process. But, wire bending, which is a major cause of cutting imprecision, is still hampering the part accuracy for various applications. This wire bending or wire deflection is called wire lag. When cutting out a corner or curved profile, the wire lag creates a geometrical error on the workpiece. This error can be of the order of a few hundred microns; which for some applications becomes unacceptable. For proper dimensional control the knowledge of wire lag value is extremely essential. An extensive study on wire lag phenomena is imperative to achieve exact dimension of job and for precision contour generation.
1.1 Mechanism of Material Removal in WEDM Process

The mechanism of material removal in wire electrical discharge machining mainly involves melting and vaporization caused by the electric spark discharge generated between the electrodes by a pulsating direct current power supply. Here negative electrode is a continuously moving wire and the positive electrode is the workpiece. A series of electrical pulses generated by the pulse generator unit are applied between the workpiece (anode) and the wire (cathode), to cause the electro erosion of the workpiece material. When a suitable voltage is built up across the wire and the workpiece, an electrostatic field of sufficient strength is established causing cold emission of electrons from the wire as shown in Fig.1.1. These liberated electrons accelerate towards the anode. After gaining sufficient velocity, the electrons collide with the molecules of the dielectric fluid, breaking them into electrons and positive ions. The electrons so produced also accelerate and may ultimately dislodge the other electrons from the dielectric fluid molecules. Thus, a narrow column of ionized dielectric fluid molecules is established connecting the two electrodes. As a result of this spark, a compression shock wave is generated and a very high temperature is developed in the range of 8000°C-12000°C. This intense heat generated near the sparking zone and the material melts and evaporates at the sparking spot, resulting in small craters on both the wire and the workpiece. But the electrode (workpiece) connected to the positive terminal generally erodes at a much faster rate as that compared to cathode (wire). This is due to the fact that the amount of heat generated at the anode spot is very large owing to the conversion of the kinetic energy of electron into heat energy. Though the mass of an electron is much smaller than that of a positive ion the striking velocity of electrons is much higher than the positive ions. An electronic pulse generator is used to maintain a fixed potential difference between the wire and the workpiece and generates sparks in the frequency which is about 1 MHz.
The gap in between the workpiece and the wire electrode is filled with a dielectric fluid to increase material removal in WEDM. Material removal is done by melting and vaporization in the sparking spot and the dielectric fluid adjacent to the sparking zone evaporates and other gas bubbles are formed. At the termination of a spark, cooling starts and the spark, plasma channel and gas bubbles collapse. This is known as cavitations. As a result, relatively cool dielectric fluid rushes into this sparking zone. This leads to the explosive expulsion of the melted material from the electrodes. However, the surrounding fluid moves towards the sparking zone and occupies the space resulting in a mechanical blast. This blast is believed to remove the molten debris of anode (workpiece) and cathode (wire) in the shape of metallic globules. Thus, the metal is dispersed into the dielectric fluid medium to form a colloidal suspension. The effect of cavitations in the material removal is important. It is an established fact that the MRR tends to be high when the pressure falls below atmospheric and is maximum when cavitations is maximum, during a single spark discharge.

The formation of debris and its effect on the process performance is another aspect. Type of electrical discharge also depends on the nature, size and concentration of debris in WEDM process. The presence of debris particles in the wire and workpiece gap increases the local electrical field strength and local current density leading to the reduction of ignition delay. Also, the breakdown characteristic of the dielectric improves in the presence of debris resulting in a high MRR. However, a too high debris concentration increases the incidence of short circuits resulting in a slower machining rate. A portion of energy in the gap is responsible for the formation of droplets of molten electrode material and the generation of mechanical shock waves. So the gap conditions determine the nature of pulses. The lower value of the breakdown field strength of the dielectric fluid causes an increase of the delay time. Thus
ignition delay time is used to control on-line monitoring of the gap condition.

**Fig. 1.1**  A typical scheme of discharge channel in WEDM
1.2 Application of WEDM Process

Wire Electrical Discharge Machining (WEDM) process finds many applications in aerospace, automobiles, medical industries, turbines and nuclear reactors component manufacturing industries etc. and particularly in tool and die making industries. WEDM is extensively used in die making industries and it can produce extremely smooth cavities having regular and irregular shapes or geometry, e.g., extrusion die, progressive die, piercing die, all sorts of punches, compound die etc. very precisely. Due to high process capability it is widely used in the manufacture of cam wheels, special gears, stators for stepper motors and similar intricate parts.

This process is very economical with respect to its complicated product geometry and difficult-to-machine materials. Simple as well as complex shapes like taper in vertical direction can be easily produced by WEDM with necessary accuracy and surface finish. This eliminates much complicated grinding operation. WEDM is very suitable for machining any electrical conductive material other properties like strength, hardness, brittleness do not impose any restriction on the process. Due to this WEDM process has gained tremendous applicability in the shop floor level as well as in the tool room applications because of its superior process characteristics and easy operational features. In addition to this, it is also equally demanded in tool room applications to manufacture components of a high degree of accuracy generally in hardened workpiece materials. These applications mainly include the followings:

(i) Fabrication of the stamping and extrusion tools and dies etc;

(ii) Manufacturing of various tool items in press tool industries, e.g., manufacturing of blanking punch and
die, piercing punch and die, stripper plate, forging die etc;

(iii) General tool making, manufacturing of templates, cams and cam wheels, lapping and polishing tools for superfinishing, electrodes for die sinking EDM;

(iv) Manufacturing of die in die casting process, e.g., machining of cavity in the die;

(v) Manufacturing of a large variety of moulding tools, i.e., core insert, cavity insert, ejector etc. in injection moulding, compression moulding, transfer moulding and grinding wheel and form tools etc;

(vi) Manufacturing of fixtures and gauges,

(vii) Manufacturing of prototypes, and medical parts and

(viii) It is used in aerospace and automotive industries and so on.

1.3 Properties of Wire Electrodes used in WEDM

Properties of the wire used have a direct effect on machining performance. The machining performance of the wire in WEDM is judged with regard to machining speed, surface roughness and wire breakage. The wire material should be easy to machine and be economical. The most frequently used materials now is brass or coated brass, copper, tungsten for machining steels and copper tungsten for carbides materials. Other wire material includes graphite and bronze. Properties of the wire mainly depend on the following factors:

(i) Mechanical properties of the wire material;
(ii) Electrical properties of the wire material;
(iii) Properties of coating material of the coated wire;
(iv) Thermo-physical (or physical) properties of the wire material;
(v) Geometric shape of the cross section of wire; etc.

In WEDM the gap between tool and workpiece is very small (0.025mm). In this small space, the workpiece is eroded by a violent, extremely localized and momentary action of the spark. Gas bubbles are rapidly formed during this process; and on the way to escape out, these bubbles press against wire in the gap. This pressure results in bowing of wire which tends to drag on bends and sharp corners as it advances. As a remedy, wire guiding and feeding mechanism should be designed such that the wire is kept at higher tension. Therefore, the effect of gap condition on the quality of the product will be minimized. Thus the important mechanical properties required for wire materials are tensile strength, the modulus of elasticity and in some cases, the co-efficient of mechanical friction. A wire material should possess a high tensile strength to withstand the tensile load applied along the wire during machining. This tensile load is essential for the wire to reduce the amplitudes of vibration of the wire and to keep the wire straight while cutting. However, a high Young’s modulus (E) ensures the less deformation (elongation) of the wire and a less coefficient of mechanical friction ensures smooth running of the wire along its path from the feed spool to the wire chopper.

To maximize the MRR, the pulse energy should be increased. Pulse energy depends on peak current (I) and for this reason current has to be maximized. But it causes the joule heating of the wire amounting to $I^2R$. $I^2R$ may be reduced by either reducing I or reducing R or reducing both. ‘I’ is reduced to ‘I/2’ by using two current pick-ups. Therefore, a low resistance (R) or a high conductivity is always advantageous for minimizing the frequent wire ruptures. So a higher electrical conductivity of the wire is always necessary to minimize the heating of the wire and
wire breakage due to the heating effect. In general, optimizing the machining process means that the energy transfer between the pulse generator and the workpiece must be maximized.

Coated or stratified wire is also in use in WEDM to obtain a much better heat sink effect in comparison with the non-coated wires. The idea is to apply a wire, which is composed of a copper or brass core and zinc (Zn) or Zinc oxide (ZnO) coating of 20 - 30μm thickness. This type of wire can carry more current therefore gives higher MRR. Zinc or zinc oxide melts at a lower temperature than copper or brass. In fact, it begins to turn to gas at a temperature lower than copper or brass. Hence the core of stratified wire gets no hotter than the temperature at which the outer zinc layer will vaporize and the core of copper will continue to absorb heat without melting and breaking. So the wire temperature is reduced. Thus, the wire can carry more electrical energy and more powerful sparks can be discharged. Thus material removal rates go up and so does the cutting speed. The effective gap size between tool and workpiece increases due to the coating evaporation, which results in a much better flushing and debris removal.

Thermal and physical properties of wire also have a significant role on the machining performance in WEDM process. The vital thermophysical properties of wire materials are as the following:

(i) Thermal conductivity;

(ii) Melting point and;

(iii) Evaporation temperature.

A higher value of thermal conductivity helps to minimize heat in the sparking zone through the conduction method in the wire. So the high thermal conductivity helps to cool the wire at a faster rate and this prevents wire breakage. High melting point and evaporation temperature
substantially reduces the depth and size of the crater formed on the wire surface and prevents the wire breakage also.

Wire diameter increases the MRR as the large diameter can deliver more energy. But the increment of the wire diameter causes the increment of corner radius of workpiece reducing the accuracy of the product. So the small diameters wire can be used in this case. The problems with small wire diameters are that they are not able of delivering a considerably large pulse power, which results in a lesser MRR. For this, 250 to 300μm diameter wires are generally used. Micro-WEDM applications require small pulse energies (<20μj) and geometrical precisions of tenths of microns. The ultra fine wires (φ up to 30μm) of tungsten and molybdenum are used for this purpose owing their high melting point, high evaporation temperature as well as high tensile strength.

1.4 Role of Dielectric in WEDM

Dielectric fluid plays a vital role in WEDM. Dielectric has several purposes like insulation, ionization, cooling, and removal of debris particles. Dielectric fluids are in general, electrically nonconductive though it acts as a conducting medium under a particular potential difference applied between different points of workpiece and tool in the medium. This potential difference, under which the molecules start breaking into atoms and atoms into free electrons and positive ions, is called the breakdown voltage. In WEDM process, a fluid dielectric used which is generally deionised water. The dielectric fluid serves as a spark conductor, concentrating the spark energy to an extremely narrow region. As soon as a spark discharge takes place, the dielectric again becomes a non-conductive medium until the required breakdown voltage is reached. The maximum potential difference that a unit thickness of a dielectric
medium can withstand (without breakdown) is defined as the dielectric strength of that medium.

The dielectric supply unit always circulates dielectric liquid through the machining gap by the use of pumps and is continuously filtered through such medium as wound cotton yarn cartridges or diatomaceous earth filter to remove the debris of machining. The latter has the capacity to remove large quantity of chips and has less maintenance problems. For normal precision work the filtering medium which does not allow particles of the size of more than 5μm is sufficient. For all high precision and high finishing applications, the filters should have the capacity to retain particles of more than 2μm. After filtering is over, the dielectric water is sent and stored in a tank. A conductivity sensor determines the effective value of conductivity and feeds back the information to conductivity controller. If the conductivity of the dielectric is higher than the set value it is pumped to pass through de-ionizing cartridges till it attains the correct set value.

Selection of appropriate dielectric is based on the following essential requirements:

i. It should have a particular stable dielectric strength to meet the process requirement,

ii. It should have high cooling rate,

iii. It should deionize rapidly as soon as the spark discharge takes place,

iv. It should have tow viscosity and a good wetting capacity,

v. It should be chemically neutral so as not to attack the wire-electrode, the workpiece, the worktable or the dielectric container,

vi. It should have properties to prevent any fire hazards,

vii. It should not emit any toxic vapour or have unpleasant odors,
viii. It should be stable enough to maintain its properties under temperature variations,
ix. It should have high MRR and good surface finish.
x. It should be easily available at a reasonable price

All the above qualities are generally found in the hydrocarbon oils having a viscosity of 5-6 Cst at 20°-22°C. This is the reason why kerosene is most widely used dielectric medium in die-sinking EDM process. The deionised water is not preferred in EDM for considerably larger tool wear whereas it is the only dielectric medium best suited to the WEDM process. The WEDM process requires a dielectric with low conductivity to provide a larger spark gap as the wire electrode under tension is subjected to vibration under various disturbing forces during and after spark discharges. Other dielectric fluids are tap water; aqueous solution of ethylene glycol etc but these are not suitable for WEDM.

1.5 Pulsed Power Supply Features in WEDM

In WEDM, pulsed dc power supply is used. Wire EDM power supply system differs from conventional EDM power supply basically in pulse frequency which is about 1 MHz. So the machining performance such as surface roughness is improved because of reduced crater size. Generally, a controlled pulse generator is used to generate the pulsed dc power. The machining performances are strongly related with the types of discharge pulses during machining. A high frequency discharge pulses between the wire and workpiece are generated to erode the workpiece. As shown in Fig.1.2, such pulse generators have a pulse controller and a power controller. The pulse controller sets a time or frequency basis and controls the on and off states of the power controller. The power controller, which consists of an electronic switch circuit and a current-limiting circuit, delivers the pulse to the gap with the required power. It
can give low peak current, short idle time, and desired length of pulse, enabling one to select either rough machining conditions i.e. high energy or low frequency of sparking, or finish machining conditions i.e. low energy and high frequency.

Ignition delay time ($t_d$) is defined as the time interval between the ignitions. When voltage is applied by the pulse generator between workpiece and tool, it takes time to reach the voltage at its peak value.
and to break the electrical field strength at spot of the spark discharge. The time to break the electrical field strength depends on the properties of dielectric and the amount of debris in the gap. The lower value of the breakdown field strength of the dielectric fluid increases of the delay time. This is the reason why the average delay time is considered as an evaluation parameter for on line process information required for adaptive control system in WEDM. It is worth mentioning here that none of these circumstances are constant not even for a stable process and a great variation of the delay time occurs for every individual pulses. However, results of various investigators have shown that generally a decreasing average ignition delay time is attended by an increased relative electrode wear and a decreased average MRR. It is estimated that pulses preceded by a very short ignition delay time are not good and ineffective. But, at the same time it has also been experimentally verified that the elimination of pulses with very short ignition delay does not yield any improvement in machining performances as expected in connection with the above mention ideas.

Depending on the ignition delay time, the normal (spark) discharge pulses may be classified into two major group, as follows:

(i) Normal discharge pulse:

These spark discharge pulses are ideal efficient and hence desirable. Those possess a definite ignition delay time. The occurrence of these types of pulses is determined by the machining conditions set such as preset servo reference voltage and table feed speed. The pulse frequency is proportional to table feed. This type of pulse sparks only at the discharge voltage ($V_d$).
(ii) Deion pulses:

When the gap is not fully insulated, these groups of pulses spark at a voltage lesser than the discharge voltage set ($V_d$). They occur just after the occurrence of the normal spark pulses. Therefore, the frequency of this type of pulses may be controlled by high-speed voltage recovery or decreasing the deionising time of the gap. It is almost impossible to separate the deion pulses from the normal spark pulses. However, for considerably large pulse off times, the number of deion pulses decreases.

In general, the pulse energy of a single pulse is calculated as follows:

$$W_p = \int_{t_1}^{t_2} I \times V dt$$  \hspace{1cm} (1.1)

Where, $t_1 = $ discharge start time, Second.

$t_2 = $ discharge finish time, Second.

$I = $ discharge current, Amp.

$V = $ gap voltage, Volt.

In WEDM, discharge takes place different in manner and these discharge pulses are classified into five major types, namely: open, spark (or normal spark), arc, off and short pulses. In open pulses (also called open circuit pulses), the discharge between the wire and the workpiece does not take place. Hence, the energy is continuously accumulated in the electrodes for a discharge to take place. Normal sparks occur when the de-ionized time is longer than the voltage recovery time and then proper discharge takes place. A normal spark pulse is an effective and the most desirable discharge with an ignition delay time ($t_d$). Ignition delay-free discharges are called arc pulses and in ‘off’ pulses, neither gap
voltage nor gap current is detected. Although arc pulses have a better MRR in relation to spark discharges, it never produces a better surface finish than spark discharges. However, this causes wire breakage due to higher thermal load. That is why arc pulses are also undesirable. When there is a direct contact between tool and workpiece then it represents short pulse.