Since the invention of WEDM machine, many efforts have been made to augment the machining performance and process stability. Process stability is the key factor for converting a material removal process into a controllable machining process. The demand for high surface accuracy at relatively high machining rate is constantly rising in manufacturing industries. The wire electrode is one of the factors amongst the various factors contributing the overall performance of WEDM. Many researchers have put their efforts towards the improvement of wire electrodes for enhancement of WEDM capabilities. The main section of this chapter focuses on the wire related factors for enhancing WEDM performance. Machining speed of WEDM is related with conductivity of wire electrodes and cryogenic treatment has been proved to be one of the effective methods to enhance the conductivity and relieving stresses in non-ferrous materials. The literature on cryogenic treatment is also included in this chapter. The detailed literature review is presented here:

2.1 WEDM PERFORMANCE CHARACTERISTICS

Wire electrical discharge machining (WEDM) is a process of causing intermittent discharge between wire electrode and work piece, through a working fluid. There is relative movement of work piece and wire electrode for cutting the work piece into a desired configuration such as various types of metal moulds, dies, punches, machine components, etc. WEDM is an indispensable machining technique used to produce complex two- and three- dimensional shapes through difficult to machine electrical conductive metals (Pandey and Shan, 1980). The performance measures in WEDM are cutting speed, surface finish and form accuracy. The main machining parameters, which affect the performance of WEDM are: pulse-on time, pulse-off time, wire speed, wire tension, servo reference mean voltage, type of wire and dielectric fluid pressure etc.. Several studies have been undertaken in the past in order to improve the performance characteristics, namely the cutting speed, surface roughness and wire wear ratio etc.
The technological aspects of the wire EDM process were analyzed by Daniels and Philips (1976). A mathematical model constructed by Scott et al. (1991) to predict the material removal rate and surface finish, when machining D2 tool steel material at different machining conditions. Tosun et al. (2003a) analyzed the effect of various process parameters and concluded that open circuit voltage and pulse duration are most effective parameters for surface roughness. Han et al. (2007) investigated that when pulse energy per discharge is constant, short pulses and long pulses will produce the same surface roughness but different material removal rates. It was also indicated that short pulse duration together with high peak value can improve surface roughness. Also reverse polarity has significant effect on surface roughness. Tosun et al. (2003b) further investigated that increasing the pulse duration, open circuit voltage, and wire speed increases the crater diameter and crater depth, whereas increasing the dielectric fluid pressure decreases these factors. It was concluded by Liao et al. (1997a) that material removal rate and surface finish are influenced by feed and pulse rate. Investigations into machining input parameters on the characteristics of surface produced by WEDM have been reported by Williams and Rajurkar (1991). Scott et al. (1991) investigated that the surface finish is increased with increase in discharge current, pulse duration and wire speed but it is affected adversely by decreasing dielectric flow rate. Tarng et al. (1995) used neural network system to find out optimal settings of process parameters (pulse duration, pulse interval, peak current and servo reference mean voltage) for the evaluation of surface finish and cutting speed. Greater discharge energy would produce large craters on the workpiece surface and hence more surface roughness (Rebelo et al., 1998). It has been reported by Liao et al. (2004) that shallow crater together with large diameters enhances the surface finish, so it is important to control electrical discharge energy at lower level by selecting shorter pulse. It was indicated by Han et al. (2007) that short pulse duration together with high peak value can improve SR. Also reverse polarity has significant effect on SR.

An EDM-wire will break when a discharge (or DC arc) introduces a flaw in the wire, which is greater than the critical flaw size necessary to produce catastrophic failure under the preload tension that has been applied. The significant factor in wire breakage is not the wire tension but the flaw created by sparks which attack the wire
A spark frequency monitoring unit was developed to detect on-line thermal load on wire (Wang and Rajurkar, 1992). Machining accuracy of the profile decreases due to breaking of wire in WEDM. A new control system was developed to control wire breakage during machining (Kinoshita et al., 1982). Temperature difference was predicted along the wire in the zone of discharge channel to understand the probable cause of wire rupture in WEDM (Banerjee et al., 1993). For eliminating the wire breakage during process a computer aided pulse discrimination system was introduced (Liao et al., 1997b). Self learning fuzzy controller was proposed to control sparking frequency by regulating pulse off time (Yan and Liao, 1996). A mathematical thermal model was developed in wire electric discharge machining to examine the influence of various process parameters on thermal load of wire (Rajurkar and Wang, 1993).

Optimal control of wire tension is required to prevent wire from breaking. Three dimensional temperature and stress distribution in micro wires were determined based on thermo mechanical analysis (Han et al., 2008). The effect of various process parameters on WRR were investigated experimentally and statistically. The ratio between WWR and cutting parameters were expressed by using a power function (Tosun and Cogun, 2003c). Uniform distribution of spark is necessary for stable machining. The effect of various process parameters on distribution of spark location were investigated by using high speed video camera (Okada et al., 2010). Alias et al. (2012) investigated the effect of different process parameters on kerf width, MRR and SR and best combination of machining parameters with machine feed rate was found out.

It is reported (Dauw and Albert, 1992) that ‘type of wire’ also play vital role on surface quality and cutting speed/ The improvement of wire electrode has yielded enormous increase of performance characteristics like cutting speed, surface finish and accuracy. A new high performance EDM wire would be expected to provide high cutting speed, better accuracy and improved surface finish. The improvement of wire electrodes was approached in controlling chemical composition of core or coating materials. Few researchers have directed their efforts to improve the surface roughness and cutting speed by using high performance wire electrodes. Zinc coated brass wire has considerably better flushability than uncoated wire (Aoyama et al.,
A graphite coating on the surface of brass wire dramatically improves flushability. High performance coated brass wire electrodes improves the cutting speed and surface finish significantly. Ranganath et al. (2003) observed that wear rate of plane brass wire is more than the zinc coated brass wire. Zinc coated brass wires performs better because of its low wear rate at increased discharge conditions as compared to plane brass wire. Morita et al. (2005) studied the fundamental effects of the thickness of brass and zinc layers on the machining characteristics of WEDM. Okada et al. (2008) investigated the effect of coating of brass and zinc on piano wire and observed that removal rate increases with increase of copper content in coated brass. Schacht et al. (2004a) investigated the effect of Cu and Zn coating on steel wire and concluded that precision in machining is due to high preload as compared to molybdenum and tungsten wires. Aoyama et al. (1999) developed high speed coated wire electrodes for super high speed cutting in order to make EDM most effective and efficient. Kuroda et al. (1999) and Aoyama et al. (2008) further developed and utilized high sonic (HIS) coated wire electrode for high speed WEDM and high falcon (HIF) for both high speed and high precision due to its good electrical and heat resistance properties. Wire electrodes of smaller diameters gives smoother finish than wires of larger diameter (Khan et al., 2006; Tomalin, 2007a; Patric et al., 2008). But these high performance wires are not only much costlier but also cause many impurities in dielectric fluid and other problems such as environmental hazards (Kern, 2007b).

2.2 WIRE ELECTRODES FOR ENHANCING WEDM PERFORMANCE

The wide range of published work relating to wire electrode development and its performance characteristics has been categorized into different sections, namely plain wire electrode, coated wire electrode, diffusion annealed wire electrode, gamma coated wire electrode, composite wire electrode and porous wire electrode (Fig. 2.1).

2.2.1 Plain Wire Electrode

The wire consists of a single homogenous component are identified as plain EDM wire electrode. These wire do not have coated or composite construction.

2.2.1.1 Copper and Brass Wires

Copper was the original material first used as electrodes in WEDM
applications owing to its excellent electrical conductivity, high elongation and its ability to be easily formed in fine wires. Its use was limited owing to its low mechanical strength and inability to control vibrations resulting in slow machining speed, inferior machining accuracy and propensity of wire breakage speed (Aoyama, 2001). Today its use is confined to earlier machines with power supply designed for copper wire electrode. Brass wires (Figure 2.2) are the combination of copper and zinc, alloyed in the range of 63-65% copper and 35-37% zinc (Schacht, 2004a). Prohaszka et al. (1997) have reported that machining speed increases with presence of zinc in the EDM wire electrode owing to stable discharge during machining. The zinc in the brass wire actually boils off, or vaporizes, which helps cool the wire and delivers more usable energy to the workzone. The addition of zinc in the wire provides higher tensile strength, lower melting point, higher vapor pressure rating and improved flushability, but its conductivity is significantly reduced. Antar et al. (2011) disclosed that machining speed can be further enhanced with more

![Classification of Wire Electrode Research Areas](image)

**Figure 2.1** Classifications of Wire Electrode Research Areas
addition of zinc (more than 40%) to wire but in that case, the drawing process to form a wire becomes difficult because of the presence of a brittle phase in the alloy.

2.2.1.2 Molybdenum and Tungsten Wire Electrodes

For smaller diameters (0.004” and under), molybdenum or tungsten wire electrodes are used because of its high tensile strength and load carrying capability (Uhlmann and Roehner, 2008). The tensile strength of the pure molybdenum is approximately 1.6 times and tungsten is 3 times as that of plain brass wire electrode. Their use is limited because of low electrical conductivity and flushing. Tungsten and Molybdenum wires also have poor discharge, low tensile strength at high temperature which leads to poor surface finish, and wire failure. This drawback was removed by using the molybdenum alloy containing one or more of the oxides of Al, Si and K and tungsten alloyed with rare earth elements like Y, La, Ce, and their oxides. The tensile strength and strains in the wire of molybdenum alloy was improved as the fine particles of the oxides are uniformly dispersed in the molybdenum, so that the recrystallization temperature of the molybdenum alloy becomes higher and accordingly the tensile strength of the molybdenum alloy at high temperature is improved (Shigeo et al., 1991). The molybdenum wire electrode is also abrasive to power feed and wire guides, moreover they are very expensive. The diameter of the Molybdenum and tungsten cutting wires can be reduced for more precise processing. The accuracy of the cut surface of the workpiece can also be improved (Gruber and Kunz, 2004, Ezaki, 1991a). Several authors have also (Tomalin, 1988; Mohammed and Richard, 1988) suggested that the molybdenum alloy, used to make the cutting wire electrode, has a characteristic called an emission effect, whereby the emission of electrons is facilitated for an improved current flow through the cutting wire. This increases the discharging capability, which subsequently produces the effective spark. The processing speed and the accuracy of the cut surface of the workpiece are improved, and the number of failures owing to breaking of the cutting wire is reduced. These wires are particularly suited for making small parts with very tight tolerances and good surface finishes.

2.2.1.3 Aluminum brass wire electrode

A small percentage addition of aluminum to brass (Fig. 2.3) enhances the tensile
strength of wire (near 1200 N/mm$^2$) without affecting the elongation property. These wire electrodes are less vulnerable to breakage than plain brass wires. They are commonly available in brand names like Somal, TAF, etc. (Kern, 2007b).

2.2.2 Coated Wire Electrodes

It is not practically possible to draw and produce brass wire with zinc content more than 40% owing to changes in the grain structure, which makes the wire brittle for further processing the wire electrode into small diameters (Wilkins, 1996). Owing to a low melting point, zinc can only be coated on the core of a metallic wire. An early attempt (Fowl, 1933) was made to draw the wires after hot dipping. The final size is attained by uniformly coating the zinc on core of the wire. The foremost requirement of zinc coated wires is to have better splashibility so that these wires perform better than conventional brass wire. Zinc coating is better than cadmium and magnesium, as cadmium is toxic and magnesium is highly reactive, also zinc has a better flush ability. During the EDM, a generated spark tend to boils off the zinc from the surface of wire, which helps cool the wire and delivers most of the useful energy (Jean-Paul, 1993). The cutting rate of these wires has a propensity to slow down owing to the spark penetration of the zinc coating.

2.2.2.1 Zinc Coated Brass Wire Electrode

An EDM wire must possess a tensile strength along with flushability that promotes cutting rate. It is known, in the early prior art (Conves et al., 1981; Briffod...
et al., 1982), to use a wire electrode with coating material having low vaporization temperature, such as zinc or alloy. The core maintains the required mechanical strength and coating increases cooling ability and flushability. The coating material easily vaporizes during spark generation and core is protected owing to the cooling effect of the coating material. Various processes, i.e. electroplating, plasma coating, and thermal spraying and hot dip galvanizing are used for zinc coating on brass wire. But owing to limitations of high cost, uneven concentration of zinc, change of characteristics of brass wire, generation of hazardous gases, a new method to coat zinc on the brass was proposed (Lee, 2006) to alleviate the limitation of prior art. The proposed invention (Fig. 2.4) is advantageous in terms of decreased manufacturing cost and prevention of environmental contamination. Combining the conductivity of core with the flushability of zinc (zinc coating on copper core) has also been suggested (Briffod et al., 1982). The wire electrode thus obtained, is more easily wetted by dielectric fluid. The cooling of the wire electrode is greatly improved, which permits an increased current flowing through the wire.

2.2.3 Diffusion Annealed Coated Wires

Hermanni and Fleisbach (1990) carried out their research to enhance the performance of zinc-coated brass/copper wires by diffusion annealing the EDM wires. Diffusion occurs at controlled elevated temperature and in an inert gas environment. In order to provide alloy of desired structure and composition, alternating layers of high conductivity, low melting, and vaporization temperature are diffused into each other. Copper atoms from brass diffuse into Zn atoms, and zinc atoms diffuse into brass. Negrerie et al., (1995) in their prior art, elucidated that Diffusion of Zinc of 0.1 to 1 micron occurs on a core of copper, molybdenum alloy copper clad steel after its annealing in an oxidizing atmosphere to form zinc oxide film on the surface. They offer satisfactory mechanical and breaking strength. The various alloys of brass and their associated properties suggested by Tominaga et al. (1987) and are shown in Figure 2.5.

2.2.3.1 X-Type Diffusion Annealed Wires

Groos and Hermanni (1990) disclosed a method of manufacturing a conducting wire electrode, which has a conductive core and coating of structural composition offering greater resistance against erosive wear. In another prior art
(Briffod, 1999) an attempt was made to provide the necessary breaking strength to the core of the wire. Zinc coating thickness was chosen in such a manner that zinc is completely diffused in to the wire to make the beta phase over the core of wire electrodes (Fig. 2.6).

Bronocut-X, Beta Cut-X, X-Kut are the brand names of these types of diffusion annealed wires. Despite of having disadvantages of poor straightness, low tensile strength and high cost, significant gains have been reported by these wires in aerospace alloys, such as Inconel and Titanium (Schacht, 2004).

2.2.3.2 D- Type Diffusion Annealed Wires

D- Type diffusion annealed wires are the further improvement over X- type wires. Beta brass encrusted over the copper-alloyed core (80%Cu, 20%Zn) has relatively elevated tensile strength (800 N/mm²). Such structural wire is disclosed by Bernd et al. (2002) for the use in WEDM. The objective of the study was to provide less expensive wire electrode with better physical and chemical properties. Other inventors (Kumar, 1998; Kumar, 2001) directed their efforts to produce wire electrode with a core of low zinc (alpha brass) with top levels of highly rich zinc beta brass to aid better tensile strength and to facilitate better erosion for accurate cutting of workpiece. The wire electrode for spark erosion cutting, so produced, was compared with normal plain brass wire electrode. Table 2.1 illustrates noticeable improvement in material removal rate with invented wire as compared with normal brass wire.
Tomalin (2007b) also recognized the desirability of such types of wires (Fig. 2.7). These are commonly known as cobra cut –D, D-cut and were initially used for Charmilles Agie machines owing to their auto threading ability.

![Figure 2.6 X-Type Wire Electrode (Conves et al., 1981)](image1)

![Figure 2.7 D-Type Diffusion Annealed Wire Electrode (Tomalin, 2007b)](image2)

**Table 2.1** Material Removal Rate Comparison of Invented Wire with Normal Brass Wire (Kumar, 2001).

<table>
<thead>
<tr>
<th>Work piece Material</th>
<th>Machine Type</th>
<th>Material Removal Rate with Normal brass (MM²/Min)</th>
<th>Material Removal Rate with Invented Wire (MM²/Min)</th>
<th>% Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardened Steel</td>
<td>ELECTRONICA</td>
<td>16.4</td>
<td>18.8</td>
<td>14.6 %</td>
</tr>
<tr>
<td>Aluminum</td>
<td>ELECTRONICA</td>
<td>13.0</td>
<td>18.0</td>
<td>38.5 %</td>
</tr>
<tr>
<td>Hardened Steel</td>
<td>MAKINO</td>
<td>36.0</td>
<td>50.4</td>
<td>40 %</td>
</tr>
<tr>
<td>Hardened Steel</td>
<td>SODIK</td>
<td>77.0</td>
<td>101.2</td>
<td>31.4 %</td>
</tr>
<tr>
<td>Hardened Steel</td>
<td>AGIE 200-D</td>
<td>78.0</td>
<td>105.0</td>
<td>34.6 %</td>
</tr>
</tbody>
</table>

**2.2.4 Gamma-Coated Wires**

The persistent development for higher cutting speed in WEDM has led to the development of gamma-coated wires (Fig. 2.8). It was reported (Briffod, 1993) that diffusion-annealed beta phase brass contains zinc content in the range 45%-50% and has high melting point, thereby providing excellent tenacity. Gamma wire takes advantage of low cost method of distributing a layer of gamma phase over the surface of wire electrode. These wires have the capability of reducing cycle time by lowering the cost of rough cuts via increased removal rate. Barthel et al. (1998) in their prior art further disclosed the desirability of gamma phase for EDM wire electrode. Gamma phase fractures, during the final drawing process, producing discontinuous surface,
thereby have the benefit of increasing the cutting speed. Many attempts (Ezaki et al., 1991b; Nakai et al., 2001a; Banazai and Shibata, 1990) have been made to improve gamma coated wires by employing low temperature diffusion annealing due to change in technology disclosed by various inventors.

2.2.4.1 Gamma-X and Gamma-D Type Wires

Inventions carried out by various inventors (Tomalin, 1999; Bariffod, 1993; Baumann and Barthel, 2002; Nakai et al., 2001b; Gonnissen and Vanvooren, 2001) also tried to cover the conductive core with a film of multiple fine layers. The alternating coating layers on the core of wire electrode are diffused into one another in order to provide alloys of desired structure and composition. These wires provide the characteristics of high conductivity and low melting and vaporization in an alternating fashion. Passivation (chromization and phosphatation processes) of the surface of the cladding of brittle phase of the gamma coating was disclosed by Chiriotti et al. (2002) to reinforce their resistance against corrosion. According to the embodiments of the invention by Barthel and Nuser (2003), the wire electrode core made of copper (X-type wires) or copper alloy (D-type wires) are first diffusion heat treated for the formation of beta phase and then stabilization treating steps are performed in order to produce the outer coating of gamma phase (Figure 2.9 and Figure 2.10). The electrode wire has a beta coating as an inner layer for fast machining and outer coating for precision machining at relatively low cost. Gamma phase coating is more brittle than
beta phase coating and epsilon phase is very unstable making it difficult to control the process for converting zinc coating to epsilon phase (Lee, 2008). However, better results are obtained by giving gamma phase layer a thickness of less than 8% of diameter of the wire (Barthel et al., 2005). These wires are commercially known as Gamma-X, Gamma-D or Versacut-H. These wire electrodes perform superior on aerospace alloys under good flushing conditions.

![Figure 2.10 Gamma-D Wire Electrode](Barthel and Nuser, 2003)

![Figure 2.11 Composite Wire Electrode](Kern, 2007a)

### 2.2.5 Composite Wires (Copper Clad Steel Core)

Composite wires, having unique property of alloying traditional EDM wire electrode (copper, brass) with nontraditional wire (steel), finds application in tall work pieces, interruptible cuts and for poor flushing conditions. The method of manufacturing of copper/zinc coating on steel core was initially proposed by Conves et al. (1981). The steel core enables the wire to maintain good mechanical strength and coating increases its cooling and splashing ability. The method of manufacturing includes zinc coating by electroplating before final sizing of wire. Tominaga et al., (1987) in their research disclosed coated wires having a copper clad steel core and a layer of beta brass that provides good conductivity and superior machining accuracy. The concentration of zinc gradually decreases radially in the inward direction. These wires offer incomparable resistance to breakage for tall workpieces. Kurth et al., (2004) unveiled the development of new copper-coated steel wires, different coatings and core combinations having features of good sparking ability, excellent straightness...
and increased accuracy. Several inventors (Blanc et al., 2008; Tomalin, 2007b; Tomalin, 1991) proposed new materials, like pearlitic steel, phosphates and chromates, which were introduced in wire electrodes. Pearlitic steel was shown to be more performant for high precision cutting. Damage to scrap choppers, high cost and straightness are the primary limitations owing to a steel core. These steel core wires (Fig. 2.11) are generally known as compeed, microcut, macrocut (Kern, 2007c).

2.2.6 Porous Electrode Wire

Tomalin (2007a) disclosed in his prior art that diffusion annealed wire electrodes may be porous, infiltrated with graphite to further enhance its discharge properties. Continuous coating is maintained during cold drawing of the heat-treated wire electrode. Tomalin (1999) further acknowledged the potential for a brittle epsilon phase by giving low temperature diffusion annealing to incorporate brittle gamma phase particle on the coating. An increase in cutting speed up to 15% was reported with wire electrode having porous surface morphology. Increased cutting speed was also observed owing to cooling of the wire because of increase in surface area. Uniform profile of the outer periphery of porous wire rather than surface protrusions does not affect machining accuracy. Porous nature of the wire is expected to improve flushability during EDM, providing spaces to eliminate particles resulting from the WEDM. Therefore, a zinc-coated porous wire, having improved performance of machining speed and flushability compared with a conventional coated wire can be provided without additional processes. The Hansen and Anderko (1958) identified epsilon phase brass as 84Zn/16Cu. Figure 2.12 shows a surface morphology of epsilon phase coating in which coated layer is compact and smooth.

2.2.7 EDM Wire Electrode Shape

Round wire electrodes have been long used in WEDM. Few other shapes of wire electrodes have also been conceived in many patents (Gonnissen and Vanvooren, 2001). Shapes other than round are found to enhance cutting rate and also convective heat transfer. Wire surface is augmented owing to altering in shape, which facilitate the enhanced feed rate owing to convection heat transfer coefficient. Spark ignition is enhanced owing to sharp edges in flat steel wire, which was patented by Dekeyser (1988). Improvement in cutting rate was also observed owing to rough wires in
WEDM (Schacht, 2004a). In prior art by Groos (1998), a drawing die was installed on wire electrical discharge machine to form the wire in different cross-sections for improvement in the process. An increase in cutting rate up to 15-20% was observed owing to enhanced heat transfer in six lobed wire electrodes (Inouse, 1983). Twisted grooves on wire electrodes were patented by Inouse (1985) in order to avoid occurrence of sparks at the same point. Zn-coated wires with varying cross-sections were reported by Gonnissen and Vooren (2005) to machine ceramics materials. Several inventors (Groos et al., 2004; Seong, 1999) disclosed in their patent that spark generated in WEDM moved close to the part and hot spots on the wire electrode are prevented owing to change in the direction of rectangular cross-section of the wire. Figure 2.13 depicts some of the different wire shapes patented to enhance the material removal rate.

2.2.8 EDM Wire Electrode Diameter

Wires of diameter range 0.02mm to 0.36 mm are generally available for WEDM. The cutting rate is enhanced with the development in wire electrodes from copper to composite, etc., not only owing to change in the composition of wire electrode but also owing to increase in the size of wire. For accurate cutting, wires of diameter 0.02mm to 0.100mm are used (Uhlmann and Roehner, 2008). Holye, (2006) reported that wire electrode material has to be matched with workpiece, so that in-

**Figure 2.12** Surface Morphology of Elipson Phase Coating (Tomalin, 2007a)

**Figure 2.13** Customized Wire Shapes (Groos, 1998; Inouse, 1983, 1985; Seong, 1999)
process variations are controlled efficiently. He further concluded that 20-30 micron wires are generally used for making small parts with very tight tolerances and fine surface finish. High-performance larger diameter wire electrode are used for fast cutting as they apply higher energy to the spark point, but at a price premium of three to four times as that of brass wires. The increase in wire diameter is due to increase in pulse power delivered in the cutting gap (Gedeon, 2001). In 1969, a wire of diameter 0.150mm used to get maximum possible cutting rate which subsequently enhanced to 0.360mm. Figure 2.14 illustrates the increase in wire diameter with the development in wire electrode for improvement in the WEDM process. Molybdenum and tungsten wires are generally used owing to low load-carrying capacity of brass and copper wires. Composite wires (Molycarb) offers considerable advantages for smaller diameter works (Schacht et al., 2004c). Efforts have been made in the past (Herrero et al., 2007) to identify and analyze the important force components acting on the smaller diameter wire electrode (0.03mm), like electrostatic, electromagnetic, dielectric flushing, wire traction, wire feed, etc. Efforts have also been made towards the development of a wire transportation system and power supply to handle fine wires of diameter less than 80 microns (Uhlmann and Roehner, 2008; Gruber and Kunz, 2004).

2.3 HIGH PERFORMANCE WIRE ELECTRODE APPLICATIONS

Tomalin (1999) revealed that composite wire has a better machining speed with improved surface roughness as compared to commercially available zinc-coated brass wire electrode, while machining on AISI 4140 chrome molybdenum steel. In one of the recent prior art by Niithe (2011), the wire of pure aluminum encompassed by layer of copper/zinc or zinc alloy finds applications in cold forming alloys for smooth surface without rupturing of wire electrode. Toshiyuki et al. (2005) investigated the effect of brass-coated steel wire electrode on the fundamental machining characteristics of SKD11 workpiece used for extrusion dies. It was concluded that material removal rate increased with the increase in thickness of the brass coating on the steel wire. They also observed that high tension could be applied to thick brass coated wire electrodes for stable machining. Okada et al. (2008) carried out experiments on the same SKD11 material to investigate the effect of optimum
thickness of brass layer on micro-steel wire and it was concluded that copper content of 60%-70% in brass layer is effective for higher removal rate. A steel core wire allows high preload on the wire electrode in WEDM, which leads to increased precision as compared to tungsten and molybdenum materials.
Experimental investigations (Schacht et al., 2004b) have revealed that skin effect has become a predominant phenomenon which results in higher electrical load leads to lower machining current. Thicker coatings on steel wires solve the problem of skin effect but thinner wires does not need a sub coating of copper to lead to good cutting speed. Technologies from brass wires to coated wires developed by Aoyama (2001) categorized the wires, namely; HIH (high hawk), HIF (high falcon), HIE (high eagle), HIR (high real), and HIS (high sonic). Ayoma et al. (2008) further compared the developed wire electrodes (HBZ, HIS, HIR) for high-speed EDM applicability, which are being utilized for mass production applications like metal moulds for IC lead frames and electronic parts. Figure 2.15 exemplifies various wire electrodes for better roughness and flatness with faster cutting speed. The structural specifications in respect of the geometry of the components can be fulfilled by adopting the bare, coated and composite wire electrode in the range of 0.01 mm to 0.30 mm. High strength coated wire electrode having a core of tungsten, molybdenum or steel has become established in the range of smaller diameters (0.02 -0.07mm) in order to realize a wire tension necessary for stable eroding process. Figure 2.16 shows the ultra fine wires for micro WEDM applications which require small pulse energies and sub micron geometrical precision. Schoth et al. (2005) in their study acknowledged the applicability of tungsten micro wires (20-30 μm) for cutting ceramics and medical instrument materials and recognized the future scope in small diameter wire EDM machines. Titanium and titanium alloys are progressively used in aerospace, automotive industries and as medical implant materials for vide range of applications. Experimental data was presented (Antar, 2010; Antar, 2011) to investigate the aerospace super alloys (Nickel based Udimet 720, Ti-6Al-2Sn-4Zr-6Mo titanium alloy) workpiece productivity using coated wires (ZnCu50 and Zn rich brass). Up to 70% increase in productivity was reported as compared with plain brass wire under same operating conditions. Several authors (Kuriakose and Shunmugam, 2004; Poros and Zaborski , 2009) studied the volumetric efficiency of cutting of hard to machine materials like titanium alloys (Ti6Al4V) and Cemented carbide B40 with uncoated brass, zinc oxide coated brass, brass CuZn20 coated CuZn50 wire electrode. In their experimental investigation they revealed that up to 50% increase in volumetric cutting efficiency was possible with brass coated wires as compared with other wires. Also,
an increase in discharge time increases volumetric efficiency of cutting. Figure 2.17 shows the influence of core material on cutting speed in WEDM. High zinc concentration represents the faster cutting rate. Coatings on already-used copper, brass, steel and molybdenum wires by a layer of a material possessing a small work function such as magnesium, alkaline metals and alkaline earth metals significantly increases the cutting efficiency (Ho et al., 2004). The effect of cryogenic treated wire electrode was investigated on the surface of EN-31 steel machined by WEDM and smooth surface was observed as compared to untreated wire electrode (kapoor et al., 2011b).

2.4 CRYOGENIC TREATMENT

The revolutionary work in low temperature by the British chemists Sir Humphry Davy and Michael Faraday between 1823 and 1845 prepared the way for the development of cryogenics. The combination of reduced temperature and increased pressure caused the evolved gases to liquefy. The temperature of about -110°C was successfully reached by evaporating the solid carbon dioxide mixed with low pressure (Bryson, 1999). The liquid oxygen was produced by the French physicist Louis Paul Cailletet and the Swiss Scientist Raoul Pierre. The first liquefied hydrogen was produced by British chemist Sir James Dewar (Collins, 1965). With the designing of a setup to produce liquid helium by Soviet physicist Peter Leonidovich and the American mechanical engineer Samuel Collins, it was made possible to conduct experiments at normal boiling point of helium -268.9°C (Weinstock, 1969).

For many years, sub zero treatment of metals has been used as a means of improving the surface hardness and thermal stability of the metals (Molinari et al. 2001). Shallow cryogenic treatment refers to the treatment of materials at very low temperature, generally at around -110°C and deep cryogenic treatment refers to the treatment of materials at temperature around -190°C. The brief literature on the effect of cryogenic treatment on ferrous and non ferrous material is given as:

Resistance welding electrodes have high thermal and electrical conductivity along with good mechanical properties. Chromium copper is widely used as resistance welding electrode. Tarr and Rhee (1977) observed that when the alloy is subjected to the liquid nitrogen temperature, the thermal conductivity is enhanced by 3-4% without affecting the hardness from re- aging. Gillin (1995) in his prior art disclosed the effect
of cryogenic treatment on electrical contacts. If an electrical contact is exposed to a low temperature for a selected period of time, it results in an extended useful life of the contact. The cryogenically treated electrical contact exhibit superior abrasion resistance and adhesion to backing, than non treated contacts. Mohan Lal et al. (2001) observed that cryogenic treatment is not just surface treatment, but it affects the entire cross-section of the materials.

Kamody (2001) describes the effect of cryogenic treatment to minimize the instability effects of workpieces, which results in regulation and compensation of wire burning action. Reitz and Pandary (2001) reported noticeable effect of cryogenically treated steels and other materials, like copper alloy, aluminum alloys, titanium, cemented carbides, ceramics and some polymers. The improved behavior in service performance is due to stress relieving in microstructure and homogeneous lattices.

Zhisheng et al. (2003) investigated the effect of deep cryogenic treatment on spot welding electrodes. It was observed that deep cryogenic treatment causes Cr and Zr atoms to disperse and makes the grains smaller, more uniform and compact than non cryogenic treated electrodes.

Wear resistance and tool life of the tool steel can be significantly increased by applying appropriate sub zero treatment (Quek, 2004). Kamody (1993) reported a process for the treatment of materials to improve stability, shock ability, hardness and extended wear ability. Stratton (2012) has recognized applicability of thermal treatment at cryogenic temperature, which enhanced the durability of tool steels by ten times owing to decrease in residual austenite quantity and formation of maximum density fine carbides. Bensely et al. (2005) acknowledged the improvement of wear resistance of steel with deep and shallow cryogenic treatment as compared to conventional heat treatment. The cryogenic treatment has been found to increase the tool life of high speed steels from 65% to 343% depending on the cutting conditions used (Molinari, 2001).

2.5 CONCLUDING REMARKS

A review of the literature has revealed that most of the research work has been directed towards optimization of WEDM operation and modeling of the process. The brass wires have been developed owing to limitations of copper wires. The brass wire has the limitation of low conductivity. The subsequent developments in wire
electrodes have lead to high performance wire electrodes leading to improved process efficiency. But these wires are rarely used owing to high cost and other environmental hazards. An appropriate treatment to brass wire may be a suitable alternative to high performance wire electrodes to enhance the performance of WEDM.