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ORIGINAL ARTICLE

Review of improvements in wire electrode properties for longer working time and utilization in wire EDM machining

Ibrahem Maher · Ahmed A. D. Sarhan · M. Hamdi

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Abstract Wire electrical discharge machining (WEDM) is an important technology, which demands high-speed cutting and high-precision machining to realize productivity and improved accuracy for manufacturing hard materials. WEDM has experienced explosive growth and complexity of equipment as well as rising demand for the basic process tool (the wire electrode). Greater taper angles, thicker workpieces, automatic wire threading, and long periods of unattended operation make the selection of the ideal wire a much more critical basis for achieving successful operation. This paper focuses on the evolution of EDM wire electrode technologies from using copper to the widely employed brass wire electrodes and from brass wire electrodes to the latest coated wire electrodes. Wire electrodes have been developed to help user demand and needs through maximum productivity and quantity by choosing the best wire. In the final part of the paper, the possible trends for future WEDM electrode research are discussed.

Keywords WEDM · Coated wires · Brass wires · Steel wires · Diffusion annealed · Composite wire electrodes

I. Maher · A. A. D. Sarhan (✉) · M. Hamdi
Centre of Advanced Manufacturing and Material Processing, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
e-mail: ah_sarhan@yahoo.com

I. Maher
Department of Mechanical Engineering, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh 33516, Egypt

A. A. D. Sarhan
Department of Mechanical Engineering, Faculty of Engineering, Assiut University, Assiut 71516, Egypt

1 Introduction

Wire electrical discharge machining (WEDM) is among the more widely known and applied non-traditional machining processes in industry today. In this procedure, improvements to the process mechanism and control have rapidly been taking place. WEDM can machine harder, they are higher strength, corrosive and wear-resistant, and difficult-to-machine materials. With WEDM, it is also possible to machine complicated shapes that cannot otherwise be achieved using traditional machining processes, such as turning, milling, and grinding. Applications of WEDM include extrusion dies, fuel injector nozzles, aircraft engine turbine blades, and machining of difficult-to-machine materials like tool steel, titanium, metal matrix composites (MMCs), and cemented carbides [1–5]. Besides machining electrically conductive workpieces, some WEDM work has also been reported on insulating ceramics and non-conductive materials [6–9].

The Russian Lazarenko couple designed the first electrodischarge machine in 1955 [10]. Ten years later, a numerically controllable wire discharge machine was developed, and in 1969, a machine for mass production was built. Most wire discharge machine controllers have been enhanced with computer numerical control equipment. As for wire electrodes, pure copper wires were used in the early 1970s but at the cost of accuracy and strength. In the second half of the 1970s, brass wire started to be used instead of pure copper wire. In 1980, copper wire electrodes coated with zinc and, in the following year, brass wire electrodes coated with zinc were developed and utilized. Brass wire electrodes with added aluminum or chromium were made as well. From 1990 onwards, brass wire electrodes coated with zinc for high-precision cutting and coated Cu-50mass%Zn for high-speed cutting were developed. Subsequently, core materials of stainless wire coated with copper were made and utilized. Also, new types of wire were developed which offered higher cutting speed due to increased zinc concentration and wire electrodes made of brass with added titanium and aluminum for improved heat resistance when cutting thick materials [11, 12]. Moreover, other special wire electrodes were developed to meet specific cutting conditions and materials, such as steel, tungsten, molybdenum, and abrasive-assisted and porous wire electrodes [13].

As for WEDM, demand is on the rise for high-speed cutting and high-precision machining for the purpose of improving the productivity of molds as well as for achieving high-quality machined workpieces. Wires used in WEDM are the core of the system. Brass wire electrodes are extensively used as WEDM tools. However, along with recent variations in manufacturing field applications, there is an expanding demand for wire electrodes with superior performance to the conventional brass wire electrodes. High-performance wires, including coated, composite, and diffusion-annealed wires are characterized by high conductivity and good sparking ability. These electrodes are generally zinc-coated wires with a copper-brass alloy or steel core, the brass containing either a small amount of chromium or high concentration of zinc. At present, WEDM users are interested in shortening the machining time of products [14–17]. A new, high-performance EDM wire would be expected to provide both high cutting speed and improved accuracy. Thus, this paper focuses on studying improvements of physical, mechanical, and electrical properties of wire electrodes for high-performance WEDM processes.

2 Wire EDM process

In WEDM, material removal is based upon the electrodischarge erosion effect of electric sparks occurring between the wire electrode and workpiece. The two are separated by a dielectric fluid, as shown in Fig. 1. A pulse voltage

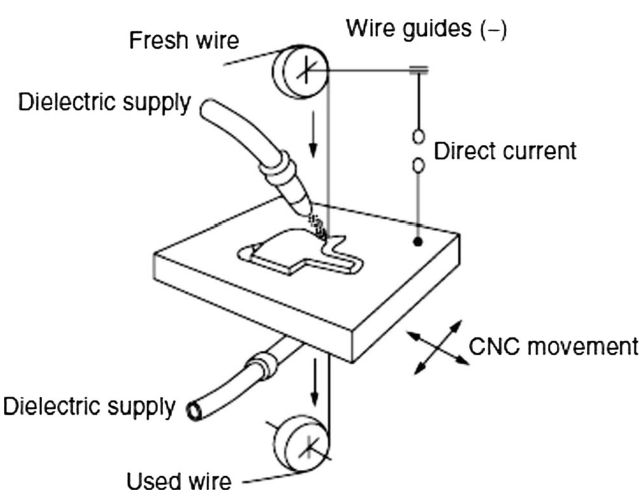

Fig. 1 Wire electric discharge machining (WEDM) schematic diagram

is applied between the wire electrode and workpiece in the processing fluid to melt the workpiece surface with the thermal energy of a spark discharge, while simultaneously removing machining dust through a vaporizing explosion and recirculation of the processing fluid. Continuous machining thus becomes possible while running the wire electrode. The residue ensuing from the melting and vaporization of a small volume of the surfaces of both workpiece and EDM wire electrode is contained in a gaseous envelope (plasma). The plasma eventually collapses during off-time. The liquid and vapor phases created by the melting and vaporization of the material are quenched by the dielectric fluid to form solid debris. This process is repeated at nanosecond intervals (depending on the cycle time) along the length of the wire in the cutting zone [18–20].

To achieve a successful operation, selecting the correct wire electrode for WEDM is a very challenging task [21]. As a result, experimentation with different wire electrodes is essential if optimum results are to be achieved. The wire electrodes used in WEDM must have two important characteristics: high electrical conductivity and sufficient mechanical strength. WEDM performance is attributed to mainly six factors, as shown in Fig. 2 [22–24].

3 Wire electrode properties

In general, the cutting performance of the WEDM procedure depends on a combination of electrical, mechanical, physical, and geometrical properties of the wire electrode. The factors not related to the wire but which are involved in WEDM, including the mechanical machine concept, improved machine intelligence, use of new pulse generators, and dielectric flushing techniques, also affect machining performance. The following section describes the key physical properties of EDM wires and how they relate to real-world cutting [25–27].

Conductivity is an important property of the EDM wire since it determines how the power supply energy is transferred over the distance from the power feed source to the actual point of cutting. This distance can be considerable, especially if the job is to cut with open guides to clear a workpiece obstruction. Low wire conductivity will result in a voltage drop and associated energy loss over the distance from the power feed to the cutting point. This is not insignificant considering that the peak current of most modern power supplies often exceeds 100 amps. Conductivity is often expressed as a percentage of IACS (International Annealed Copper Standard), which is a unit of electrical conductivity for metals and alloys relative to standard annealed copper [28].

Tensile strength indicates the wire's ability to withstand the tension imposed upon it during cutting in order to

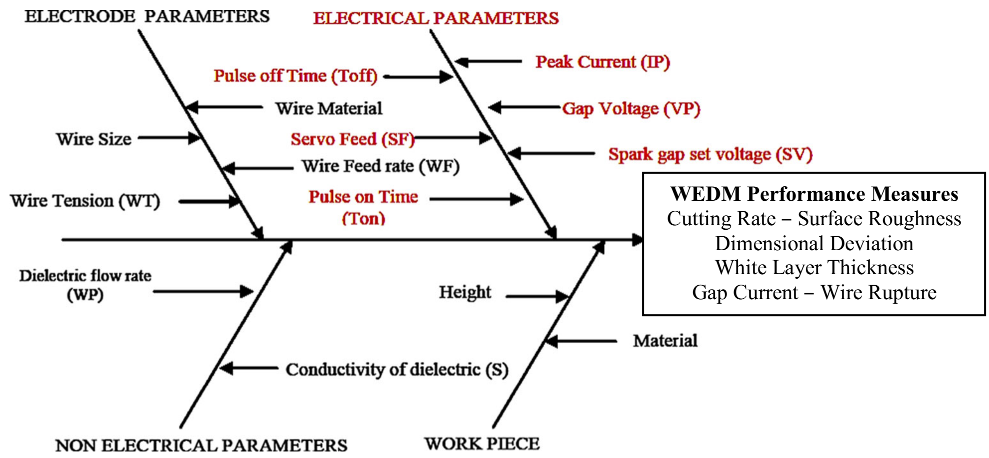

Fig. 2 Effect of various factors improving the WEDM performance [22]

make a vertically straight cut [29]. EDM wires are considered "hard" at tensile strengths of 900 MPa or above, "half hard" at tensile strengths around 490 MPa, and "soft" at tensile strengths below 440 MPa. Hard wires are commonly used for most work, while half hard and soft wires are primarily used for taper cuts where the taper angle is greater than 5°, since a hard wire will resist bending at the guide pivot and cause inaccurate taper cutting. Half hard and soft wires are often unsuitable for automatic threading unless the machine is specifically designed to work with such wires [30].

Elongation is an important property since EDM wires operate in hostile environments under high tension and get attacked by thousands of sparks at their cross section. Elongation describes to what extent the wire gives or plastically deforms just before it breaks. Elongation is measured in the percent of gauge length used in a given test. It could also be stated that elongation relates to how brittle the wire is. Usually, hard wires have considerably less elongation than half hard wires. A brittle wire might break at the first overload condition, while a more ductile wire is expected to accept a temporary overload.

Melting point is not normally specified for a given wire but is obviously important since WEDM is a spark erosion process. Also, the wire electrode should be somewhat resistant to the rapid melting by the sparks.

Straightness is another important property of EDM wires that is seldom specified but is critically important to successful autothreading and cutting thicker workpieces.

Cleanliness is a property that is not specified for EDM wires. Wires may get dirty due to contamination by residual metal powder left over from the drawing process, drawing lubricant, or paraffin added to the wire by some manufacturers prior to spooling. Dirty wires result in clogged guides and power feeds or slipping belts or rollers.

Geometrical properties are the wire's diameter, shape, and coating and layer structure. Wires ranging in diameter from 0.02 to 0.36 mm are generally available for WEDM. An increase in diameter results in an increase of pulse energy supplied to the working gap, thus increasing the overall material removal rate [31, 32]. On the other hand, for micro-WEDM where small pulse energies are predominant, using ultra-fine wires less than 30 microns in diameter is required [33]. A number of other wire electrode shapes have also been conceived in many patents [34–36]. Meanwhile, the use of modified cylindrical wires is rather limited due to their high manufacturing cost. A cutting rate increase of up to 15–20 % has been observed owing to the enhanced heat transfer in six-lobed wire electrodes [37]. Wire electrodes with twisted groves have been patented in order to avoid the occurrence of sparks at the same point [38]. Regarding their patents, several inventors have disclosed that sparks generated in WEDM moved close to the parts and hot spots on the wire electrode are prevented owing to the change in direction of the wire's rectangular cross section [39, 40]. Figure 3 depicts some of the different wire shapes patented to enhance material removal rate [37, 38, 40, 41]. In 1969, a 0.15-mm diameter wire was applied to achieve the maximum possible cutting rate; the diameter was subsequently enhanced to 0.36 mm. Figure 4 illustrates the increase in wire diameter with the developed wire electrode for WEDM process improvement [42, 11]. Efforts have been made in the past to identify and analyze the important force components acting on the smaller-diameter wire electrode (0.03 mm), like electrostatic, electromagnetic, dielectric flushing, wire traction, wire feed, etc. [43, 44].

Like most other things in life, finding the optimum wire for any application means reaching an acceptable compromise among the above-mentioned properties, since they are frequently conflicting. For example, high conductivity wires often have low tensile strength.

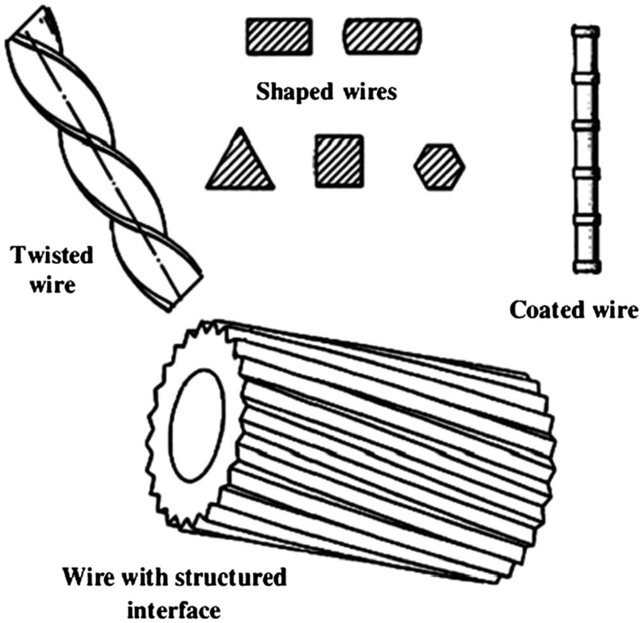

Fig. 3 Customized wire shapes [37, 38, 40, 41]

4 Development of EDM wire electrodes

The first machines in the early 70s were extremely slow, with cutting rates of about 21 mm^2/min. Cutting rates went up in the early 80s to 64 mm^2/min, while today, machines are equipped with automatic wire threading and can cut over 20 times faster than the earliest machines [45, 20].

For high-speed cutting and high-precision machining, any wire electrode should have key physical properties, viz high electrical conductivity, tensile strength, elongation, melting point, and straightness [46–48].

Technologies with brass-coated wires are categorized as HIH (high hawk), HIF (high falcon), HIE (high eagle), HIR (high real), and HIS (high sonic) [27]. HIS and HIR wire electrodes were developed for high-speed EDM applicability and are being utilized for mass production applications like metal molds for IC lead frames and electronic parts. Figure 5 shows various wire electrodes built for better roughness and flatness with faster cutting speed [49].

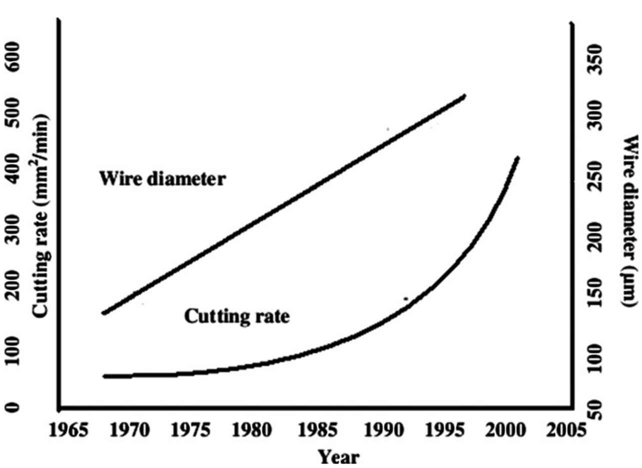

Fig. 4 Higher cutting rate machines using thick wires [11]

Adding zinc to the wire electrode helps control electrical discharge properties, subsequently enhancing machining performance. The addition of conductive alloying elements to the core surface of wire electrodes controls clarification and heat release [50]. Several inventors [51–53] have focused their efforts toward enhancing wire electrode performance by controlling the above methods. Significant increase in the performance of WEDM has been reported with single (plain wire electrodes) or multi-component (zinc-coated, diffusion annealed, etc.) wire electrodes [54, 55]. Brass wire electrodes are extensively used on account of their ability to generate stable discharge, but their electrical conductivity is low. Many wire electrodes have been developed by considering the electrical conductivity and heat resistance of the coated layer or core material. One property that noticeably affects WEDM performance is fracture toughness. Fracture toughness is the ability of the wire electrode to resist breakage and withstand the formation of craters on its surface [56–58]. Wires with high tensile strength can be made, but as a result have a tendency to break. Composite wire electrodes with a steel core and high fracture toughness have been developed to address the wire fracture and electrical conductivity problems. An EDM wire will break when a discharge introduces a flaw into the wire that is greater than the critical flaw size needed to trigger catastrophic failure under the preload tension applied (Fig. 6) [59]. Many high-strength materials, including EDM wires, are notorious for their low fracture toughness, that is, their inability to withstand relatively small flaws without failing. Each and every discharge in the WEDM process makes a crater, which is termed a defect or flaw, in both the wire and workpiece. As flushing conditions deteriorate, those flaws tend to become larger and larger, eventually causing disastrous wire failure [60–62]. Figure 7 shows the rapid advancement rate of WEDM with standard wire and high-performance wire electrodes since its introduction [42, 63, 64].

5 Plain EDM wires

Typically, brass wire begins as a continuously cast 20-mm diameter rod. This rod is either cold rolled or cold drawn until it is approximately a 6-mm round or hexagonal cross section. The wire is then annealed and drawn through a series of dies until it is around 0.9 mm in diameter. In this state, it is commonly called a "redraw" wire. The redraw wire is subsequently drawn through another series of diamond dies until it reaches the final size. At final size, the wire is resistively annealed or thermally tempered in an inert atmosphere, cleaned, and then spooled [65–67].

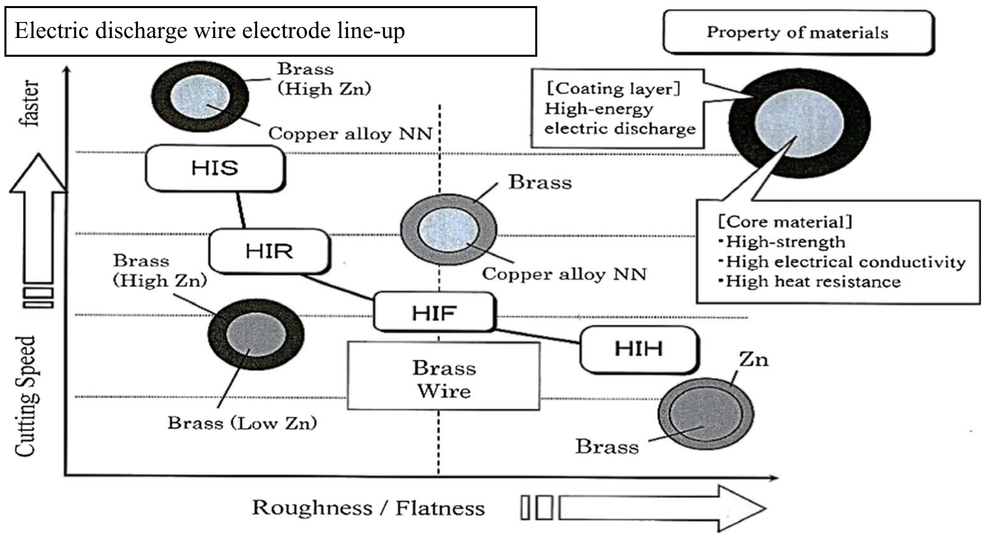

Fig. 5 Characterization of electrical discharge wire electrode [49]

In the EDM wire trade, plain merely means the wire consists of a single homogeneous component and does not have a coated or composite construction [30].

5.1 Copper wire

Copper wire, shown in Fig. 8, was the original material used in WEDM. At the time, it was believed that because copper wire had high electrical conductivity it would make the ideal EDM wire. Unfortunately, copper wire has low tensile strength, high melting point, and low vapor pressure rating [68]. This soon became apparent with the development of the second-generation pulse-type power supplies, and copper wire was shortly replaced by brass wire. It should be noted that copper wire is still used occasionally for applications in which zinc (contained in brass or coated wires) is considered an unacceptable contaminant [69, 30].

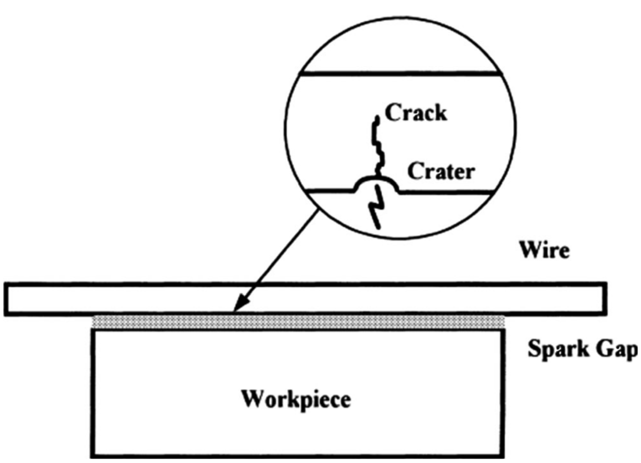

Fig. 6 Showing a defect and a fracture in the wire EDM process [62]

5.2 Brass wire

Various attempts have been made in the past to improve wire electrodes. Brass EDM wire is a combination of copper and zinc, typically alloyed in the range of 63–65 % Cu and 35–37 % Zn (Fig. 9) [63]. It has been discovered that the addition of zinc improves cutting performance and speed compared to copper in several ways [46]. During the cutting process, the zinc in the brass wire actually boils off or vaporizes, which helps cool the wire and deliver more usable energy to the work zone. Adding zinc provides significantly higher tensile strength and greater vapor pressure rating, which offsets the relative losses in conductivity. Also, some zinc particles that are not filtered out of the dielectric fluid would remain in the gap between the electrode and the workpiece to help the gap ionization and cutting process [42]. Brass rapidly became the most widely used electrode material for general-purpose wire EDM.

It is worth noting that even a small amount of zinc added to copper wire severely reduces conductivity. The conductivity of hard brass wire is typically only 20 % that of copper wire. Since it is zinc that gives the brass wire its improved flushability, some manufacturers now offer a high-zinc brass of Cu60%Zn40%. This increase in zinc content can increase cutting speed up to 5 % in some optimized applications [70]. However, it is not practical to cold-draw wire with zinc content in excess of 40 %. Changes in the wire grain structure make the wire too brittle for further processing into the fine diameters necessary for wire EDM. In some circumstances, significant brass deposit can remain on the workpiece after the cut, which is proven to be difficult to remove. These facts have led to the development of coated wires [71, 72, 14].

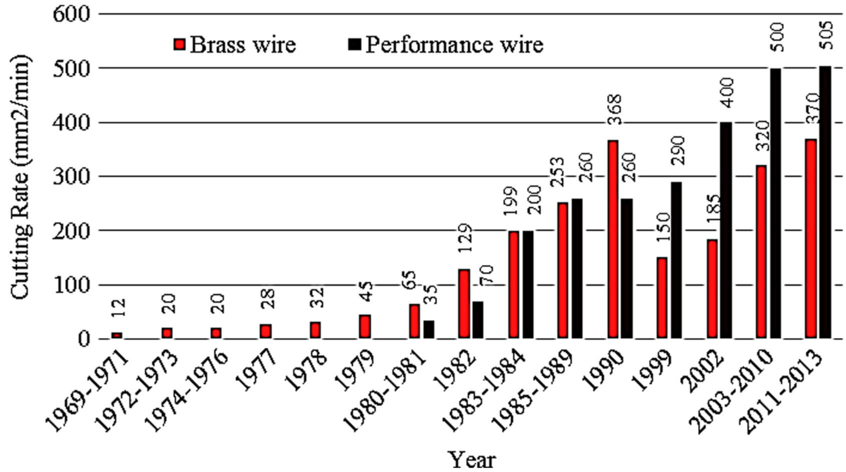

Fig. 7 Advancement of the WEDM rate since its development

5.3 Aluminum-brass wire

Adding a small percentage of aluminum to a brass wire creates a specialty alloy wire, as shown in Fig. 10. Such alloy additions improve the wire's tensile properties, allowing for tensile strength to be brought up to as high as 1,200 MPa without adversely affecting elongation. Some users claim these wires are less prone to breakage than other types of plain brass wire [30].

6 Coated EDM wires

US Patent No. US1896613-1933 is one of the earliest patents on zinc-coated wires directed toward improving the quality of such wires [73].

Due to the limitations in producing plain brass wire with alloy percentages greater than 40 % zinc, coated wires were developed in an attempt to put zinc on the surface of the wire while retaining a core wire material that could be successfully drawn [74]. Coated wires are produced by plating or hot dipping redrawn wire and subsequently drawing it to the final size. This is a difficult process since the plated surface zinc has to endure the final drawing process and still present a uniform coating to the cut. Currently, no EDM wires are manufactured by a process in which the coating is deposited at the final wire size. They typically have a core of brass or copper for conductivity and tensile strength and are electroplated with a coating of pure or diffused zinc for enhanced spark formation and flush characteristics [75–81].

6.1 Single-layer coated wires

Zinc-coated brass wire was one of the first attempts to present more zinc to the wire's cutting surface. This wire consists of a thin (around 5 microns) zinc coating over a core, which is one of the standard EDM brass alloys (Fig. 11). Zinc-coated brass wire offers a significant increase in cutting speed over plain brass wire, with no loss in any of the other critical properties [82]. Exceptional surface finish can be obtained when cutting tungsten carbide, and this wire is often utilized for cutting polycrystalline diamond and graphite. This wire is also utilized in circumstances in which brass wire produces unacceptable brass plating on the workpiece.

Zinc-coated copper wire was another early attempt to combine the conductivity of a copper core with the flushability of zinc. It has no current application because when sparks penetrate the thin zinc coating, the cutting rate slows to the sluggish pace of pure copper wire [83, 84].

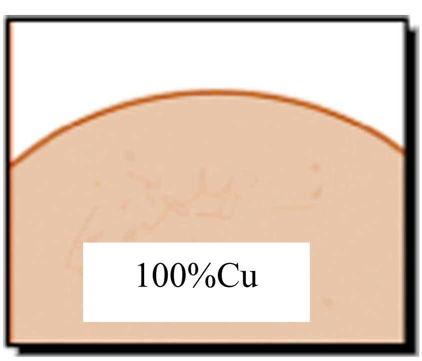

Fig. 8 Solid copper [30]

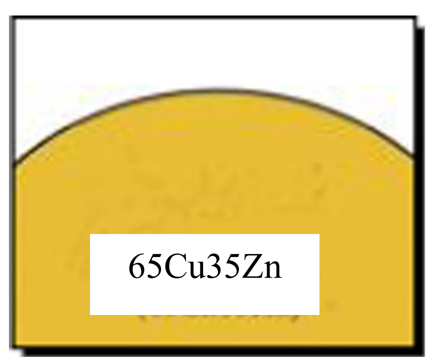

Fig. 9 Solid brass [30]

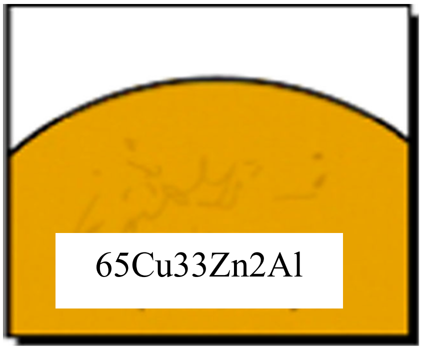

Fig. 10 Aluminum-brass alloy [30]

US Patent No. US4287404 disclosed that coating a wire electrode with a metal or alloy having a low vaporization temperature, such as zinc, cadmium, tin, lead, antimony, bismuth, or alloys thereof, protects the core of the wire against thermal shock resulting from the occurrence of electrical discharge. Additionally, increasing the frequency of the electrical discharges without running the risk of rupturing the wire is feasible [85]. Patent No. US6300587 is for a wire electrode containing a core, and coating layer formed on the outer periphery of the core contains copper. The coating layer comprises an alloy of 55.5 to 75 wt% copper and at least one element selected from the group consisting of Zn, Cs, Se, Te, and Mg. The coating layer does not have an oxide film thereon other than a natural oxide film [86]. Patent No. US6348667 refers to a wire electrode that prevents the corrosion, particularly of the non-eroded surfaces of the hard metal block. This purpose is attained by selecting a wire electrode for the spark-erosive cutting of hard metals, the outer coat of which consists of a metal or metal alloy and which is not nobler than the binder contained in the hard metal. Thus, small metal particles of the outer coat come loose during cutting due to wear of the outer wire electrode coat, and they remain in the dielectric. However, since these small metal particles are not nobler than the metal contained in the hard metal, electrochemical corrosion, namely pitting of the hard metal, can therefore not occur as soon as the small metal particles come into contact with the hard metal block. Consequently, the pitting phenomena in the hard metal block are avoided. As a rule, the hard metal block contains cobalt, aluminum, magnesium, zinc, or iron [87].

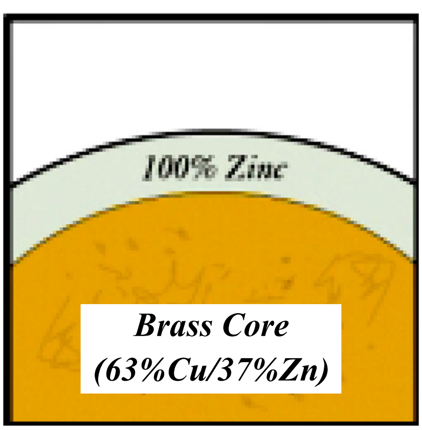

Fig. 11 Zinc-coated brass wire [30]

6.2 Double-layer coated wires

US Patent No. US4968867 discloses a wire electrode with a core wire having relatively high thermal conductivity, a lower coating layer formed by a low boiling point material and an outermost brass layer with high mechanical strength. Here, the core wire is made of copper, silver, aluminum, or alloys (Fig. 12). Certain effects, such as the vibration dumping effect, heat transfer effect, and resistance to breakage, were observed, all of which ultimately increase machining speed. Figure 12a shows a cross-sectional view of the first embodiment of the wire electrode invented. A core wire (6) is covered by a coating layer (7). In this embodiment, brass containing 35 % Zn is used for the core wire coating layer, and a Cu-Sn alloy including 0.15 % Sn balanced by Cu is used for the core wire. Besides brass, a Cu alloy containing Cu as the main component and less than 50 % Mg and/or Cd may be used for the core wire coating layer. As the second embodiment of the present invention, a wire electrode in composite form is obtainable by determining the coating layer thickness so that the cross-sectional area of the coating layer to the entire cross-sectional area of the wire electrode of the first embodiment is in the range of 50–90 %. In this embodiment, tensile strength is large, as the coating layer thickness is large too. The cross-sectional area of the coating layer to the total cross-sectional area of the wire electrode is about 69 %. In the third embodiment, the core wire (6) is covered by a layer (7) which is in turn covered by a layer (8), as shown in Fig. 12b. For the wire electrode, Zn is used in the outermost layer. The outermost layer is formed by a metallic material including Zn, Cd, or Mg as the major component, which has a low boiling point. Accordingly, machining speed can be improved. Figure 12c shows a cross-sectional view of the fourth embodiment. The outermost layer (9) is an oxide film onto coating layer (7). Unnecessary electric discharges at the lateral side of the wire electrode can be reduced because an oxide layer forms on the wire electrode surface. This realizes narrow machined groove width. In the fifth embodiment, the wire electrode constitutes a core wire (6) of a Cu alloy having high thermal conductivity, a layer (10) that is formed by twisting thin wires of brass with high mechanical strength, and an outermost layer (11) formed by Zn or Zn alloy (Fig. 12d). It was confirmed that the electric discharge characteristic can be increased to thereby realize uniform electric discharge so that the surface roughness of a workpiece can be improved. This is because the coating layer, as an intermediate layer with high mechanical strength, is covered by a low boiling point material. Figure 12e shows a cross-sectional view of the sixth embodiment. The wire

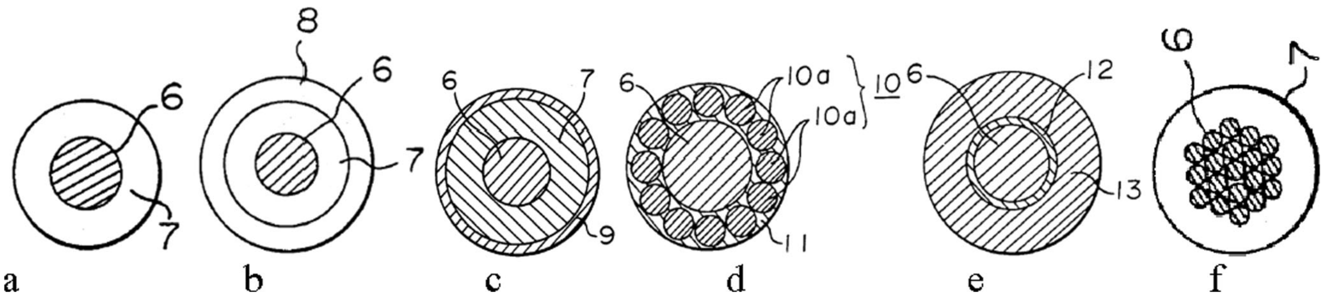

Fig. 12 Construction of wire electrodes [88]

electrode comprises a core wire coating layer (12) on the circumferential surface of the core wire by plating a material of Zn and an outermost layer (13) formed by brass. A linear material made of a Cu alloy including 0.15 % Sn balanced by Cu is subjected to zinc plating to obtain the core wire (6). Figure 12f presents a cross-sectional view of the seventh embodiment, where brass with 35 % Zn is used for the coating layer and a Cu alloy including 0.15 % Sn balanced by Cu is used for the core wire. At least one piano wire may be incorporated in the twisted linear elements to improve the mechanical strength of the core wire so that the performance of the electrode can be further improved [88].

Patent No. US4977303 disclosed a method of forming an EDM wire electrode by coating a copper wire core with zinc and then heating the coated wire in an oxidizing atmosphere to simultaneously provide a copper-zinc alloy layer over the copper core and a zinc oxide surface over the alloy layer. The resulting electrode wire permits for greater current density and traction force to be employed, yielding a significantly greater machining speed in the EDM process than achieved with earlier electrode wires [89].

6.3 Multi-layer coated wires

The main object of Patent No. US4341939 is to provide an increase in machining speed by eliminating the short circuits that cause a decrease in machining efficiency, more exactly by rapidly affecting the transformation of non-erosive short-circuited electrical discharges into electro-erosive effective discharges. The electrode is characterized by a structure comprising a wire coated with at least one layer of a second material, provided in turn with a thin film of non-metallic material; the thin film has a thickness sufficient to provide a semi-conductive effect when the film is in contact with the electrode workpiece and when a few volts are applied between the electrode wire and electrode workpiece, the film completely becomes a conductor by electrical and/or thermal breakdown when the voltage thus applied rises between a few volts to about 100 V. The wire coated with at least one layer of metal has low vaporization temperature and a metal oxide film coating the metal layer. The metallic coating is preferably made of zinc and is subjected to an oxidizing thermal or electrolytic treatment such that on the surface of the metallic layer a thin film of zinc oxide would form.

Figure 13a illustrates a schematic of a section through an electrode wire having a core (1) of copper and a superficial copper core coating of a copper-zinc alloy film (2) coated in turn with a thin film (3) of zinc oxide. Other materials, such as brass or steel may be used as the wire core (1) as long as they satisfy the requirements of good electrical conductivity, good mechanical strength, and resistance to rupture. Good results have been achieved with a coating of metal such as magnesium, cadmium, tin, lead, antimony, bismuth, or alloys thereof. Tests have shown that favorable machining results are not only limited to zinc oxide but also other metallic oxides may be used. It has been found practical to coat the top of the zinc coating with a film a few microns thick of another metal that can be easily oxidized by heating in the presence of oxygen. Other oxides also known for being semi-conductors have been used, for instance CuO, Cu_2O, CdO, In_2O_3, PbO, TiO_2, MnO_2, MgO, and NiO. Nonetheless, dielectric oxides such as $A1_3O_3$ can also be employed. The films adhering to the metallic layer surface may consist of other non-metallic materials too, such as carbides, borides, silicides, sulfides, and nitrides of various metals. Figure 13b illustrates a cross section through a wire having a copper core (1) provided with two, copper-zinc superimposed coatings (2) and (4) each covered with a zinc oxide film as shown in (3) and (5), respectively. Instead of a single, 8-micron thin zinc coating, a first coating (2) of 2 to 4 microns has been affected followed by a first heat treatment under the conditions disclosed previously to form a thin film (3) of ZnO. A second zinc coating (4) of about 4 microns is subsequently applied on the surface of the thin

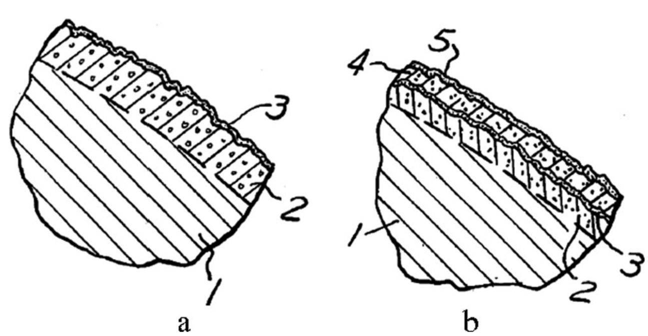

Fig. 13 Schematic section of wire electrodes [90]

oxide film (3), followed by a second heat treatment similar to the first, providing a thin film (5) of ZnO onto the surface of the second zinc coating (4). With the structure in Fig. 13b, the same phenomena of copper diffusion into zinc and vice versa have been observed, together with coating porosity resulting in outer surface irregularities and roughness [90]. An electrode wire with multi-coated layers for EDM that is capable of rapidly and precisely machining a workpiece into a desired shape without changing the electrode wire was disclosed in US Patent 20080245773. The wire has at least two coating layers including an outer layer made of zinc for precision machining and a lower layer made of zinc alloy for fast machining, thereby machining a workpiece continuously without change thereof (Fig. 14). Moreover, the electrode wire can be manufactured at a relatively low cost. Also, when discharging for machining a workpiece, no debris separates from the core wire so the machining work is not interrupted by the electrode wire [91]. US Patent No. US5196665-93 was another attempt to improve the mechanical strength of electrodes while maintaining benefits such as heat shield effect and the elimination of short circuits. The core is covered with a film of multiple, fine layers. The layers are characterized by high electrical conductivity and low melting and vaporization temperatures in an alternating fashion. The alternating wire electrode layers may diffuse into one another in order to produce alloys of desired structure and composition. The core, which is a metal selected from the group consisting of copper, brass, steel, or copper clad steel, is covered with superimposed alternate layers of copper and a metal selected from the group consisting of zinc and zinc alloys containing 30 to 60 % zinc content with thickness less than 0.5 microns [92]. Patent No. EP0734805A1 and Patent No. US5721414 produced an electrode wire having a thicker surface layer of diffused copper-zinc alloy by thermal diffusion method, such that spark erosion machining was accelerated [93]. The surface of the wire obtained in accordance with the invention is just rough enough for spark erosion, thus requiring no mechanical surface treatment apart from sizing. The wire electrode is characterized as comprising a core (17) of copper or copper alloy made up of a central core (19) covered with an upper layer (18) of copper or copper alloy that itself covers the surface layer (20) of diffused copper and zinc alloy or copper alloy. Surface layer (20) has a slightly granular surface (21) as shown diagrammatically in Fig. 15.

7 Diffusion-annealed coated wires

If zinc has such great flushability, it would be presumed that a pure zinc coating would produce the ultimate wire. In theory perhaps, but in reality it does not quite work out that way. This is because zinc has a low melting point, and it is only plated onto the surface of the core wire, and the intensity of the spark discharge tends to blast the zinc off the wire core surface before it has a chance to live up to its full potential [94]. Thus, a coating with high zinc content and relatively high melting point will result in good adhesion to the core wire. All these effects can be achieved by heat-treating the zinc-coated wire, a process called diffusion annealing. Under the right conditions at a controlled, elevated temperature and an inert gas environment, diffusion will occur. Diffusion is the process whereby atoms diffuse from areas of high concentration to areas of lower concentration. The zinc atoms diffuse into the brass, and the copper atoms from the brass diffuse into the zinc. This diffusion process transforms the zinc coating into a high-zinc brass alloy which is zinc-rich, has a relatively high melting point, and is metallurgically bonded to the core material [95, 96].

7.1 Alpha phase wires

The brass alloy phases commonly applicable to EDM wires are alpha phase, beta phase, gamma phase, and epsilon phase, as shown in Fig. 16. Alpha phase has the highest melting point (approximately 910 °C at its highest commercially feasible zinc content of 35–39 wt%); beta phase has the next highest melting point (approximately 890 °C in a diffusion-annealed coating with a typical 40–53 wt% zinc content); gamma phase has the next melting point (approximately 800 °C in a diffusion-annealed coating with a typical 57–70 wt% zinc content); and epsilon phase has the lowest melting point (approximately 550 °C in a diffusion-annealed coating with a typical 85 wt% zinc content) [97, 98].

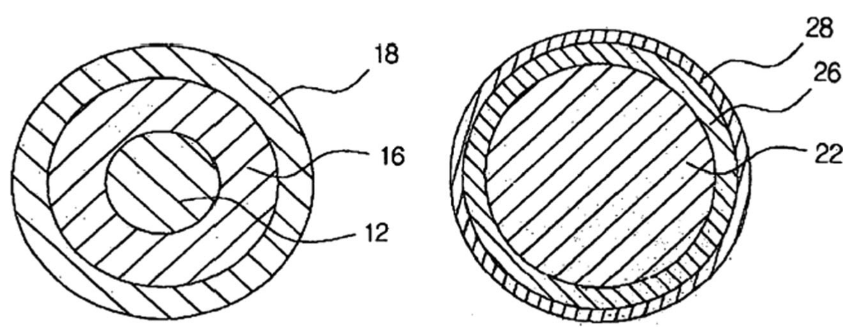

Fig. 14 Cross section of wire electrodes [91]

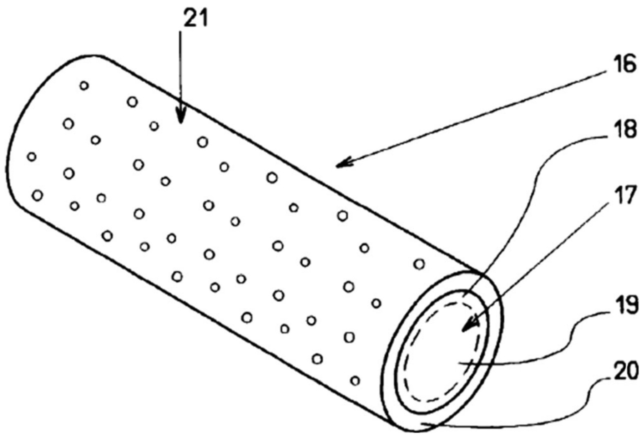

Fig. 15 Diagram of wire electrode [93]

7.2 Beta phase wires

The X-type wire was the first diffusion-annealed wire commonly known as SWX, BroncoCut-X, BetaCut-X, X-Kut, or other brand names. The wire consists of a beta brass coating over a pure copper core (Fig. 17a). It has the advantage of combined high copper conductivity and coherent zinc-rich coating. Its disadvantages are tensile strength equivalent to half hard brass combined with poor straightness and high cost relative to brass wires. However, it produces significant productivity gain in aerospace alloys such as Inconel and Titanium [99, 100].

D-type wire, shown in Fig. 17b, was the second diffusion-annealed wire generally known as CobraCut-D, D-Kut, and other brand names. The wire consists of a beta brass coating over a copper core alloyed with 20 % zinc. It has the advantage of combined improved conductivity of the 80 % Zn to 20 % copper core, a coherent zinc-rich coating, and relatively high tensile strength (800 N/mm^2). Its disadvantage is the high cost. This wire produces significant productivity gain in virtually all materials and on many different machines [30].

US patent No. US4935594-90 entails a wire electrode with a structural composition, whereby in its outer coating there is

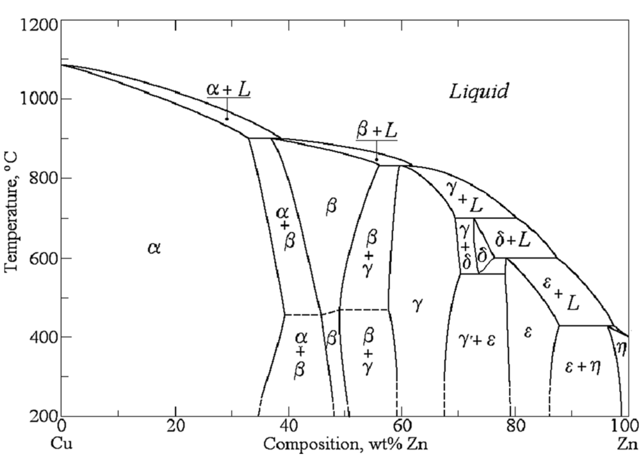

Fig. 16 Cu-Zn phase diagram [97]

much greater resistance with respect to erosive wear than the common eroding electrode. It was disclosed that the outer layers of a coated wire have a zinc-rich alloy.

Referring to Fig. 18, making an eroding electrode according to the invention, a core (2) of 0.1- to 0.6-mm diameter can be used as an initial material. Onto the core, an original material coat (3) (Fig. 18a) is applied, consisting of zinc, cadmium, bismuth, antimony, or an alloy of these metals. Such a wire (1) is annealed at 700–850 °C most advantageously while passing through a protective gas and is subsequently cooled off to less than 80 °C—again using a protective gas. In this manner, an altered coating (3') (Fig. 18b) with the aforementioned advantageous characteristics is produced. The core (2) of the wire (1') consists favorably of electrolytic copper having more than 99 wt% copper and very low oxygen content. A copper-zinc-alloy with 79.5–80.5 wt% Cu, the remainder being Zn, can also beneficially be used. The altered coating (3') includes layers of a mixed structure of metallic phases, and its content of low volatilization temperature metal decreases as the altered coating (3') extends from its outer surface to the core (2). The metallic phase layers include alpha-beta phases and beta-gamma phases [99].

European Patent No. EP0526361A1 introduced an electrode to obtain high-stability electric discharge while machining an object. A layer of Zn is formed on a copper or copper-alloy wire. The wire is heat-treated at a temperature below the beta prime-beta transition temperature of the binary alloy Cu-Zn until an outer layer (31) consisting of a homogeneous beta prime phase is formed. Then, the wire is drawn at a drawing ratio greater than 100 % in order to obtain an electrode (1) as shown in Fig. 19. Electrodes for electro-erosion have an outer metal layer (3) made of Cu-Zn alloy in the homogeneous beta prime phase free of oxide inclusions with a junction (32) of low thickness. The wire (20) is made of copper or copper alloy doped with one or more elements selected from Fe, Co, Ti, P, Mg, Cr, Zr, Si, at a global content between 0.1 and 1 wt% or with one or more elements selected from Al, Sn, Ni up to 4 wt% overall. The outer metal layer (3) has a Zn weight concentration in the region of 46.5 % +/−1, substantially constant throughout its thickness [96].

In Patent No. US5858136, copper wire coated with a layer of zinc is heated to 750 °C, sufficient for the formation of a brass beta phase. The temperature is maintained until zinc completely diffuses, as shown in Fig. 20a. The wire is then heated to a temperature of 950 °C, which is necessary for the formation of a brass phase, and the central copper part of the wire transforms into a brass alpha phase (Fig. 20b). It has the advantage of both high conductivity and relatively high tensile strength [100].

Patent No. US7687738 concerns an electrode wire comprising an unalloyed copper core coated with a diffused zinc alloy with thickness greater than 10 % of the wire diameter. The coating layer is optionally plated with a thin Zn, Cu, Ni,

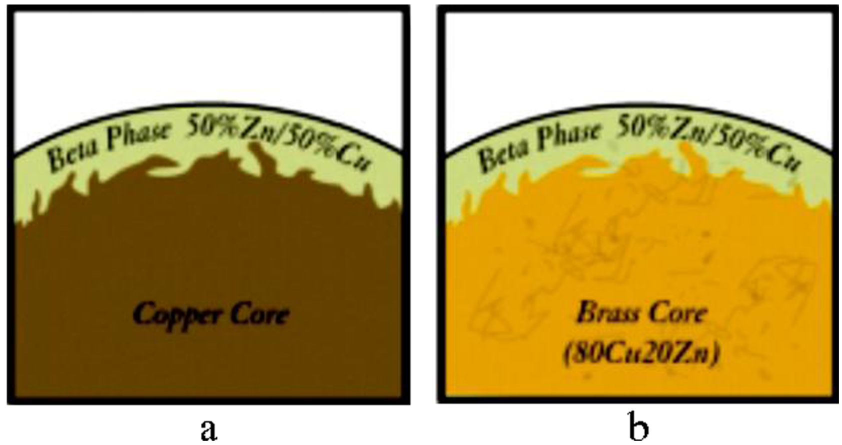

Fig. 17 X- and D-type wire electrodes [30]

Si, or Au surface contact film. In all cases, an increase in the spark erosion rate of approximately 30 % was observed compared to a brass or zinc-plated brass wire of the same diameter. A second aspect of the invention highlights the influence of the overall conductivity of the electrode wire on spark erosion performance, exploiting this influence to increase the machining rate on the assumption that electrical energy will be supplied by more and more powerful generators. It has been observed that the overall electrical conductivity of the electrode wire may advantageously range from 65 to 75 % IACS. Below 65 % IACS optimum spark erosion, cutting performance is not achieved because of the insufficient conductivity of the electrode wire. The wire breaks more easily as a result of heating in the sparking area. This is caused by the more intense Joule effect and by the reduced cooling associated with lower thermal conductivity. The required type of electrode wire cannot be obtained above 75 % IACS, because it would then be obligatory to reduce the thickness of the diffused layer to under 10 % of the electrode wire diameter. Failing this, the wire is too rigid and brittle and must not be drawn during fabrication. The recommended overall electrical conductivity of the electrode wire is in the order of 69 % IACS, corresponding to a diffused layer approximately 35 pm thick for a 0.33-mm electrode wire, i.e., a relative thickness of approximately 11 %. The relative thickness of 11 % and overall electrical conductivity value of 69 % IACS yield good results for wires ranging in diameter from approximately 0.20 to 0.35 mm [101].

7.3 Gamma phase wires

Gamma phase brass has higher zinc content than beta phase brass. Gamma phase brass is very brittle; therefore, the gamma coating thickness is usually limited to less than 5 microns; thicker coatings will fracture and strip off in the final drawing process. Due to the brittleness, the gamma phase brass actually fractures during the final drawing process producing a somewhat discontinuous surface. Such surface has the benefit of increasing the cutting speed by improving flushing as the wire passes through the cut, enhancing water flow and scouring debris from the gap. The discontinuous surface has the disadvantage of being slightly dirtier than other zinc-coated wires [91].

Gamma brass-type wire features a brass core and a gamma phase brass outer layer, and it is commonly known as Z-Kut, Topaz, Gamma-Z, DeltaCut, and other trade names. It is similar to zinc-coated brass wire, except that the pure zinc coating is replaced by a gamma phase brass coating as shown in Fig. 21a. It is available with both hard and half hard brass cores. Performance is typically 10 to 25 % faster than pure

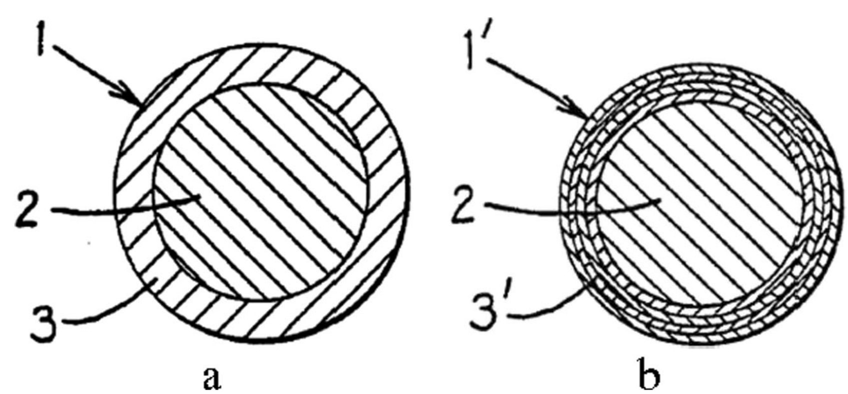

Fig. 18 Cross section of wire prior to and after the process [99]

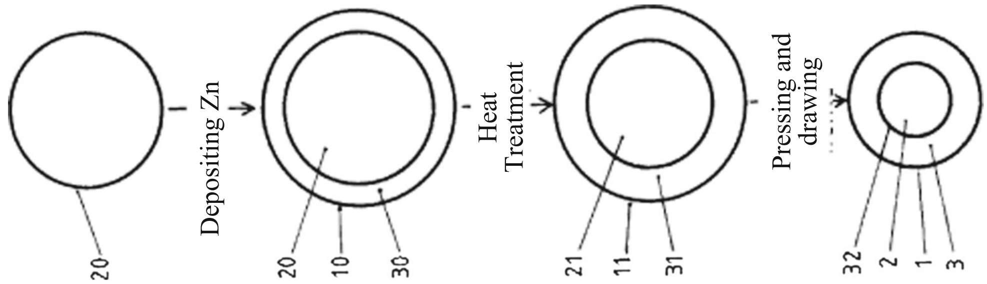

Fig. 19 Shows the different steps of the process according to the invention [96]

zinc-coated wires [30]. According to the embodiments of invention No. US6566622 B1, the wire electrode core made of copper (X-type wire) or copper alloy (D-type wire) is first diffusion heat-treated so a beta phase forms, after which stabilization treating steps are performed in order to produce the outer coating of the gamma phase (Fig. 21b, c) [102]. It can be used in the same range of applications as traditional X and D wire types, but this offers enhanced performance of approximately 10 % [103]. It has been reported that diffusion-annealed beta phase brass contains zinc content in the range of 45–50 % and has a high melting point, thereby exhibiting excellent tenacity. Gamma wire has the advantage of a low-cost method of distributing a layer of gamma phase over the wire electrode surface. These wires have the capability of reducing cycle time by lowering the cost of rough cuts via increased removal rate [104]. Many attempts have been made to improve gamma-coated wires by employing low-temperature diffusion annealing owing to changes in technology disclosed by various inventors [88, 86]. A range of inventors have also tried to cover the conductive core with a film of multiple fine layers. The alternating coating layers on the core of the wire electrode are diffused into one another in order to obtain alloys of desired structure and composition. These wires have the characteristics of high conductivity and low melting and vaporization in an alternating fashion [105–107]. Cladding surface passivation of the brittle gamma coating phase appears to reinforce resistance against corrosion [108].

It was disclosed that the coating in US Patent No. US5945010-97 is comprised of a copper-zinc gamma phase alloy or a nickel-zinc alloy. The core may contain copper, copper clad steel, brass, or other suitable materials. The second coating metal may consist of a metal selected from the group including Zn, Mg, and Al by employing low-temperature diffusion anneals. The resulting EDM wire achieves faster and better surface finish than conventional EDM wire electrodes. A further advantage of US Patent No. 945010-99 is that the higher zinc content in the coating compared to the earlier US Patent No. 5945010-97 will result in significantly lower volumetric heat of sublimation for the coating and therefore cause the wire to flush more efficiently while having enough tenacity to survive the EDM erosion process. The tensile strength rises very rapidly with the appearance of the beta phase. At 32 % zinc content, the tensile strength of brass reaches a maximum when alpha and beta phases are present in approximately equal proportion [106]. Keeping the above aspect in view, the present invention, Patent No. EP0799665A1 and Patent No. US5808262, is meant to produce a spark erosion electrode, the core of which is of comparatively low zinc alpha brass with a top layer of highly rich zinc beta and gamma brass to facilitate better flushability of the electro-erosion process and also to achieve comparatively higher tensile strength of the electrode core material [109].

Patent No. US2011/0290531A1 relates to a wire electrode (1,1’) for electric discharge cutting processes. The wire electrode (1,1’) has a core (2) containing a metal or metal alloy, and a coating (3, 4; 3, 4, 5), at least one (3) of which contains a phase mixture of beta brass or beta prime brass and gamma brass as shown in Fig. 22. The beta phase or beta prime phase and the gamma phase are arranged next to each other in a fine-grained structure in which the mean size of the beta brass or

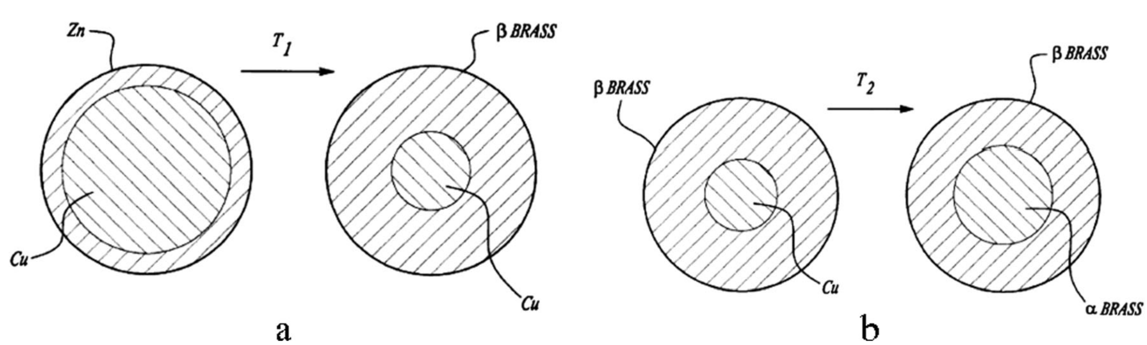

Fig. 20 Shows different wires with different coated thickness [100]

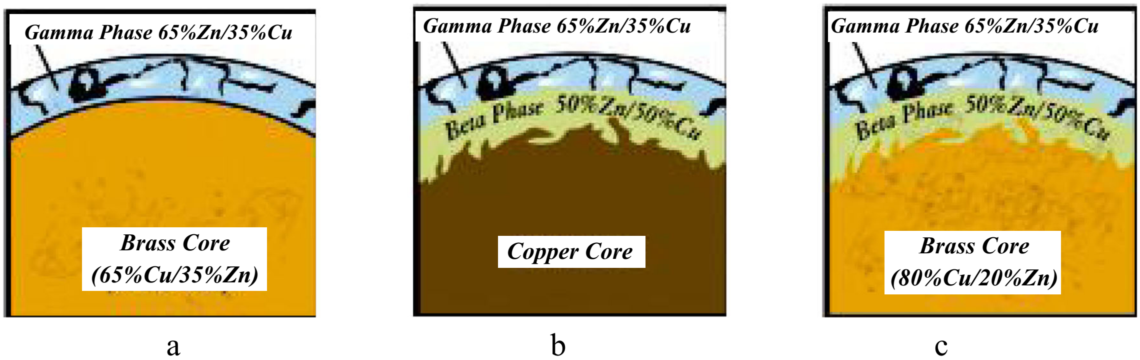

Fig. 21 Gamma phase wire electrodes [30]

beta prime brass grains and the gamma brass grains amounts to a maximum of 5 microns relative to the cross section of the wire electrode (1, 1'). In the preferred embodiment according to Fig. 22b, a core (2) is formed from Cu-Zn20%; the covering layer (4) which adjoins the core is formed predominantly from beta or beta prime brass having a zinc content of about 45 wt%; the covering layer (3) is formed principally from a phase mixture of beta or beta prime brass and gamma brass having a mean zinc content of about 53 wt%; the top layer (5) consists primarily of zinc oxide. The wire electrode (1') has a tensile strength of about 750 N/mm^2 and electrical conductivity of about 17 m/Ωmm^2 [110].

Patent No. US8338735 comprises a brass core (1) covered with a gamma phase brass coating (2) having a structure fragmented into blocks (2a) between which the core (1) is exposed. The blocks (2a) have a thickness E_2 with a narrow distribution and cover the core (1) according to a coverage rate greater than 50 % as shown in Fig. 23. This produces regular fragmentation of the coating, which improves the finish state of the machined parts [111].

US Patent No. 5762726-98 is recognized for higher zinc content phases in the copper-zinc system, specifically the gamma phase, which would be more desirable for EDM wire electrodes. It has even better cutting capacity than a wire electrode with a sheath layer consisting of a pure beta phase. The choice of a pure gamma phase, to which hard inert materials are added where appropriate, has proved even more advantageous than the beta phase in terms of cutting behavior. With conventional processes, that is to say longtime diffusion, it is scarcely possible to produce such a gamma phase in pure form. As a rule, a mixed structure with fractions of alpha, beta, and/or gamma phases is obtained. Figure 24a represents the starting material, which consists of a core of alpha brass and a sheath layer of zinc (eta zinc). After heating has taken place and following the shortest possible holding time, an epsilon zinc layer forms in the region between the core and sheath layer (Fig. 24b), the eta zinc layer transforms into an epsilon zinc layer during increasing annealing time and therefore diffusion increases (Fig. 24c). It is possible to see in Fig. 24c that a narrow layer, especially a gamma brass layer, forms in the transitional region between the core and epsilon zinc layer while annealing time continues. The gamma brass layer expands so that the epsilon zinc layer is transformed into a

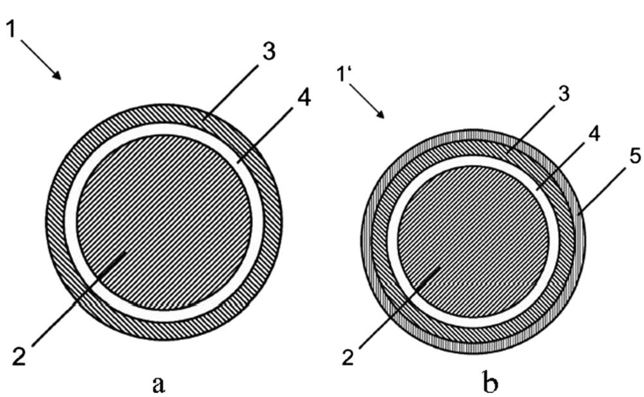

Fig. 22 Schematic cross section of wire [110]

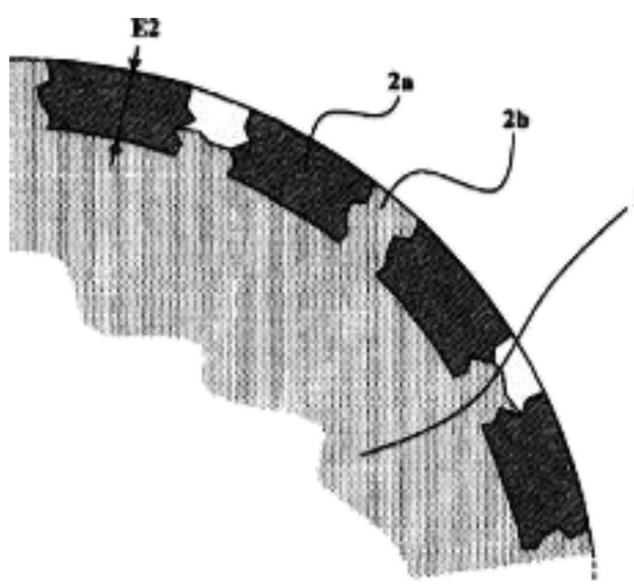

Fig. 23 Large-scale diagrammatic view in cross section wire [111]

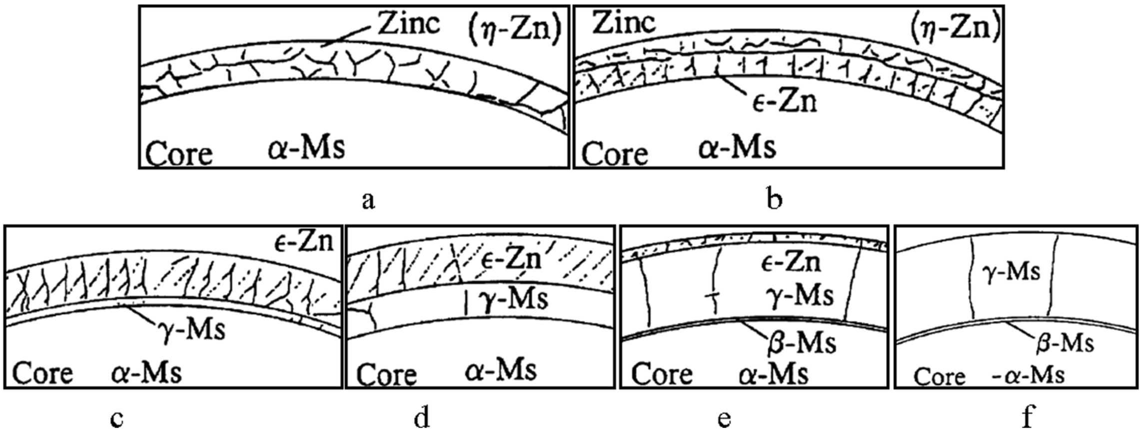

Fig. 24 Shows an enlarged representation of the detail of the sheath layer and of the core [112]

gamma brass layer as a result of the diffusion processes (Fig. 24d). A narrow beta brass layer forms at a substantially lower growth rate in the transitional region between the gamma brass layer and the alpha brass core (Fig. 24e). Figure 24f illustrates the moment at which the sheath layer transforms into a gamma brass layer with the beta brass sheath layer growing only slightly larger in the transitional region between the core and gamma brass sheath layer with respect to the stage represented in Fig. 24e. Finally, Fig. 24f illustrates the end of the time sequence in which the eta zinc layer is largely decomposed and beta crystals expand to form a thin layer around the core. But the inability to cope with the brittleness of these phases limits the commercial feasibility of manufacturing such wire [112].

There is still a need to machine as quickly as possible for a given machining current and also to be able to use the highest possible machining current for a given wire diameter. It is surprising that with respect to Patent No. US8378247, with an EDM wire having a metal core covered with a layer of alloy, appreciably enhanced EDM performance can still be obtained by providing a core (2) made of copper or brass with a coating layer that combines a fractured gamma brass surface layer (4) and a beta brass sub-layer (3) (Fig. 25). As an advantageous embodiment, beta brass at least partially fills the fractures in the gamma brass surface layer. The beta brass sub-layer may favorably be continuous, affording better results than a discontinuous sub-layer. Better results, combining both a higher EDM rate and good surface finish of the machined workpiece are obtained by giving the fractured gamma brass surface layer a thickness of less than 5 % of the wire diameter [113].

7.4 Epsilon phase wires

The lower melting point of the epsilon phase is considered a disadvantage of epsilon phase coatings compared to beta or gamma phase. However, the higher zinc content of the epsilon phase has been found to offset some disadvantages, such that epsilon phase coatings have been found to match the performance of beta phase coatings while being competitive with gamma phase coating performance. Therefore, epsilon phase coatings provide similar cutting performance but at a lower manufacturing cost than either beta or gamma phase [14].

An EDM wire with a copper bearing core and a substantially continuous coating of porous epsilon phase brass, wherein the said porous coating is infiltrated with graphite particles, was disclosed in US Patent No. 20070295695. Infiltrating the porous epsilon phase coating with graphite can further improve epsilon phase coating performance [114].

Patent No. US8067689 provided an EDM wire containing an outer coating of gamma phase brass with an overlayer of continuous unalloyed zinc or ductile epsilon phase brass

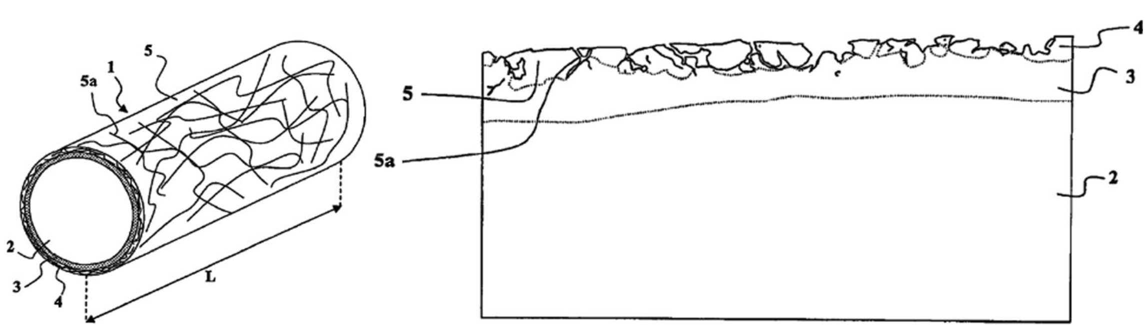

Fig. 25 Schematic perspective view and a longitudinal section through an EDM wire [113]

entrapping the gamma phase, thereby filling in any discontinuities and thus presenting a workpiece surface with homogeneous electrical properties (Fig. 26). For rough cuts where speed is of utmost interest and accuracy is of lesser importance, any zinc or epsilon phase brass covering the underlying gamma phase brass alloy particles will quickly be consumed because, it will be proportionately thinner than that filling the gaps between the gamma particles, thereby giving evidence of high-performance gamma coating. Referring to Fig. 26a, a high brass core (12) is covered with a zinc coating (15) with an initial thickness of 10 pm. After heat treatment at 1,700 °C for 6 h in a nitrogen atmosphere, the wire is depicted in Fig. 26b, with a gamma phase brass coating (18) on the high brass core (12). Since a non-oxidizing atmosphere of nitrogen gas was employed during the heat treatment, the wire can be electroplated again with a zinc coating (15) 10 pm thick as depicted in Fig. 26c. Cold drawing the composite wire to its final diameter of 0.25 mm causes the brittle gamma phase to fracture and form discrete particles (19) as portrayed in Fig. 26d. However, the zinc coating (16) is sufficiently ductile to flow around these particles and encapsulate them on the high brass core (12). According to the invention, the core substrate preferably includes copper at or near its outer surface. Thus, a variety of substrate materials are contemplated for the present invention, including, but not limited to, pure copper, brass, brass on copper, copper clad steel, brass on copper clad steel, brass clad steel, and brass on brass (e.g., high zinc content brass on lower zinc content brass) [115].

8 Steel wires

Evidently, due to electric discharge, a force opposite to the machining direction is created on the machined sections of the wire electrode. Electrostatic and electromagnetic forces are also created on the wire electrode. On account of all these forces as well as the wire vibrations, the actual wire position differs from the programmed position. This leads to accuracy and precision problems [116–119]. Deviation from the programmed outline at the corners leads to obtaining round corners instead of the desired sharp corners [120]. Consequently, plain molybdenum or tungsten wires form due to the high tensile strength (>1,900 MPa) [121, 33]. Owing to the drawback of being expensive and having poor flushability, a new type of wire was developed that comprises a high-strength pearlite steel wire with over 0.06 % carbon content and a coating of copper-free zinc or zinc alloy coating. As a result, improved precision and accuracy with increased mechanical load is achieved [91, 14].

8.1 Molybdenum wire

This type of wire is used in limited applications which require very high tensile strength to provide a reasonable load carrying capacity in small-diameter wires. Moly wire has both high melting point and high tensile strength. It is often used for small diameter EDM wires of 0.1 mm and under. Unfortunately, Moly wire has both low electrical conductivity and very low flushability. In addition, it is very abrasive to power feeds and wire guides and is often difficult to auto thread. Finally, Moly wire is very expensive [122, 30].

8.2 Tungsten wire

Tungsten wire has greater tensile strength and melting point than Moly wire. Tungsten wire is often an economical alternative to Moly wire in diameters of 0.05 mm and smaller. In high-precision work on wire EDM machines, tungsten wire is preferred, as it requires small inside radii in the range of 0.025–0.1 mm. Since brass and coated wires are not practical due to their low load-carrying capacity in these sizes, molybdenum and tungsten wires are used. However, because of the limited conductivity, high melting point, low vapor pressure rating, and slow cutting tendency, it is not suitable for very thick work [122, 123].

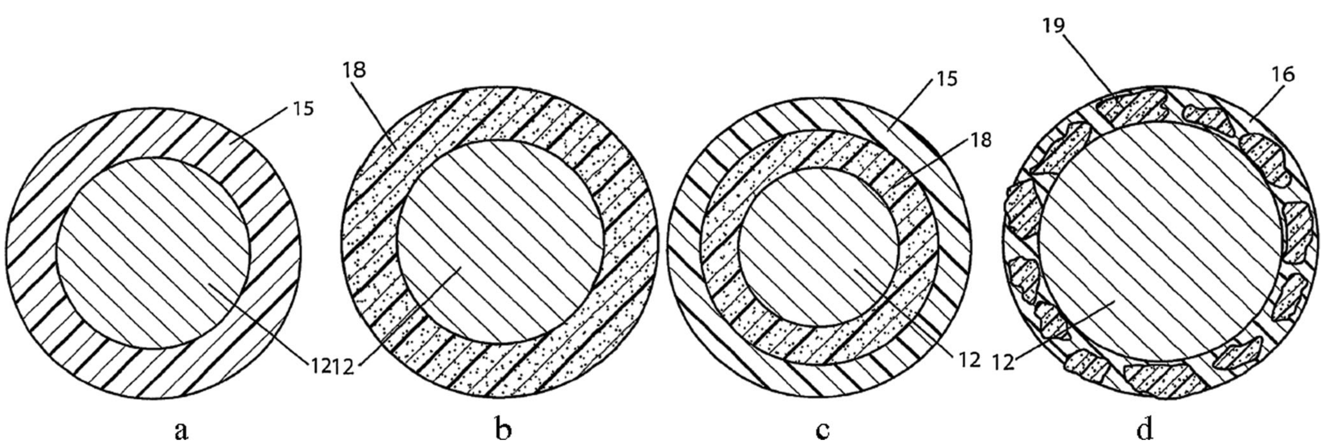

Fig. 26 Cross-sectional view of development wire [115]

8.3 MolyCarb wire

A composite wire called MolyCarb offers significant advantages for small-diameter work. Moly wire is coated with a mixture of graphite and Molybdenum oxide, thus improving its flushing characteristics [124, 30].

8.4 Steel core wires

For optimum machining performance, EDM wire electrodes must have good electrical conductance, which enables high machining current to flow through the electrode. They must also have high mechanical strength for increased traction force through the machining zone.

Steel core wire, containing a steel core, is commonly known as Compeed, MicroCut, MacroCut, or other trade names. The steel core in this wire type offers exceptional tensile strength and ductility, and there is a copper intermediate layer to provide conductivity besides a beta phase brass outer layer (Fig. 27). Steel core wire exhibits exceptional resistance to breakage for tall workpieces, interrupted cuts, or poor flushing conditions, all while providing excellent performance. Its primary limitations are high cost, straightness issues, autothreadability, and possible damage to scrap choppers due to the steel core [75, 30, 113].

In order to reap the benefits of the wire electrode with a first copper coating on steel wire and then plating with a coating of zinc, cadmium, tin, lead, antimony, bismuth, or alloys thereof, US Patent 4287404-1981 was developed [85]. The objective of this invention is to provide an electrode which greatly facilitates electrical discharge triggering and which decreases any tendency to cause short circuits. The result would be that the wire electrode of this invention enables machining at higher speeds than with conventional wire electrodes. Also, Korean Patent No. 10-1-0009194 and US Patent NO. US20080245773 represent a wire electrode for electrical discharge machining, which includes a steel core coated with copper or other components, and a copper-zinc alloy layer of CuZn10-CuZn50 coated onto the steel core [91]. US Patent No. US4686153-87 provides an electrode wire with a core including a steel wire coated with copper or another conductive material as well as a surface coating layer of zinc or the like. The average concentration of zinc in the copper-zinc alloy layer should preferably be less than 50 wt% but not less than 10 wt%.

Referring to Fig. 28, an electrode wire (10) comprises a copper clad steel wire (13) including a steel core wire (11) covered with a copper coating layer (12) of uniform thickness and a copper-zinc alloy layer (14) of generally uniform thickness ranging from 0.1 to 15 microns [95]. The wire electrode of US Patent No. 4998552-91 has a core made of steel, a lower layer made of homogeneous copper (Cu of 100 %) and an upper brass layer including 50 wt% zinc. The steel core is surrounded by copper or copper alloy to form a multi-layer structure, thereby having relatively great mechanical strength [14]. US patent No. 6875943-2005 represents a high-strength pearlitic steel wire having carbon content higher than 0.6 % and tensile strength higher than 3,000 MPa. The steel wire is coated with copper-free zinc or zinc alloy coating. The electrode is particularly suitable for high-precision performance applications.

Alternatively, a steel strip may be used as shown in Fig. 29b. If wires with a circular cross section are used as seen in Fig. 29a, the diameter is preferably lower than 0.35 mm and even more preferably lower than 0.25 mm, for example 0.1, 0.07, or 0.03 mm. Wires with thickness below 0.25 mm, for instance 0.1 mm, 0.05 mm, or 0.02 mm, can be considered flat wires. The high strength pearlitic steel core performs the strength function while the zinc or zinc alloy coating performs the heat dissipation and machining functions. In one embodiment, the zinc alloy is a zinc aluminum alloy. Such zinc aluminum alloy ideally comprises between 2 and 10 % Al. Between 0.1 and 0.4 % of a rare earth element such as La and/or Ce can be added. An intermediate layer is possibly applied between the steel and zinc or zinc alloy layer. Such intermediate layer can be aluminum or silver or it can

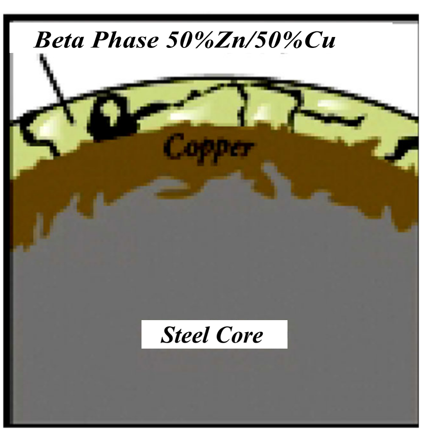

Fig. 27 Steel core wire [30]

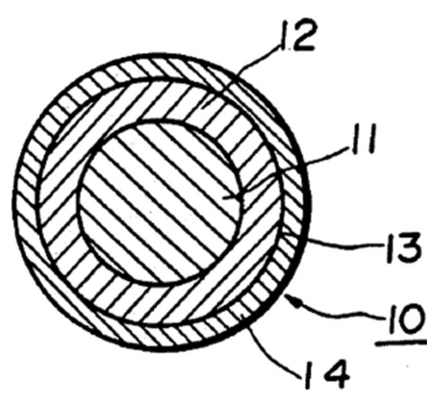

Fig. 28 Sectional view of the electrode wire [95]

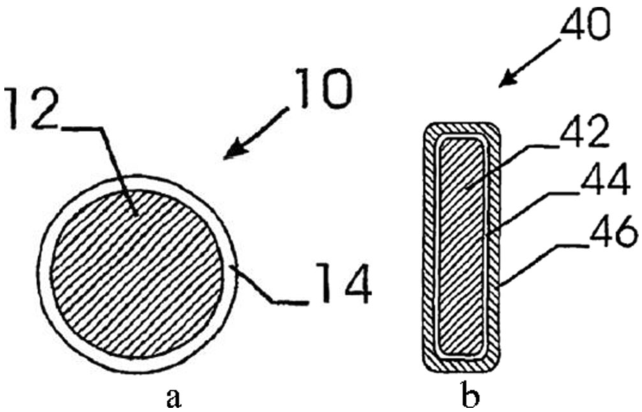

Fig. 29 Round and flat EDM wires [41]

comprise alloys thereof. By applying such intermediate layer, the electrical conductivity of the electrode can be improved. Also, a nickel or nickel alloy layer can be considered for the intermediate layer. In one embodiment of the present invention, the electrode comprises an additional layer on top of the zinc or zinc alloy coating. Examples of an additional coating layer are graphite, oxide, such as ZnO, Cr_2O_3, $A1_2O_3$, TiO_2, ZrO_2, or a conductive layer such as Ag [41].

9 Special wires

9.1 Abrasive-assisted wire

Machining speed and surface integrity continue to be central issues in current wire EDM research. Along this line, the proof-of-concept of a hybrid wire EDM process that utilizes a wire embedded with electrically non-conducting abrasives has been presented in US 20100012628 A1 as shown in Fig. 30. Material removal in this novel process is realized through electrical erosion that is augmented by two-body abrasion. This seems to bring about a significant improvement in removal rate and generate surfaces with minimal recast material compared to an equivalent wire EDM process.

Machined surfaces were further shown to entail negligible recast material. Although the bulk of this work pertained to machining steel, A WEDM could be advantageous in the processing of metal matrix composites such as polycrystalline diamond that are difficult to process by WEDM. The procedure seems better suited for roughing sequences considering that the force from abrasion would negatively influence machining accuracy and is hence ideally implemented in a twin-wire machine tool. Although it was expedient to use a diamond wire in this work, wire bonded with aluminum oxide abrasives would demonstrate better performance and pose lower cost [125, 126].

9.2 Hot dip galvanized wire

In certain cases, diffusion-annealed wires are not beneficial due to the non-uniform zinc and alloy composition [127]. This has led to the development of the hot dip galvanization method as US patent No. 20060138091. This method is useful in terms of uniformly coated zinc formation on the wires [128, 129]. Firstly, the wire is subjected to a surface-forming process followed by a pre-coating process. Then, the wire is subjected to a main-coating process, after which it is exposed to a second surface-forming process. Finally, the wire is subjected to a homogeneously heat-treating process. Environmental contamination problems by harmful gas and waste water generated from conventional methods can be prevented with this type of wire. Further, increasing the thickness and adhesion of a zinc-coated layer leads to diminished generation of waste powder, thus improving all functions of the electrode wire [129].

9.3 Porous electrode wire

It has been disclosed in prior work that diffusion-annealed wire electrodes may be porous and infiltrated with graphite to further enhance discharge properties [114]. Continuous coating is maintained during cold drawing of the heat-treated wire electrode. Also, the wire improves machining speed by at least 15 % compared with a conventional zinc-coated wire, thanks to an increased cooling ability of the wire with a cooling liquid. This is due to the enlarged surface area of the wire that has a porous surface morphology [106].

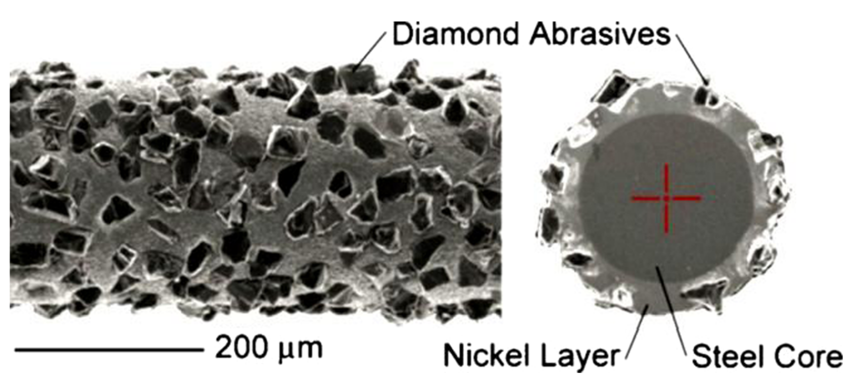

Fig. 30 Surface and section of abrasive-assisted wire [125, 126]

Patent No. US6482535 relates to a porous electrode wire for use in EDM, as shown in Fig. 31. The purpose of the invention is to provide a coated wire for EDM with improved machining speed by increasing the surface area and inner part of the wire. The inner part will be in contact with a cooling liquid so as to increase the wire's cooling ability. Therefore, the steps to achieve the above-mentioned purposes are as follows: provide a wire with an initial diameter made of a first metal; hot dip galvanize the wire by passing it for a desirable amount of time through a molten second metal with lower vaporization temperature than the first metal; form an alloy layer by the diffusion reaction between the first and second metals, the second metal has higher hardness and less elongation than the first metal and a coating layer made of the second metal; finally, draw the wire with the alloy and coating layers to form a second diameter, thereby forming cracks in the alloy and coating layers due to the high hardness and low elongation of the alloy layer. At this time, copper or brass having 63–67 wt% copper and 33–37 wt% zinc may be added to the first metal. Furthermore, zinc, aluminum, or tin may be used in the second metal. The porous nature of the wire arises from the cracks in the alloy and coating layers during the drawing step [130].

10 Discussion and future trends

After a thorough investigation of the published works in this field, the following conclusions can be drawn.

- The development of economical wire electrodes with high conductivity and elevated fracture toughness for high-speed cutting will remain a key research area.
- Few efforts have been made to identify electrode materials, keeping in view their thermal properties from the perspective of cutting speed [131, 132].
- Preventing wire from rupture has an edge over improving machining efficiency of the WEDM process. Wire breakage and wire flaking during machining have also restricted accuracy and efficiency, which subsequently affect the overall productivity of the WEDM process [133–136].
- Few studies have been conducted on measuring the temperature distribution of wire and the influence of non-uniform temperature fields on the vibration and stability characteristics of EDM wires [137–140].
- Very little work has been reported on finding changes in the mechanical properties and surface integrity of WEDM-worked material. Therefore, this area is still open for future research work [141–143].
- Not many studies have been conducted on the machining of ceramics like ZrO_2 and Al_2O_3 by using assisting electrodes to facilitate sparking of these highly electrically resistive materials [144–146].
- The advent of newer and more interesting materials that are productive in a wide variety of applications has challenged the feasibility of future manufacturing environments. Higher zinc content leads to faster cutting, but results are sometimes achieved only when machine settings are optimized. Optimized settings for WEDM are necessary to achieve the performance attainable with next-generation wires [147–152].
- Developing wires with smaller diameters and improved wire guides for fine wires to handle small workpieces is a challenge for future manufacturers.
- More research and experimentation is required to enhance cutting efficiency with new combinations of core and coating materials, since existing wires do not fulfill all requirements. High-performance wire electrodes with high conductivity alloy materials for high-speed cutting applications will be extensively used for automobile parts and die manufacturing in the future [11].
- The surface generated in dry WEDM with high-performance wire electrodes was studied [153–155].
- An attempt has been made in prior work to develop a new, high-performance wire with a core of pure aluminum and coating of alpha brass and gamma brass, but with the

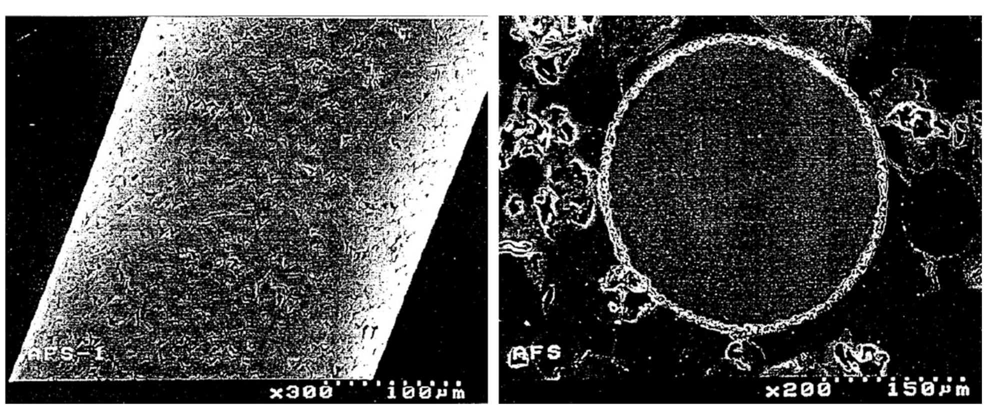

Fig. 31 Photograph of a porous coated wire showing the surface morphology and the cross section [130]

limitation that tensile strength is less than that of plain brass wire [156].
- Skin effect problems caused by steel-cored wire electrodes are resolved by coating brass/copper with a thick layer, which ends in performance similar to that of brass wire. Smaller-diameter wires that do not need thick coating result in good cutting efficiency.

11 Conclusions

The focus of this paper was on the evolving technologies of EDM wire electrodes from using copper to the widely utilized brass wire electrodes and from brass to the latest coated wire electrodes, which have been developed and assist user demand and needs in terms of maximum productivity and quantity. Special wire electrodes were introduced as abrasive, hot dip galvanizing, and porous wire electrodes. The copper wire electrode was replaced by brass owing to the low material removal rate and low wear or erosion resistance. The conductivity of brass wires was scarified for strength and better fusibility. Various metals or alloys with good electrical conductance and low vaporization temperature, such as zinc, tin, lead, etc., have been tried to coat wire electrodes against thermal shock resulting from electrical discharge without running the risk of rupturing the wire. The purpose of gradually changing the zinc content in coating alloys is to provide enhanced cooling ability and flushability compared to conventional brass wire electrodes. Alloy with higher zinc content leads to increased cutting speed. The layer of pure zinc on brass wire quickly becomes worn and does not protect the core of the wire when cutting tall pieces. Zinc has a low melting point, and it can only plate the wire core. As zinc tends to blast off during sparking, coating with higher zinc content causes good adhesion to the core wire. This can be achieved by diffusion annealing the zinc-coated wires. But owing to their inability to cope with the brittleness of the gamma phase besides the limited commercial feasibility of manufacturing, these wires have prompted the development of composite wire electrodes. Gamma phase coatings on a wire core are more brittle than beta phase coatings, but epsilon phase coatings are even more brittle than gamma phase. Owing to the limitation of instability of the epsilon phase, the process of converting zinc coating to epsilon phase is difficult. These high-performance wires significantly increase WEDM productivity over plain brass wires. The primary limitations of these wires are high cost, damage to the scrap chopper, straightness issues, and environmental hazards. The authors believe that the challenge faced by WEDM manufacturers is to continuously push the envelope in the area of developing EDM wire electrodes that have high conductivity, are environmental friendly, and can undergo unattended machining operations. Achieving high conductivity and strength without sacrificing fracture toughness are key research areas.

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