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Surface Modification of Die Steel Materials Machined by Powder Mixed Electrical Discharge Machining: A review

Nitin K. Khedkar
PhD Scholar,
Symbiosis International University,
Lavale, Pune, Maharashtra State,
India

T.P.Singh,
Director and Professor,
Symbiosis Institute of Technology,
Symbiosis International University,
Lavale, Pune, Maharashtra State,
India

VijayKumar S. Jatti
Assistant Professor,
Symbiosis Institute of Technology,
Symbiosis International University,
Lavale, Pune, Maharashtra State,
India

Abstract-Electrical discharge machining (EDM) is a non traditional machining process that has become a well recognized machining option in manufacturing industries throughout the world. EDM is capable of machining geometrically intricate or hard material components that are accurate and difficult to machine. With the continuous process enhancement in EDM, the demand for high precision machining with low surface roughness at comparatively high machining rates required in die, mould and tool manufacturing industries. To accomplish this requirement a comparatively new advancement in the direction of process capabilities is the addition of powder in the dielectric fluid of EDM. Powder mixed electrical discharge machining (PMEDM) can specifically improve the surface finish and surface quality. Analysis of various researches on the effects of powder mixed EDM had reveals that characteristics of powder material like particle size, particle concentration, thermal conductivity and electrical conductivity play major role in affecting machining performance in the EDM process. This paper presents a review on the work done related to powder mixed EDM process and influence of powder mixed EDM on surface characteristics. The papers highlight the direction and focus of ongoing research in PMEDM and bring out the potential areas of research.

Keywords: Powder mixed dielectric fluid, Electrical Discharge machining, Surface improvements, and Surface roughness.

Introduction

Electrical discharge machining (EDM) is a well-established method for manufacturing of geometrically complex and hard material parts that are extremely difficult-to-machine by the conventional machining processes. In 1770, English chemist Joseph Priestly came to discover that electrical discharge or sparks had erosive effects and it is believed to be the basis of EDM (Kalpajian and Schmid, 2003). In 1943, B.R. Lazarenko and N.I. Lazarenko at the Moscow University were able to use sparks and developed resistance-capacitance type power supply to use with Lazarenko EDM System which was able to machine difficult to machine materials in a controlled process by vaporizing material from workpiece surface (Webzell, 2001). This RC type power supply was extensively used in EDM machines in 1950s. At about the same time three American employees used electrical discharges to remove broken taps and drills from hydraulic valves. They were able to use electronic-circuit servo system which maintained space between electrode and workpiece automatically for sparks to occur (Jameson, 2001). In 1980, the introduction of CNC in EDM automated the EDM process. With this after inserting the electrodes in tool changer, there is no requirement to monitor the process till the final product is ready (Houman, 1983). Since then EDM has been used in manufacturing industry and has become an area of research. Through the years, the machines have improved drastically – progressing from RC (resistor capacitance or relaxation circuit) power supplies and vacuum tubes to solid-state transistors with nanosecond pulsing, from crude hand-fed electrodes to modern CNC-controlled simultaneous six-axis machining.

Principles of EDM Process

Electrical discharge machining is based on the material erosion of electrically conductive materials. It is set through the series of small discrete high-frequency electrical sparks between the tool and the workpiece (Llanes et al., 2001). When sparks are generated the electrode materials erodes and in this way material removal is realized. Every spark melts a small amount of material from both the tool and the workpiece. Part of this material is removed by the dielectric fluid and the remaining solidifies on the surface of the electrodes. The net result is that each discharge leaves a small crater on both workpiece and tool electrode (Allen et al., 1996). In the EDM process, as the electrode charged with a high-voltage potential, comes close to the workpiece, an intense electromagnetic flux or 'energy column' is formed and eventually breaks down the insulating properties of the dielectric fluid (Guitrau, 1997). The voltage then drops as current is produced, and the spark vaporizes anything in contact with it, including the dielectric fluid. The area struck by the spark will be vaporizes and melts, resulting in crater being formed. Thus metal is predominantly removed by the effect of intense heat locally generated and collapse of the vaporized dielectric. Melting and vaporization actions are the causes of removing material in the EDM process.

Figure 1(Konig and Klocke, 1997) presents the phases of a discharge in EDM process. The first one is the ignition phase which represents the time delay corresponding to the occurrence of the breakdown of the high open circuit voltage $\hat{u}_i$ applied across the working gap until the fairly low discharge voltage u_e, which normally ranges from 15 to 30 V. This phase is known as ignition delay time t_d (μs). The second phase is the formation of a plasma channel surrounded by a vapour bubble, which occurs after the first phase when the current rapidly increases to the operator specified peak current $\hat{\imath}_e$ (Amperes). The third phase is the discharge phase, when the high energy and pressure plasma channel is sustained for a period of time t_e (µs) causing melting and evaporation of a small amount of material in both electrodes. The fourth phase is the collapse of the plasma channel caused by turning off the electric energy, which causes the molten material to be violently ejected. This time is known as interval time t_o (µs), a part of the molten and vaporized material is flushed away by the flow of the dielectric fluid across the gap and the rest is solidified in the recently formed crater and surroundings. During the interval time t_o their also occurs cooling of the electrodes and the de-ionization of the working gap necessary to promote an adequate dispersion of the successive discharges along the surface of the electrodes.

EDM Process Parameters

Parameters in EDM can be classified into three categories: control parameters, process parameters, and sensing parameters. The complete set of parameters is machine dependent. Different EDM machines have different set of parameters due to the difference in their designs. Control parameters include those related to the work piece, tool electrode, generator, servo system, dielectric system, and the NC unit.

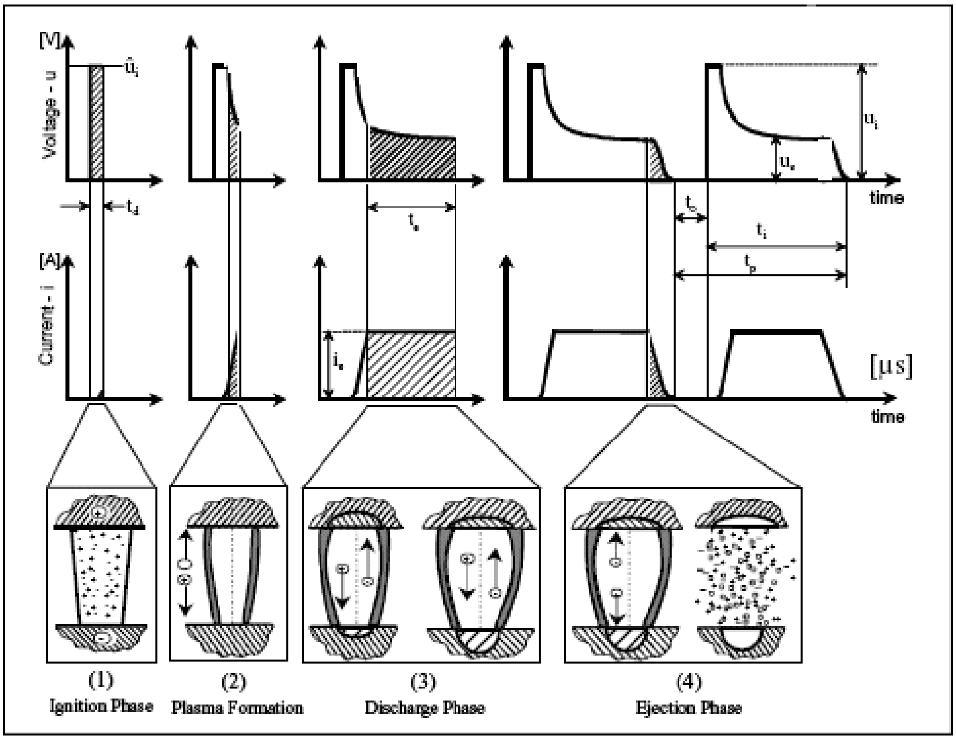

Fig.1 Phases of an electric discharge in EDM (Konig and Klocke, 1997)

Generator

Generator or power supply provides electrical energy in the form of pulses to the working gap. Generators can be roughly classified into two categories: RC-relaxation generators and static pulse generators. RC-relaxation generators use charging circuitry to charge parallel capacitors to the gap. Discharges occur when the voltage across the gap reaches a certain level. The control parameters on generator are most important because they directly determine the power applied to the working gap. Open-circuit voltage specifies the voltage of applied pulses. It is not the voltage across the gap during electrical discharges. Pulse duration determine the length of the applied voltage pulses. During pulse duration, the lengths of ignition delay and discharge duration depend on the gap state. The actual discharge duration is not controllable. Together with peak discharge current, pulse duration sets the amount of energy generated during a single electrical discharge. The setting of peak discharge current on static pulse generators generally determines the number of power units connected parallel to the gap rather than the exact current level. The larger peak discharge current means the higher power intensity during electrical discharge. Pulse interval determines the separation of pulses. Duty factor is defined as the ratio of pulse duration over pulse period. In machines with duty factor setting, pulse interval is set indirectly by setting pulse duration and duty factor. Pulse frequency is also used to set the pulse interval on some machines.Polarity specifies the polarity of work piece and tool electrode. Depending on the application, the polarity can be either way.

Servo System

The servo system controls the tool motion relative to the work piece to follow the desired path. It also controls the gap width within such a range that the discharge process can continue. If tool electrode moves too fast and touches the work piece, short circuit occurs. Short circuit contributes little to material removal because the voltage drop between electrodes is small and the current is limited by the generator. If tool electrode moves too slowly, the gap becomes too wide and electrical discharge never occurs. Another function of servo system is to retract the tool electrode when deterioration of gap condition is detected. The width cannot be measured during machining; other measurable variables are required for servo control. The ignition delay affects the average gap voltage; both average ignition delay and average gap voltage are usually used as the indirect measurement of gap width. The servo reference voltage and reference average ignition delay set the reference values for servo control.

Dielectric System

The liquid dielectric plays a crucial role during the whole process. It cools down the electrodes. It guarantees a high plasma pressure and therefore a high removing force on the molten metal when the plasma collapses. It solidifies the molten metal into small spherical particles.It also flushes away these particles. The most widely used types of dielectric liquid are mineral hydro-carbon oil for die-sinking EDM and deionized water for wire-cut EDM. The post-discharge is in fact a crucial stage, during which the electrode gap is cleaned of the removed particles for the next discharge. A bad control of the process and poor machining quality occurs if particles stay in the gap. To enhance the flushing of particles, the dielectric generally flows through the gap. In addition, the electrode movement can be pulsed, typically every second, performing a large retracts movement. This pulsing movement also enhances the cleaning, on a larger scale, by bringing “fresh” dielectric into the gap.

Mechanism of Powder Mixed EDM Process

In powder mixed EDM process the suspended powder assist in the ignition process by creating a higher discharge possibility and lowering the breakdown strength of the insulating dielectric fluid. As a result, material removal rate is improved, tool wear rate is reduced and sparking efficiency is improved. Suspended powders increase the spark gap distance due to their presence between tool and workpiece. It has two outcomes: firstly, increased spark gap is useful in effective removal of debris from the gap; secondly, it makes the PMEDM process highly stable with effective discharge dispersion throughout the gap (fig. 2).

An increase in the distance decreases the electrostatic capacitance of the gap. Due to the discharge of the capacitor in the circuit, a spark is initiated. This creates a plasma channel in between workpiece and electrode gap resulting in breakdown of dielectric. Each spark generates a very high temperature resulting in melting and vaporization of the workpiece at the point of discharge. Under appropriate process conditions some constituents of the electrode and the dielectric are deposited on the machined surface. In addition to this, there is an improvement in the surface finish due to reduction in the spark energy (fig.3).

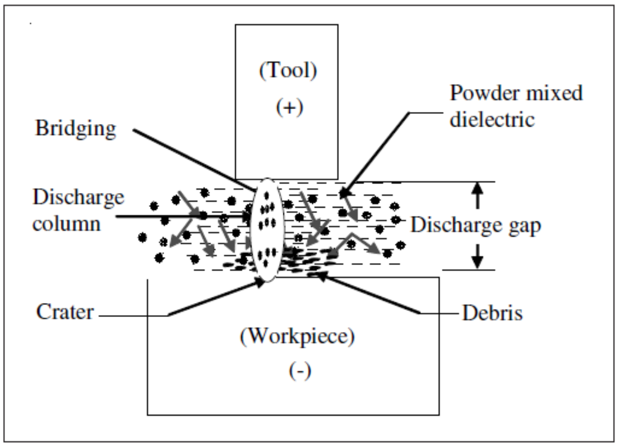

Fig. 2 Mechanism of PMEDM process (Kansal, 2007)

And more random discharges throughout the surface result into migration of some of the alloying elements on the machined surface. The material transfer may be either in free form or as carbides produced due to breakdown of the hydrocarbons present in dielectric.

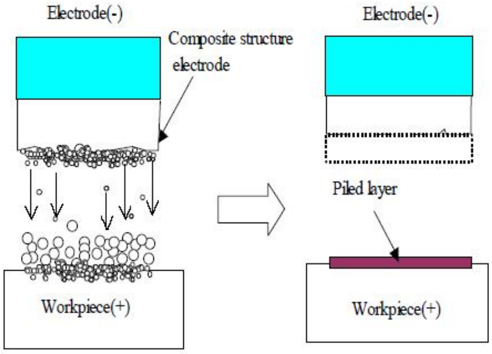

Fig. 3 Principle of PMEDM

This deposition results in change in chemical composition of the machined surface. Subsequent cooling by the flowing dielectric may result in desirable improvements in material properties.

Literature Review on PMEDM Process

There have been various attempts made to improve the surface finish after EDM by polishing and other means. But if surface finish gets improved during machining using EDM it will shorten the machining time and save cost. From this viewpoint powder EDM is a process which has shown potential for improvement in surface finish. Suspended powder in EDM not only imparts fine surface finish but also modifies the surface. The study of surface characterization of die steels reveals that the composition of die steel materials plays a significant role. The alloying elements of die steel material includes silicon, zinc, magnesium, chromium, nickel, cobalt, copper, and tungsten.Out of these alloying elements tungsten, copper, and nickel have significant effect on surface characterization of die steel material. Surface modification is a novel application of EDM that has added a new dimension to this technology. This section presents review on available literature on the aspects of surface modification and material accretion. The phenomenon of surface modification has been observed in the EDM process for over five decades now. In this section past research work has been classified into two categories namely, surface modification of top layer in terms of hardness and composition, hardness and surface roughness.

Surface Modification in Terms of Hardness and Composition

Koshy et. al. (1983) has used the, Cr, Cu, Ti, Ni, Co, Fe, Al C (graphite), Mo and Si metal powders. The grain size was between 1 and 100µm in dielectric medium. during experimentation work of hardening of surface layers using EDM techniques and conclude that the addition of doping elements to the dielectric medium could be used to impart desired properties to the surface layer of the work-piece. He established that the addition of doping elements to the dielectric medium could be used to impart desired properties to the top layer of the workpiece. Carbon in the hydrocarbon dissociated and combined with the doping elements to form their respective carbides. The workpiece was positive and the tool electrode was negative for such applications. For the same powder concentration, the two main parameters that influenced the doping characteristics were pulse current and pulse duration.

Okada et al. (2000) EDMed surface with metal powder mixed fluid has smaller surface roughness and higher resistance to corrosion because of the diffusion of electrode and/or powder materials into the machined surface. In this study, a new surface modification technique is proposed to obtain high surface wear resistance using EDM with powder mixed fluid. reported that at high temperatures of the plasma and powders combine with carbon (from the breakdown of the hydrocarbon dielectric) to form hard carbides on the machined surface. The hardness of the modified surface became higher with increase in pulse duration and powder concentration.

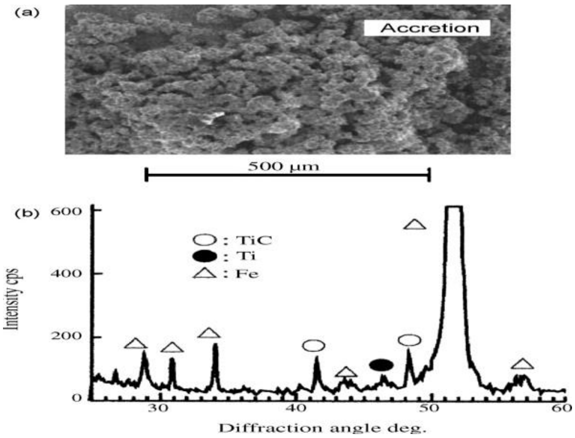

Fig. 4 (a) SEM micrograph and (b) XRD pattern of AISI-1049 carbon steel after machining with Titanium powder-mixed dielectric (at I_p= 3 A, P_{on} = 2 µs and P_{off} = 1024 µs), electrode-copper, polarity-negative

Furutani et al. (2001) used titanium powder in kerosene dielectric and obtained titanium carbide layer of hardness 1600HV on carbon steel with a negatively polarized copper electrode, 3A peak current and 2µs pulse duration. Rotating disk electrode kept the powder concentration high in the machining area. Both titanium and titanium carbide were found in the X-ray diffraction analysis of the machined surface and it was concluded that carbon came from the breakdown of the dielectric (fig. 4).

Moro et al (2001) Used EDM with semi-sintered product made of TiC powder as an electrode for surface modification. He found that the growth of the TiC layer on the work piece tends to stop at a certain thickness according to pulse duration but it does not depend on the electrode area. From the hardness distribution of the machined surface, hardened region expands into the inside of original work piece. In this case the carbon in TiC accumulated on the work surface (fig.5).

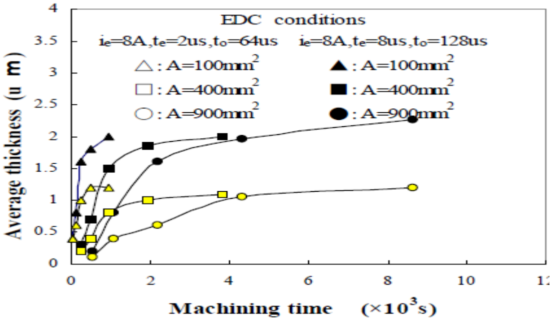

Fig. 5 Relation between average thickness and machining time

Uno et al (2001) experimented using the NC electrical discharge machine with transistor switching circuit and single pulse discharge device. The tool electrode was a copper cylinder of 15 mm in diameter. Kerosene and nickel powder mixed fluid (NPMF) were used as machining fluids. During experiment it was found that in case of kerosene type fluid, the thickness of the re-solidified layer is very thin, and the thermal affected layer is about 10µm in thickness below it. However, it was observed that as the nickel powder concentration increases, the re-solidified layer becomes thicker and more uniform. The hardness of the re-solidified layer for Cn=40 g/l is larger compared to that of the thermal affected layer for Cn=0g/l which is also harder than the base material. From this result, it was clear that the re-solidified layer containing nickel could be generated on EDMed surfaces by using NPMF. The composition of the layer was analyzed using XRD (X-Ray Diffraction) as shown in fig. 3. According to this figure, besides the components of the base material suchas Fe, Fe_3C (cementite) and Fe, C (network cementite), the component TiC also exists on the EDMed surface.

Furutani and Shimizu (2003) proposed a deposition method for solid lubricant layer of molybdenum disulphide by suspending its powder in the dielectric to produce parts for ultra-high vacuum applications (such as space environment). High open circuit voltage, low discharge current, short pulse duration and medium pulse interval were used to deposit the lubricant layer on carbon steel and stainless steel. The process has some drawbacks, which include the difficulty in ensuring that the powder is held in suspension.

Simao et al. (2003) An L_8 fractional factorial Taguchi experiment was used to identify the effect of key operating factors on output measures (electrode wear, workpiece surface hardness, etc.). With respect to micro-hardness, the percentage contribution ratios (PCR) for peak current, electrode polarity and pulse on time were ~24, 20 and 19%, respectively. Typically, changes in surface metallurgy were measured up to a depth of ~30 µm (with a higher than normal voltage of ~270 V) and an increase in the surface hardness of the recast layer from ~620 $HK_{0.025}$ up to ~1350 $HK_{0.020}$. Experiment found that use of partially sintered electrodes made from WC/Co resulted in the formation of a uniform alloyed / modified surface layer with relatively few micro-cracks and an average thickness of up to 30 µm (fig.6).

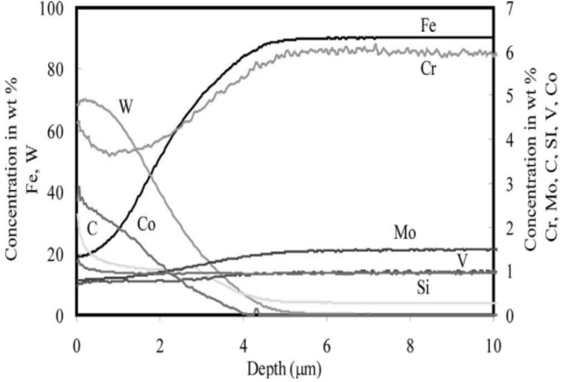

Fig. 6 Presence of elements in the electrical discharge machined workpiece

Klocke et al. (2004) found a larger plasma channel with aluminium powder-mixed dielectric in contrast to the standard dielectric. With a pulse on-time of 100 µs, photos were taken after a delay of 60 µs, in order to snap shot a fully developed plasma channel. It was concluded that in such cases, the discharge energy got distributed on a bigger workpiece surface.

Yan et al. (2005) added urea to distilled water as the dielectric medium for machining titanium and obtained TiN on the work surface which exhibited improved friction and wear characteristics. Micro-hardness values of the order of 250 Hk were achieved.

Bai and Koo (2006) compared the effect of different dielectric media on surface modification, using distilled water and kerosene to carry out surface modification of super-alloy Haynes 230 with Al–Mo composite electrode. Distilled water gave higher hardness whereas kerosene gave better surface finish, finer surface morphology, thicker alloyed layer and slower oxidation rate. They concluded that surface alloying effect was better in kerosene as compared to distilled water.

Cogun et al. (2006) conducted experiments on prismatic steel workpiece using copper electrodes with graphite and boric acid powders mixed kerosene dielectric at different powder concentrations and pulse time settings. They found that for both powders, increasing powder concentration and pulse time increased hardness of the machined workpiece surface with respect to the base metal. The hardness values for both powders were higher than for the pure kerosene case. Graphite powder mixing gave higher hardness values than H_3BO_3 powder mixing. This is attributed to the formation of a hard martensite layer on the work surface when using graphite mixed kerosene.

Kumar and Batra (2012) have investigated the response of three die steel materials to surface modification by EDM method with tungsten powder mixed in the dielectric medium. They concluded that under appropriate machining conditions, significant amount of material transfer takes place from the powder suspended in the dielectric medium to the work material. All the three work materials reported more than 100% increase in micro-hardness. Fig. 7 shows the SEM structure on the surface of OHNS die steel machined by EDM using tungsten powder suspended in kerosene dielectric.

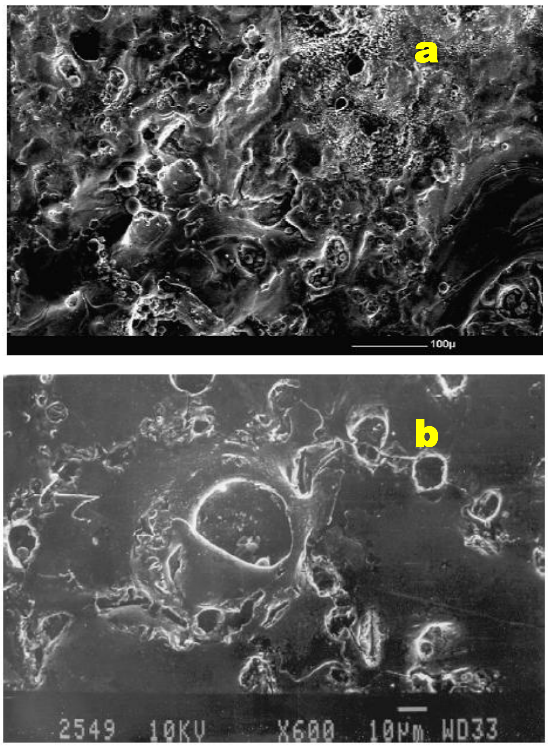

Fig. 7 a) SEM of OHNS die steel after machining with tungsten powder-mixed dielectric

b) SEM of D2 die steel after machining with tungsten powder-mixed dielectric

Syed and Kuppan (2013) studied the effect of aluminium powder when mixed in the distilled water dielectric fluid with work and tool electrode materials as W300 die steel and electrolytic copper respectively. They found that low peak current of 6 A, and high concentration of Al powder of 4 g/l suspended in the distilled water produce minimum thickness of white-layer of 17.14 µm on the machined surface with positive polarity.

Surface Modification in Terms of Hardness and Surface Roughness

Narumiya et al. (1989) reported that the workpiece machined using the powder (Si, SiC or Al) suspended oil had better surface finish and increased corrosion resistance compared to the surface machined without powder.

Miyazaki (1995) applied a plasma arc produced through a small diameter nozzle on steel. Ceramic powder of silicon carbide was supplied to the processing region with theshielding gas of argon. The initial and running cost of plasma arc is much cheaper than laser beam and it is generally used in industries for cutting and welding applications. It was possible to obtain a hardness of 1000 VHN on AISI 1010 steel by self-quenching without any powder and 1200 HV with silicon carbide particles. Fig. 8 (a),(b) and (c) shows the SEM micrographs of OHNS die steel after machining with tungsten powder, graphite powder, and silicon powder mixed in the dielectric. Remarkable surface modifications can be observed in these figures. After this, in order to address the problem of powder settling, when a surfactant along with aluminium powder were added in the dielectric and a more apparent discharge distribution affect was observed which resulted in a surface roughness Ra value of less than 0.2µm. It was possible to achieve near mirror-finish using conductive powders (such as graphite and aluminium) and semi conductive silicon powders.

Wong et al. (1998) concluded that graphite and silicon powders gave mirror-finish on SKH-54 work material, Aluminium powder failed to give the same (fig.9).The use of negative electrode polarity was found to be essential for achieving mirror-finish condition.

Rozenek and Kozak (2001) EDM performance characteristics experimentally studied using powder suspended working fluid instead of pure dielectric such as kerosene and deionized water. It was found that application of powder in the dielectric lead to reduce surface roughness. The investigation results show that there are chances for replacing the conventional dielectric with powder suspended deionized water and that would imply considerable economic and ecology advantages (fig 10.)

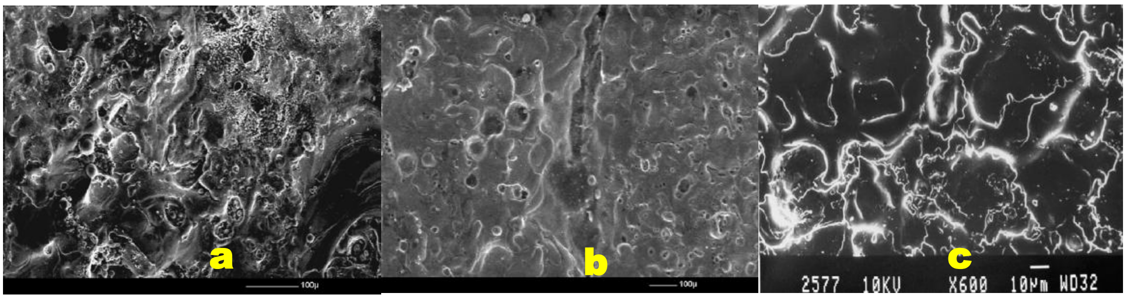

Fig. 8 SEM micrographs of OHNS die steel after machining

a) with tungsten powder(at I_p =6A, P_{on}=5µs and P_{off} =85µs, electrode—copper)
b) with graphite powder (at I_p =2 A, P_{on} =5 µs and P_{off} =57 µs, electrode—copper)
c) with silicon powder (at I_p =2 A, P_{on} =5 µs and P_{off} =57 µs, electrode—copper)

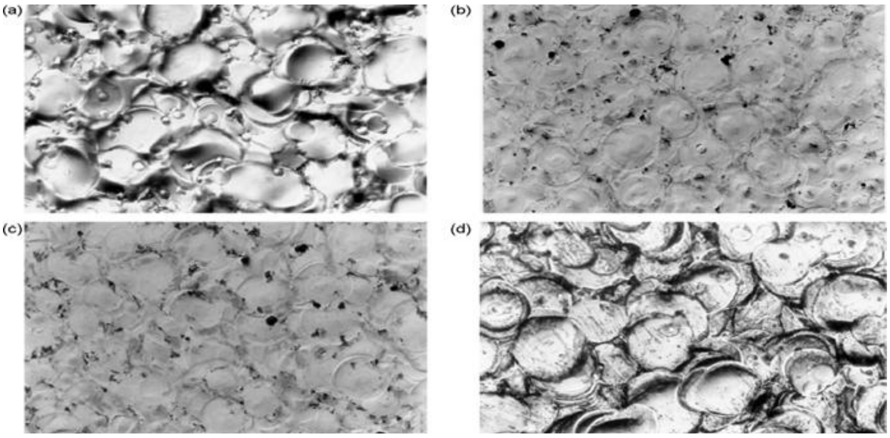

Fig. 9 SEM micrographs of SKH-54 tool steel after machining with copper electrode
(a) Without any powder, (b) with graphite powder, (c) with silicon powder and (d) with aluminium powder (at I_p =1 A, P_{on} =7.5 µs and P_{off}=11 µs, magnification = 50X, polarity negative

Pecas and Henriques (2003) found that presence of silicon powder in the dielectric almost eliminated undesirable machining conditions. Smooth and highly reflective craters were formed and improvement in surface roughness depended on the electrode surface area.This increased value compares extremely favorably with hard chromium surfaces, typically applied by electroplating, which are extensively used for cold mill work rolls producing steel and aluminum alloy strip / sheet.

Wu et al. (2005) addressed the problem of powder settling by adding a surfactant along with aluminium powder in the dielectric and observed a more apparent discharge distribution effect which resulted in a surface roughness value of less than 0.2µm. The dominant EDM parameters for optimized surface roughness in this work are (1) Al powder concentration 0.1 g/L; (2) positive polarity; (3) peak current 0.3 A; (4) peak duration 1.5 ms and (5) surfactant concentration 0.25 g/L. Dielectric mixed with both aluminum powder and surfactant can reach an optimized thin re-casted layer due to well dispersed aluminum powder and uniform distribution discharge energy during EDM process. Furthermore, the value of surface roughness is also improved up to 60% than machined under pure dielectric.

Tzeng and Chen (2005) reported that the use of negative electrode polarity was found to be essential for achieving mirror-finish condition. On the other hand, when experiments were conducted on SKD-11 steel with significantly different thermo physical properties, including aluminium (Al), chromium (Cr), copper (Cu), and silicon carbide (SiC) powders are studied. Experimental results show that the particle size of additives in the dielectric oil affects the surface quality of EDMed work. While the smallest particles (70–80 nm) generates the best surface finish of the machined work, the greater the particle size the less the improvement in the surface roughness. However, particle size has opposite effect on the recast layer, as the smallest particles generated the thickest recast layer of the EDMed surface, and the greater the particle size the thinner the recast layer. Among the additives, Al powder produces the best surface finish and the thinnest recast layer in the machined work, whereas the process without foreign particles and with copper powder, generates the worst surface characteristics.

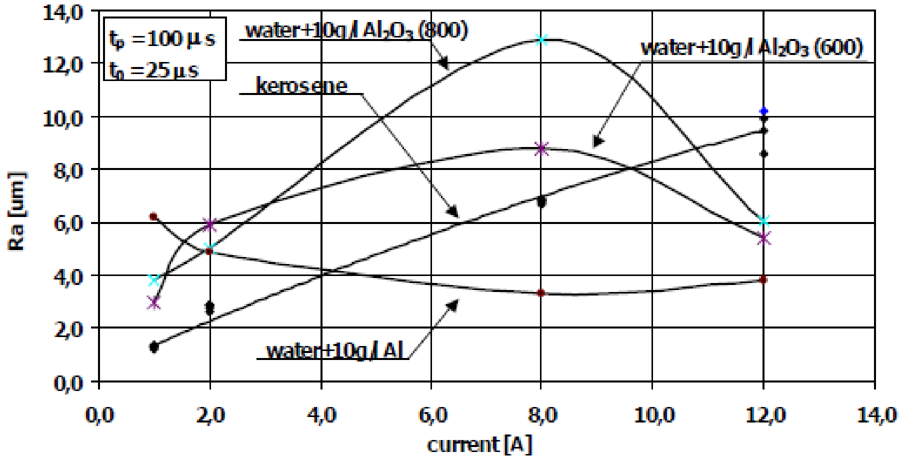

Fig. 10 Effect of grain concentration in kerosene on Ra

Kansal et al. (2006) Taguchi method with multiple performance characteristics has been adopted to obtain an overall utility value that represent the overall performance of powder mixed PMEDM. The four input process parameters ,with silicon powder and optimized electrical parameter supported by powder mixed dielectric circulation system. The obtained experimental results indicate that the peak current and concentration of the silicon powder suspended are most significant parameter.

Celik (2007) investigated surface roughness values during EDM of powder metal material having same chemical qualities of cold work tool steel with different electrode materials. He reported lower surface roughness value on powder metal workpiece in comparison with the literature. However, it’s observed that the surface roughness on powder metal material in EDM processes experimented by different electrode materials does not indicate a distinctive feature.

Prihandana et al. (2009) presents a new method that consists of suspending micro-MoS_2 powder in dielectric fluid and using ultrasonic vibration during µ-EDM processes. The results show that the introduction of MoS_2 micro-powder in dielectric fluid and using ultrasonic vibration significantly improves surface quality by providing a flat surface free of black carbon spots (fig.11).

Kumar et. al. (2009) presented material transfer through powder metallurgy electrodes and through powders suspended in the dielectric medium; both these methods offer a viable alternative to the other currently used expensive methods of surface modification such as ion implantation and laser surface processing. But the use of conventional electrodes for this application has not met with much success. There is a need to independently study the effect of this important input process parameter on the phenomenon of surface modification. Some of the important die steel materials such as OHNS die steel, molybdenum high-speed tool steels and water-hardening die steels have not been explored on EDM.

Chatha et al. (2010) found that addition of TiO_2 powder into dielectric fluid reduces the surface roughness in comparison to conventional EDM process. The micro hardness increases with the increase in powder concentration and still higher value of hardness can be achieved at higher concentration levels. A certain amount of powder (TiO_2) migrated from the dielectric to the work piece, which results in surface modification fig 12. Cross-section of SEM surface is also done to analyze the surface texture and recast layer. The results showed that small amount of powder was migrated to machined surface, which resulted in surface improvement. The dielectric with added powder also shows significant improvement in material removal rate.

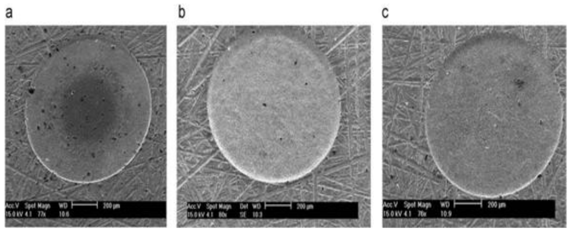

Fig. 11 Microstructures of Cu–W surfaces with brass as the tool electrode, obtained by µ-EDM process using (a) pure dielectric (b) MoS_2 concentration of 2g/l (c) MoS_2