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A Review of Research on Improvement of Surface Quality and Material Removal Rate in EDM Process

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***Abstract*— Electrical discharge machining (EDM) is one of the earliest non-traditional machining processes. EDM process is based on thermoelectric energy between an electrode and the work piece. The non-conventional energy sources like sound, light, mechanical, chemical, electrical, electrons and ions uses for manufacturing. The difficult part is to machine materials, with the industrial and technological growth which find wide application in aerospace, nuclear engineering and other industries outstanding to their heat resistance qualities, hardness and high strength to weight ratio has been witnessed. This paper reviews the research work carried out by researchers for the advancement of Electrical Discharge Machining processes. This study is focused on facet related to surface quality and metal removal rate which are the most important parameters for the optimum condition of processes. Since long, EDM researchers have optimized the MRR and explored a number of ways to improve the traditional EDM sparking phenomenon.**

***Keywords* — Electrical discharge machining, EDM parameters, Machining characteristic, Surface Quality, Material Removal Rate.**

I. INTRODUCTION

Advanced researches introduced many new engineering materials, composite materials and high quality ceramics having good mechanical, chemical, thermal and electrical properties. There is a lot of improvement in the conductivity of materials so that they can easily be machined by spark erosion. The problems of high complexity in shape, size and higher demand for product accuracy and surface finish can be solved through non-traditional methods. Currently, non-traditional processes possess unlimited capabilities to increase the material removal rates. As removal rate increases, the cost effectiveness of operations also increases.

Electrical discharge machining (EDM), one of the earliest non-traditional machining processes is based on thermoelectric energy transfer between the work piece and an electrode. This process is used to produce dies, punches and moulds, finishing parts for aerospace and automotive industry, and surgical components [2]. By improving Material removal rate (MRR), we can readily improve performance of the system in EDM process. Researchers found several ways to improve and optimize MRR using different experimental concepts in EDM sparking phenomenon [1]. Electrically conductive parts irrespective of their hardness, shape and toughness can be easily and effectively machined using this process [3-5]. It is a process consisting of erosion of material from the work piece due to series of discrete sparks between work piece and electrode separated by a thin film of dielectric fluid medium.

A. COMPONENTS OF EDM

1. ***Work-piece-*** all conductive materials can be machined.
2. ***Tool Electrode-***The EDM tool electrode determines the shape of the cavity to be produced.
3. ***Dielectric fluid-*** It is used to work as a medium between electrode and workpiece. In EDM tank, Electrode & workpiece is submerged into the dielectric fluid for the purpose.
4. ***Servo system-*** It is used to control the feed of electrode & work piece to precisely match MRR.
5. ***Power supply-***The power supply is required in the form of direct current (DC) to produce the spark discharge at the machining gap. So a transformer is used to convert alternating current from the main utility supply into pulse direct current (DC).
6. ***The DC pulse generator*** is responsible for supplying pulses at a certain voltage and current for specific amount of time.

B. WORKING PRINCIPLE OF EDM PROCESS

EDM is a thermo-electric process in which a series of discrete sparks is generated between tool and work electrodes immersed in a dielectric fluid for removing the material. A small gap, also called as spark gap, is maintained between workpiece and electrode to ionize the dielectric. Pulsed arc discharges occur in this gap filled with an insulating medium such as hydrocarbon oil or de-ionized (de-mineralized) water [6-9]. Schumacher [10] described the technique of material erosion employed in EDM. The working principle of EDM is shown in Fig. 1.1.

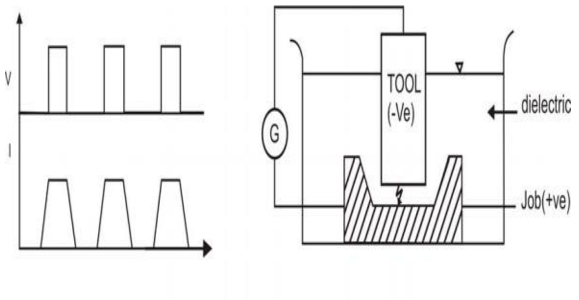


Fig.1.1 Schematic representation of the basic working principle of EDM process

The material is removed from tool and work-piece with the erosive effect of electrical discharges [13]. The electrical resistance of dielectric influences the discharge energy and the time of spark initiation [14]. Low resistance results in early discharge. If resistance is large, the capacitor will attain a higher charge value before initiation of discharge. When the measured average gap voltage is higher than that of the servo reference voltage, preset by the operator, the feed speed increases.

In some cases, the average ignition delay time is used in place of the average gap voltage to monitor the gap width [15] The RC circuit employed in EDM did not give high material removal rate and to improve removal rate, surface finish is being compromised. A major portion of the time of machining was spent on charging the capacitors as shown in Fig. 1.2. [16]. The arc column diameter increases with the passage of time [17-19] and equal to the diameter of the generated discharge crater [17].

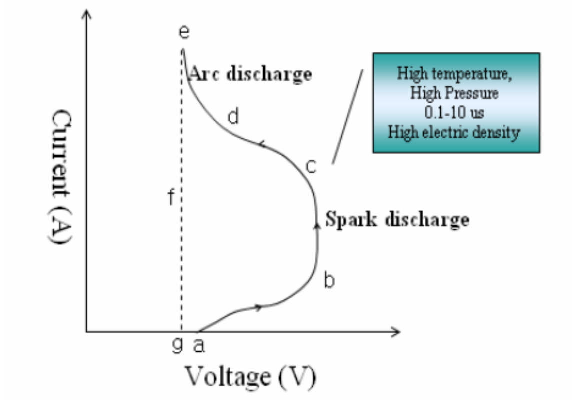
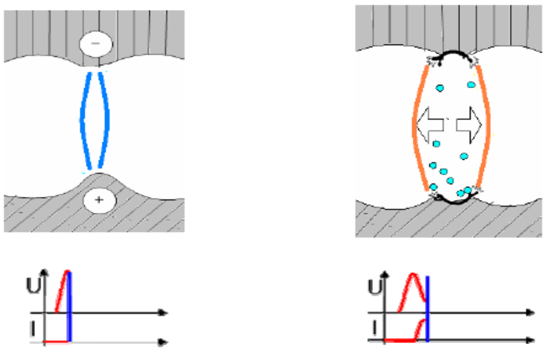
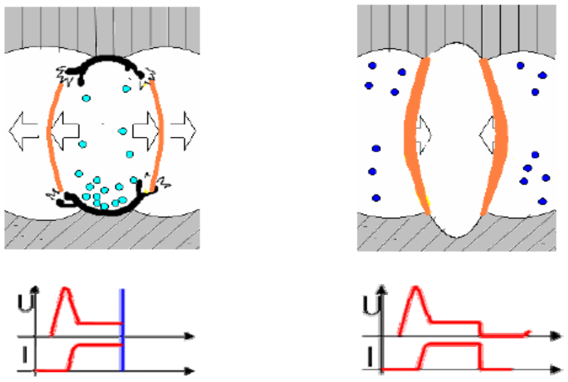


Fig.1.2 Graph for current variation with voltage

In the spark gap electrode materials and dielectric liquid are evaporated, molecules are dissociated, and atoms are ionized, resulting in a rapid expansion of the bubble from dielectric fluid. Since the expansion is restricted by the inertia and viscosity of the dielectric, the pressure inside the bubble becomes extremely high and the boundary between the bubble and liquid expands [20, 21].



(a) Ignition phase (b) Formation of Plasma channel



(c) Melting and evaporation (d) Ejection of liquid molten material

Fig.1.3 (a-d) Successive Stages of EDM Process

It is still believed that the dielectric liquid plays a significant role in material removal because the high pressure and velocity field in the bubble may serve as the dynamics of the material removal in EDM [22, 23]. Rajurkar [24] has indicated some future trends activities in EDM: machining advanced materials, mirror surface finish using powder additives, ultrasonic-assisted EDM and control and automation.

C. *PROCESS PARAMETERS*

The process parameters can be divided into two categories i.e. electrical and non-electrical. Major electrical parameters are discharge voltage, peak current, pulse duration and pulse interval, electrode gap, polarity and pulse wave form. The EDM process is of stochastic thermal nature having complicated discharge mechanism [25]. Therefore, performance measures which are affected by these parameters cannot be easily defined. However, process analysis is a good option for optimizing parameters to identify the effect of operating variables on achieving the desired machining characteristics.

Lin et al. [26] applied grey relational analysis for solving the complicated interrelationships between process parameters and the multiple performance measures. Many other researchers also used Taguchi method to analyze and design the ideal EDM process [27-29]. Main non-electrical parameters are flushing of dielectric, work piece rotation and electrode rotation. Many researchers performed experiments to measure the effect of flushing pressure on surface roughness and tool wear rate. They also identified that it is helpful in flushing away the debris from machining gap [30-32].

Because of the rotary motion of the work piece, the circulation of the dielectric fluid in the spark gap improves and the temperature distribution of the work-piece yield better MRR and SR [33].

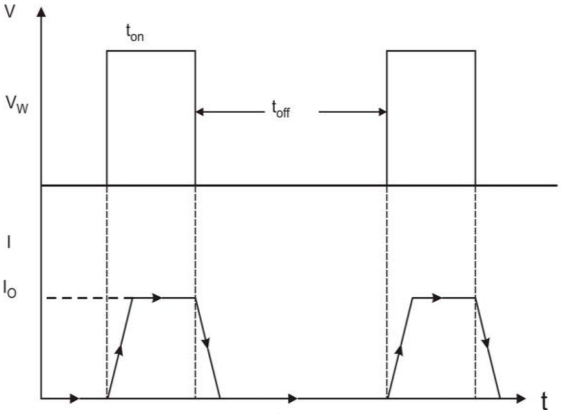


Fig. 1.4 Waveform used in EDM

Similarly, due to electrode rotation, there is a good flushing action and sparking efficiency [34]. Therefore, improvement in MRR and surface roughness has been reported due to effective gap flushing by electrode rotation [35-37].

Major performance measures in EDM are MRR, TWR and SR. For MRR improvement, Erden A. developed a mechanism for material removal [38-40] and methods of improving MRR [41-44].

Similarly for TWR, some researchers developed a process to work on tool wear process and some reported methods of improvement in TWR [45-47]. Though EDM is essentially a material removal process, efforts have been made to use it as a surface treatment method and/or an additive process also. Many surface changes have been reported ever since the process established itself in the tool rooms of manufacturing industry [48].

II. MECHANISM OF MATERIAL REMOVAL

Dijck[49] attempted to provide a physical explanation of the material removal during electric discharge machining for the first time. In his research, firstly he developed a simple cathode erosion model for the process [50]. This point heat-source model was different as it accepts power rather than temperature as a boundary condition at plasma/cathode interface.

Optimum pulse times were predicted to within an average of 16% over a two-decade range after the model is tuned to a single experimental point. In this model, a constant fraction of the total power supplied to the gap was transferred to the cathode over a wide range of currents. A universal, dimensionless model was then presented which identified the key parameters of optimum pulse time factor (g) and erodibility (j) in terms of the thermo physical properties of a cathode material.

After this, he published his second paper introducing an erosion model for the anode material [51]. Even in this model, the power is accepted as a boundary condition at the plasma/anode interface rather than temperature. A constant fraction of the total power supplied to the gap is transferred to the anode. The power supplied was assumed to produce a Gaussian-distributed heat flux on the surface of the anode material. Furthermore, the area upon which the flux is incident was assumed to grow with time.

In his third paper, he developed a variable mass cylindrical plasma model (VMCPM) for the sparks created by electrical discharge in a liquid media [52]. Numerical solution of the model provides plasma radius, temperature, pressure, and mass as a function of pulse time for fixed current, electrode gap, and power fraction remaining in the plasma.

Singh and Ghosh [53] proposed the material removal process that would be able to mechanically remove material and create the craters in the presence of the electrical force. They proposed thermo-electric model as a general method of calculating electrostatic force on the surface of the cathode and the stress distribution inside metal during discharge. They finally got some results such that the stress distribution deep inside the metal, where the surface stress acts as a point force, can be extended for any kind of discharge, the electrostatic forces are the major cause of metal removal for short pulses and melting becomes the dominant phenomenon for long pulses. They also found out that the reason for short pulses obtained when there is constant crater depth with varying discharge duration.

Gangadhar observed that reversing the polarity of sparking alters the material removal phenomenon with an appreciable amount of electrode material depositing on the work piece surface [54].

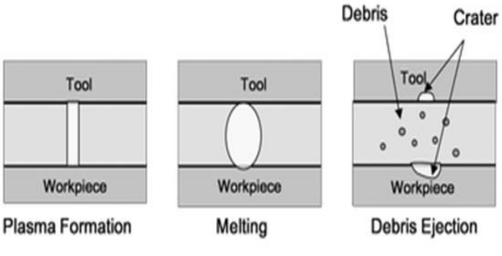


Fig 2.1 Material removal Mechanism in EDM process

Gadalla and Tsai [55] investigated the material removal of WC–Co composite. However, Lee and Lau [56] explained that using thermal spalling contribute to the material removal mechanism can be used during the sparking of composite ceramics.

The work-piece material may diffuse into electrode surface and influence its wear resistance [36, 57-60]. Several other researchers have also reported presence of considerable quantity of opposite electrode material in the surface treated and debris produced [39, 61, 62].

Roethel [39] proposed a mechanism of mass transfer of electrode material and determined the change in thermally influenced zone.

Pandey and Jilani [63] proposed a thermal model on plasma channel growth and thermally damaged surface layer. The change in chemical composition of material was found to be confined within re-solidified layer [39, 40, 51, 64-66].

III. METHODS OF IMPROVING MATERIAL REMOVAL RATE

The review presented in this paper is on different techniques proposed and investigated by researchers resulting in improvement in material removal rate in EDM. This paper summarizes review of all the results and conclusions made by different researchers of such work in following six sub-sections.

A. By Electrode Design Modification

Several researchers have tried to improve surface quality and material removal rate using alternate types of tooling design. The research work in this area can be classified into following categories.

- Investigating suitable electrode material for a particular work piece material to improve and optimize the surface quality and material removal rate.
- Kaneko, T. explained various processes related to electrode geometries and designs. These machines works to create complex shapes without using complicated shaped electrodes [44].
- Bayramoglu and Duffill [41, 42] investigated to machining mild steel work pieces with a frame type copper cutting tool.
- Saito et al. [43] conducted a comparative investigation between soli electrode and wire frame electrode for producing cubic cavities.
- Some researchers have been mentioned that the plate type form tool gives better surface quality and material removal rate in comparison with 3-D form tool [67]. It has been observed that electrodes and hollow tube electrodes with eccentric drilling results in better material removal rate [34, 68-70].
- Research on 3D form tool with different geometries revealed that best tool shape for higher surface quality and material removal rate and lower TWR is circular in shape, followed by triangular, rectangular, and square cross sections [71].
- The plate type and frame type tools are suitable for basic like conics, spheres, 2D sweeps, Ruled surfaces and fillets shapes [67].
- Bayramoglu, mentioned in his survey that various CNC capabilities are not being utilized by ‘toolmakers’ [67].

B. By Controlling Process Parameters

The surface quality and material removal rate can be improved by controlling various process parameters. The main parameter affecting surface quality and material removal rate are discharge voltage. Discharge voltage is basically related to dielectric strength and spark gap [72].

The energy can be controlled by pulse duration and peak current applied during machining [73]. Longer pulse duration results in higher material removal resulting in broader and deeper crater formation.

In theory, the shorter interval results in faster machining operation. But if the interval is too short, the ejected work piece material will not be swept away by the flow and the fluid will not be deionized resulting in unstable next spark. Material removal rate is highly affected by types of dielectric and method of flushing [31].

Flushing is a useful procedure to remove debris from discharge zone even if it is difficult to avoid concentration gradient and inaccuracy [74, 75]. The influence of flushing on MRR and electrode wear has been studied by mathematical models and experimentally and many flushing methods have been proposed [76].

C. By variations in EDM

Performance measures can be improved different EDM variations. An important variation is the development of hybrid machining processes in which we involve combined operation of other machining processes with EDM. Many researchers investigated the effects of ultrasonic vibrations on electrode.

Efficiency can be improved by employing ultrasonic vibration involving improved dielectric circulation in the electrode. Better dielectric circulation facilitates the debris removal and the creation of a large pressure change between the electrode and the work piece, as an enhancement of molten metal ejection from the surface of the work piece [77].

Ghoreishi and Atkinson [78] compared the effects of high and low frequency forced axial vibration of the electrode, rotation of the electrode and combinations of the methods (vibro-rotary) in respect of MRR, tool wear ratio and surface quality in die sinking EDM with flat electrode. The vibro-rotary increases MRR by up to 35% compared with vibration EDM and by up to 100% compared with rotary EDM in semi finishing.

Zhang et al. [79] investigated to incorporate ultrasonic EDM method in gas also. The gas was applied through the internal hole of a thin-walled pipe electrode. The result showed an increase in MRR with respect to the increase of open voltage, pulse duration, amplitude of ultrasonic actuation, discharge current and the decrease of the wall thickness of electrode pipe.

Gunawan et al. [80] studied the effect of vibrated work piece on the process. They observed that flushing effect gets increased if we vibrate the work piece while processing.

Han et al. [81] proposed a novel high speed EDM milling method using moving arc. They connected a copper electrode rotating rapidly around its axis and a work piece to a DC power supply to generate a moving electric arc. Researchers introduced a hybrid machining process (HMP) involving high-speed machining (HSM) [82-84].

If single cutting / dielectric fluid is easily available and has a good performance characteristic, an increase in material removal rate can be achieved. Xu et al. [85] introduced a new kind of electrical discharge machining technology named tool electrode ultrasonic vibration assisted electrical discharge machining in gas medium.

Inducing ultrasonic vibration in electrode results in a better MRR as per the experimental results. After comparing traditional EDM in gas and ultrasonic vibration assisted gas medium EDM in cemented carbide work piece, it was found that MRR is higher for a particular discharge pulse-on time for ultrasonic vibration assisted machining.

D. By Powder Mixed Dielectric in EDM

Powder mixed electric discharge machining (PMEDM) is a very innovative and different approach towards improving the performance of EDM process. In this process, the dielectric fluid is made by adding some material in a fine powdered form, which actually helps to improve the breakdown characteristics of the dielectric fluid. The insulating strength of the dielectric fluid decreases and as a result, the spark gap distance between the electrode and work piece increases [86-88]. A voltage of 80–320V is applied between the spark gap of 25–50 μm and an electric field in the range of 105–107 V/m is created [89]. The powder particles become energized and behave in a zigzag fashion. These charged particles are accelerated due to the electric field and act as conductors promoting breakdown in the gap. A number of research works have been reported for different combinations of materials, powders and operating conditions.

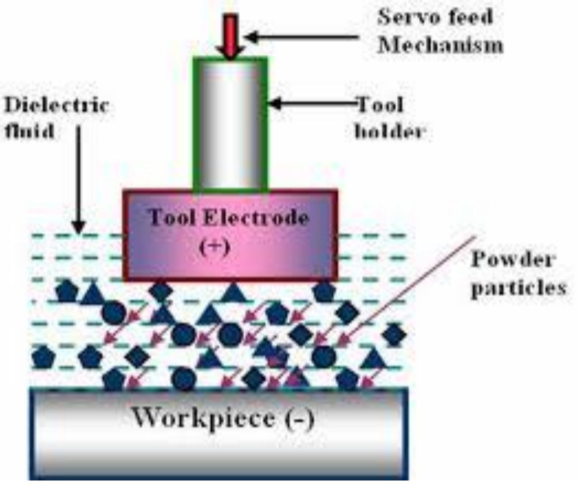


Figure 3.1: Principle of powder mixed EDM [2]

Erden and Bilgin [90] investigated mixing of copper, aluminum, iron and carbon powders in kerosene oil as dielectric for machining of brass–steel and copper–steel pairs. The machining rate was found to increase with powder particle concentration obtained due to the decrease in time lags at high impurity concentrations.

Jeswani [91] investigated the effect of the addition of fine graphite powder into kerosene oil as dielectric. The experimentation resulted in 60% increase in MRR and 28% reduction in wear ratio.

Yan and Chen [92-94] investigated the effect of suspended aluminum and silicon carbide powders on EDM of SKD11 and Ti–6Al–4V. The result showed that MRR improves considerably whereas the SR increases.

Ming and He [95] observed 0some of the conductive and inorganic particles to be used as powder so as to increase MRR, decrease in the TWR and improvement in the surface quality of the work piece.

Yu et al. [96] investigated the effects of aluminum powder on EDM of tungsten carbide. The aluminum powder allowed both higher discharge gap and MRR.

Wang et al. [97] investigated the effect of mixing Al and Cr powder mixture in kerosene. It was observed that machining parameters have remarkable influence on the machining characteristics such as it reduces the isolation and increases the spark gap.

Tzeng and Lee [87] investigated the effect of various powder characteristics on machining of SKD-11 material. The various additives mixed in the working fluid were Al, Cr, Cu and SiC. It was found that the concentration, size, density, electrical resistivity and thermal conductivity of powders significantly affect the machining performance.

Kansal et al. [72] established optimum process conditions for rough machining phase using the Taguchi method with graphite powder.

Tani et al. [98] experimented of insulating Si_3N_4 ceramics by mixing the various powders into the dielectric fluid and reported some results such that MRR increased considerably while the surface finish was not improved so much.

Rozenek et al. [99] compared machining characteristics by using kerosene dielectric and mixture of deionized water with different abrasive powders at different concentrations on hard material. He observed that the addition of powder in the dielectric enhances both MRR and TWR. The thermo physical properties of the suspended particles require a thorough investigation through experiments and research work.

Pecas & Henriques[100] performed a survey and found out that because of difficulty in operation of dielectric interchange, the higher amounts of powder consumption, the environmental requirements of fluid disposal and its higher initial cost (two to three times higher than the one required for a conventional EDM system) this process is not used frequently.

E. EDM with Water and Dry EDM

Kunieda and Yoshida [101] have discussed the principle of dry EDM and compared its performance with EDM in oil as dielectric. Dry electrical discharge machining is a process that uses gas as dielectric medium. The principle of dry EDM is shown in Fig. 8 [105].

This dry technique has been firstly presented by Kunieda et al. [102] for environmental preservation, human health and prevention of fire hazards. The authors found that the material removal rate is increased due to the enlarged volume of discharged crater and more frequent occurrence of discharge.

Kunieda et al. [103] have made improvement in dry EDM technique by introducing high speed 3D milling. The MRR increased when the discharge power density on the working surface exceeded a certain threshold limit due to thermally activated chemical reaction between the gas and work piece material. The maximum removal rate obtained was almost equal to that of high speed milling of quenched steel work piece on a milling machine.

Yu et al. [104] reported a comparison in machining characteristics of oil EDM milling and dry EDM milling. According to the results, the material removal rate of dry EDM milling is about 6 times larger than that of oil EDM milling.

Other improvement in dry EDM technique is ultrasonic vibration assisted dry EDM. Water as an alternative to hydrocarbon oil has been taken to promote green EDM process because hydrocarbon oil as dielectric decomposes and releases harmful vapors.

Jeswani [106] compared the performances of kerosene and distilled water over the pulse energy range of 72–288 mj.

IV. REMARKS AND FUTURE TRENDS

The objective of the review has explored a different ways to improve and optimize the surface quality as well as material removal rate including some experimental concepts. After reviewing the published work, the following remarks are being concluded

- A lot of researchers have used 3D form tools in Electrical Discharge Machine for their work. Along with this, at some places frame type and plate type tools are also used for more work tool interface.
- The models on material removal rate mechanism proposed by various researchers are not suitable in all the conditions because these models are based on several assumptions.
- The design of electrodes lays an important role to evaluate case to case effects with different work materials. Due to flushing conditions, material removal rate has positive impact by using eccentric drilled holes and hollow tube type electrodes.
- It is found that the rotational motion of electrode and work piece improves the flushing condition and material removal rate at the time of machining.
- Due to wide applications of hybrid technique of ultrasonic vibrations, most of the researchers have used this technique on steel based materials with copper electrode for their work.
- In future, some materials like chromium and vanadium in powder form may be used as work materials which were not being used in the previous researches.
- In future, some techniques in combination like sinking EDM, wire EDM, ultrasonic assisted EDM and EDM milling may be used to optimization of material removal rate and surface roughness etc.

V. SUMMARY

Recent advancements in several facets of electrical discharge machining that shows the art in above discussed processes are presented. Researcher works on improvement of surface quality, reduction of tool wear rate, material removal rate by experimental investigations. These investigations approaches like vibro-rotary mechanism based EDM, vibration, water based EDM has been employed to increase the electrical discharge machining efficiency, Dry EDM use of gas instead of oil electrolyte, PM-dielectric Electric Discharge Machining. It also plays an important role in automotive, optical, Jewellery, medical, aeronautic industry and making different types mechanical components.

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