ADVANCED MANUFACTURING SYSTEMS

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Preface

To start with I, on behalf of the organizes of the India-Japan Science Cooperation Programme on Manufacturing Science, extend a very hearty welcome to the participants from Japan and India to one of the most beautiful academic campuses in India. The 10th Joint Seminar on Manufacturing Science of Advanced Composites and the 8th Joint Seminar on Advanced Manufacturing Systems are being held at Indian Institute of Technology, Kanpur from 21st to 25th February 2005. In view of the great importance of the emerging area of 'Microfabrication, it has been proposed to create a new subsection to promote this field with effect from this seminar. There 18 joint activities is going to result in a deep mutual understanding and a close professional relationship among the researches from India and Japan. It is expected that this will lead to more collaborative technological and scientific joint activities in the future and bring both the countries much closer in the professional and social worlds.

These seminars have been sponsored by the Department of Science and Technology (DST), New Delhi and The Japan Society for Promotion of Science (JSPS), Tokyo. Theirkind help is Thankful acknowledged.

I expect everyone to participate and enjoy the discussions. On this occasion, I would like to express my deep sense of appreciation to Prof. M. Kiuchi, Prof. T. Machida and Prof. N.K. Naik for their kind help and guidance, I am also very thankful to the Director, Dy Director, Dean R&D, Head Mechanical Engineering Department and my colleagues and the members of the staff from Manufacturing Science Laboratory.

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ON THE DEVELOPMENT OF A MICRO ELECTRO DISCHARGE MACHINE

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Abstract:

An attempt has been made to design and fabricate a micro spindle turning (micro lathe) attachment with a micro EDG. The main hollow spindle of the former is positioned horizontally (can also be vertically, if required), located over two tungsten carbide V-bearings and steel ball as end-thrust bearing on a carbide support. This can be rotated about the horizontal axis by a balanced miniature DC motor via a belt-pulley system, reducing the spindle speed to about 3000 rpm (can also be either decreased or increased continuously). This spindle system may also be used as an attachment to any NC table of any type of EDM through its motor housing structure, to receive transverse motions in the horizontal plane. The spindle accommodates micro collets on the free end for holding jobs from 0.5 to 2mm diameter. To ensure a compact mono-block design with minimal components and low stray capacitance in the system, the entire housing and support structure is of single-piece made of ABS plastic.

The design and fabrication of a compact wire feeding mechanism for micro EDG ensures in situ processing of the micro tool on the spindle. Traveling wire is used as the tool electrode and moves around a carbide wire guide. The wire tension and speed are controlled using a spring loaded friction pad and directly driven wind-up system. The supply and wind-up spools, both are of insulating material sandwiching the friction pad and mounted on a shaft. A precision miniature geared (balanced epicyclical) DC servomotor drives the shaft. An insulating bracket developed in an FDM (RPT) system is used to hold the motor and the shaft in place. A metallic tailstock centre supports the shaft at the other end. Horizontal and vertical pulleys are used to guide the wire perpendicularly and move it around the wire guide. The entire setup is mounted on a precisely ground metallic base plate. This setup ensures accurate positioning of the wire edge as opposed to problems of wire lag and vibration experienced in wire EDM.
The concept of the development is to incorporating both the systems to any configuration for micro EDMing.

Keywords: Electro discharge machine (EDM), micro EDM, micro lathe, rapid prototyping (RPT), fused deposition modeling (FDM), Micro EDG, Wire feeding mechanism, Discharge gap, and Discharge energy.

1. INTRODUCTION

Micromachining is the most basic technology for production of miniaturized metallic parts (electrically conductive) and components having dimensions between 1μm and 999μm technically cannot be achieved directly by any conventional manufacturing technology [1].

Although focus has been on the production of micro-electronic components using etching and other photo fabrication techniques, with the growing need for development of micro machines, micromachining of metallic as well as non-metallic parts using modified forms of existing conventional machine tool technology is also becoming very popular. "Micro-machine" is a generic term for very small machines ranging from millimeter to sub millimeter/micron size like micro-robots, capsules inserted into human body for medical treatment, micro sensors, micro actuators etc.

However, micromachining using machine tools possesses the distinct advantage of creating three-dimensional shapes with ease because these methods basically copy the tool shape and its path onto the work piece through high precision CNC operation. Out of all available methods (Table 1), techniques like micro-EDM, laser beam machining (LBM), electron beam machining (EBM), electro chemical machining (ECM), ultrasonic machining (USM) etc. play the most significant role.

Table 1 Different category of micromachining methods [2]

MICROMACHINING METHODS			
With Tools		With Mask	
Solid Tool	Image Tool	Anisotropic process	Isotropic process
Cutting Grinding Milling EDMing ECMing Punching Embossing Injection etc.	LBM EBM IBM etc.	Wet etching IBM LIGA LBM etc.	Wet etching Plasma Etching Electroforming etc.

All these non-traditional micro-manufacturing techniques have the advantage of machining hard, high strength and temperature resistant materials, which are very difficult to machine using conventional techniques like milling, grinding etc. Moreover, mechanical deformation is a common problem in conventional machining owing to the presence of high cutting forces. This problem is even more prominent at the micron level. Since there is no mechanical tool-work piece contact in most of these non-traditional machining processes, they have a distinct advantage over conventional manufacturing processes. Also the serious problem of manufacture of cutting tools like milling cutter is avoided here.

In micromachining, the following two guidelines have to be adhered to at all costs:

a. Reduction of unit removal (UR) [3] and
b. Improvement in equipment precision

The concept of unit removal is the 'processing unit' to explain the difference in removal phenomena between micromachining and conventional machining. UR is defined as the part of a work piece removed during one cycle of removal action. For example, the volume of material removed from the work piece by one pulse of electrical discharge is UR in EDM. Depending on interest, UR can be expressed in terms of one, two or three-dimensional values, i.e., length, area, cross-sectional area or volume. Since UR gives the limit of the smallest adjustable dimensions of the product, it should be much smaller than the size of the product.

When a miniaturized product is required, for example, a product whose size is $1/10^{th}$ of the original one, it is desirable that the dimensional error of the product be likewise reduced to $1/10^{th}$ of the original value. Therefore, higher precision of the micromachining equipment is desired although it is often impossible to reduce the dimensional error in exact proportion to the reduction in the size of product.

In order to maintain the precision of manufacturing, it is important to know the error generation factors, or EGFs. Refining the process should minimize the influence of the EGF. In micromachining with tools, the main causes are mechanical deformation, thermal deformation, and surface-integrity, the gap change between the tool and the work piece and the coordinate shift during machining and in handling. It is difficult to hold the tool and/or the products in good alignment because there is not enough area on their surfaces to put reference planes. This problem leads to the necessity of using common coordinates for as many stages of production as possible, starting right from tool making up to final assembly.

EDM has become an indispensable process in modern manufacturing industry because of its ability to produce complex shapes with a high degree of accuracy. With the developments in Computer Numerical Control (CNC), the versatility of EDM has reached tremendous heights. Techniques like orbital EDM and EDM milling nowadays play a very crucial role in the application of EDM, particularly in die and mold making industry. Some of the more widely used and some not-so-well-known EDM systems are: Electrical discharge machining (EDM), Wire electrical discharge machining (WEDM), Electrical discharge milling, Rotary EDM, Electrical discharge dressing (EDD), Ultrasonic aided EDM (UEDM), Abrasive electrical discharge grinding (AEDG), Micro electrical discharge machining (MEDM), Micro wire EDM (MWEDM), Mole EDM and Double rotating electrodes EDM

The phenomena associated with micro-EDM are the same as conventional EDM but in micron level (UR) and the relevant micro energy for machining. Since small energy is the key to make micro products with high accuracy and good surface finish, the energy per single discharge should be minimized and discharge frequency should be increased. Therefore, the energy of a single pulse discharge is generally being in the order of 10^{-6} J to 10^{-7} J.

Micro EDM machines are primarily miniature sinker type machines having the spindle rotating about 10,000 rpm over normally two diamond V-grooves to rotate the tool electrode up to 10,000 rpm. Electrode diameters down to 5 micron are possible that are used for producing micro holes or other shapes in thin electrically conductive materials. The electrodes are made by a reverse polarity method using another variant of EDM process known as wire electrical discharge grinding (WEDG). The most common size range for micro EDM is from 20μm to 250μm.

Moving on to the relative advantages and drawbacks of this process, it must be said that it has the ability to machine any conductive material irrespective of their mechanical properties. However, this ability to erode away only conductive and semi-conductive material is a big disadvantage. Micro EDM can process materials such as quenched and hardened steel, and carbides, which are mainly used for producing cutting tools owing to their high hardness values. It can also process materials such as silicon and ferrite, which have high specific resistances but suffer from the problem of cracking when machined by ordinary EDM. Silicon is a very attractive and popular semiconductor material, is widely used in the electronic industry because of its good mechanical and electrical properties, cheapness and abundant availability. This ability of micro EDM enables it to play a very crucial role in the manufacture of micro mechatronics systems.

The micro EDM system is designed to maintain a gap between the tool and the work piece in order to ensure electric discharge between them. Therefore, machining of material can be done without applying pressure on the material, allowing people to carry out high precision operation on curved or inclined surfaces and very thin sheet of materials which are difficult to drill otherwise. Micro EDM is applied to minute curved surfaces to form super fine nozzles like those used for fuel injection in diesel engines and to do the high precision metal masking for printing used in the electronic device manufacturing techniques.

High aspect ratio machining can also be done easily using this process. In an ordinary perforation process, micro EDM can easily drill a hole to a depth equivalent to five times the bore diameter. Traditionally, this method has been used for the generation of molds and dies, which require intricate designs. Die strength is another criterion there, since they have to be used for deformation based processing such as blanking of machine parts. Therefore, obtaining aspect ratio of 5 to 10 is an absolute necessity.

High precision and high quality machining is achieved using this method. Under ideal conditions, it is possible to set the roughness of the machined surface to 0.01mm R_{max} [4] by minimizing the electrical energy to an infinitesimal amount. The shape of the tool electrode, its traveling locus and the discharge gap between the electrode and the work piece together determine the precision of the machined shape. Moreover, micro EDM produces very small burrs, much smaller than those seen in mechanical drilling and milling operations and therefore does not need any subsequent deburring operations.

Some of the key technological features associated with a micro EDM set up include presence of a relaxation (RC) type-of circuit which generates a saw tooth waveform, efforts to minimize stray capacitances and fabrication of micro electrodes in situ by micro EDG. The next sub-section deals with this last aspect.

Generally, the same electro-discharge principles are used to machine the electrode material itself. However, several problems arise while machining small electrodes with increasing aspect ratio (length/diameter) in the conventional manner. Hydrodynamic and electrostatic forces as well as debris between the electrode and the tungsten carbide block often force the electrode to break. All these problems can be avoided by the use of micro EDG method. This technology allows the machining of small and complex shaped tool electrodes on the machine itself with a high and repeatable accuracy.

A wire being fed around a wire guide support and back into a take-up spool characterizes micro EDG. Processing takes place at the apex of the supported wire. As new wire surfaces are fed constantly, attrition of the wire at the processing point is avoided and high-precision electrode processing can be achieved. Primarily, since this method substitutes the tungsten carbide block by a continuously unreeling wire, the discharge zone and the process forces are minimized, which enables the machining of very filigree electrode structures (Fig. 1).

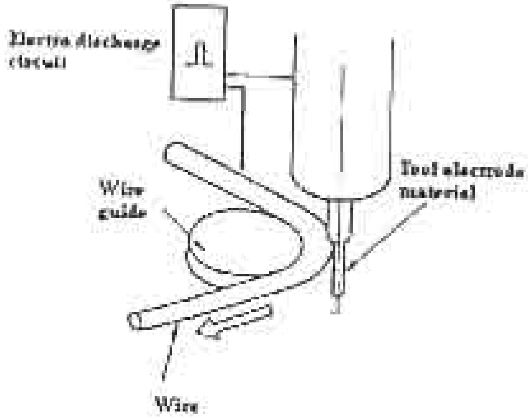

Fig.1 Micro electro discharge grinding [4]

Thus, it may be concluded that while micro EDM is the process of die-sinking a rotating micro pin (electrode) into a stationary work piece to produce a micro feature or a micro hole, micro EDG is the process by which micro pins and micro spindles are themselves manufactured by machining the rotating work piece (micro pin) against a traveling wire electrode. A comparison can be easily drawn from Fig. 2 shown below.

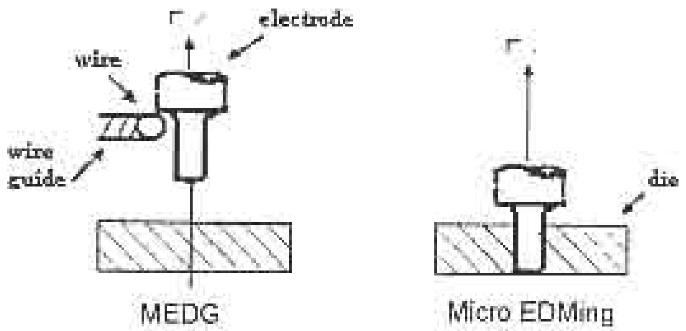

Fig. 2 Micro EDG and micro EDM

Iwata et al [5] first conceptualized manufacturing a high-speed horizontal micro drilling machine where both the drill and work piece are fixed to the spindle and relative rotary motions are applied. The axial feed motion is applied to the drill spindle head and controlled by a microprocessor via a stepper motor. Motivated by this, later Masuzawa's research group at the University of Tokyo [6] designed a horizontal EDM coupled with a wire EDG to fabricate small-diameter cylindrical pins and shafts in situ. The basic reason behind going for a horizontal EDM instead of a conventional vertical one was to circumvent the difficulty in the removal of debris from the gap because of the long lift from the deep bottom against gravity. A 200μm diameter brass wire was used for grinding electrodes to 40 μm and 80 μm diameters. These were utilized to conduct studies on clearances at entrance and exit and electrode wear using deionized water as dielectric. V guides of sapphire supported the main shaft, which was driven by a stepping motor via a lever mechanism to provide servo motion. A schematic representation of the entire set up is shown in Fig. 3 below.

The development of the horizontal EDM has given a global impetus to come up with various types of ingenious micro EDM with their unique characteristic features.

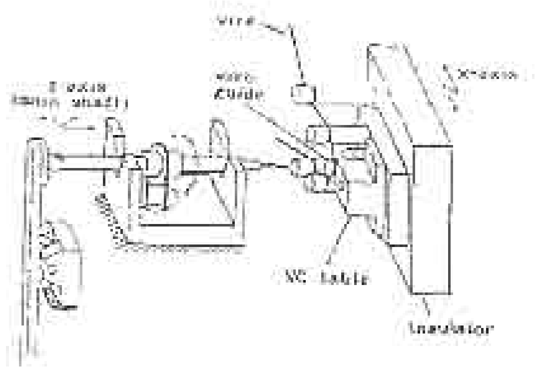

Fig. 3 Horizontal micro EDM setup developed by Masuzawa [6]

Masuzawa et al [7] developed a wire drive system comprising of a wire guide, a brake and a wind up system to regulate wire tension and speed better and experimented to show straightness and repeatability within 1micron for a 34µm diameter rod, rotating at 2000 rpm. Later, his group [8] reported the development of an EDM lathe having WEDG head and electrode spindle guided by V blocks and belt-driven by DC motor. They realized grooves of 80µm in 200µm micro holes and tested eccentric drilling which yielded good profile accuracy at the bottom of the hole as well.

Paul-Henri et al [9] reports machining of microelectrodes (ϕ34µm x 1170µm), fitted on a spindle rotating at 3500rpm. Triangular (37µm side, 772µm length) and rectangular electrodes (19µmx26µm, 758µm length) were also fabricated, modifying the AGIE compact die-sinking machine with a micro generator micro machined silicon using deionized water as the dielectric.

H. S. Lim, Y.S. Wong et al [10] report the development of a multi-purpose, high precision, desktop miniature machine tool (Fig. 4) for micromachining for micro milling, micro turning and micro grinding. This may also be used with EDM and ECM principles with proper electrical insulations.

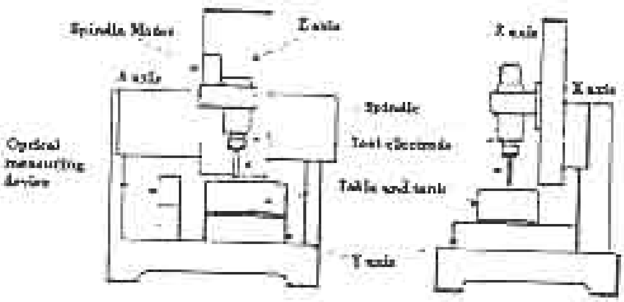

Fig. 4 Structure of desktop miniature machine tool [10]

J D Huang and C L Kuo [11] developed a novel hybrid machine combining micro EDM and Nd-YAG laser welding workstation. Laser welding workstation has maximum pulse energy of 50J/pulse; the pulsed laser is delivered by three-fiber optic delivery system placed at 120° to each other with an incidence angle of 45 °. Micro EDM mechanism is composed of WEDG, RC discharge circuit and spindle rotating at (0- 2000) rpm. This hybrid machine is applied for precise micro pin plate assembly by molten separation joint process.

It has been seen that miniaturization of products is essential for realizing micro features in MEMS devices, aerospace and automotive industry, and bio-medical sciences. Micro EDM can be successfully applied to manufacture such micro components. Hence, the present work first aims to design and develop an accurate micro lathe or a micro turning head as an attachment to any CNC wire EDM machine or conventional EDM, independently or in conjunction with a micro-EDG for micro-EDM or ECM.

Some of the essential features and novelties introduced in the attachment are briefly mentioned as follows:

- The micro lathe is flexible that with minor alterations it can be used as a horizontal/vertical micro EDM for drilling deep micro holes.
- The structure reduces the effect of stray capacitance since much of the metallic part has been replaced by plastic.
- The mono-block modular design minimizes the number of assembly components to achieve precision (a mechatronics approach).

2. DESIGNS AND MANUFACTURE

2.1 Micro-Spindle Turning Attachment

The main spindle is kept horizontally and rotated about horizontal (X) axis by a DC motor. However, the spindle is also fixed to a NC table (of the existing wire EDM) through a motor housing structure. This table is capable of imparting both axial (X) and transverse (Y) traverse in the horizontal plane. The motor torque is transmitted via a rubber belt-pulley system, which isolates the vibration from being transmitted from motor to spindle. Two carbide V-bearings with a support from housing structure are added to align and guide the spindle. They provide kinematical point contact at each support [12, 13]. A steel ball is placed at the end of the hollow spindle to take up the thrust on the spindle. The belt is positioned inclined to press the spindle against the ball and provide the third support at the V-bearings. The spindle on the other end has a Morse taper to hold the collets, which in turn hold the rod (work piece) to be machined.

The most critical and ingenious design aspect is the motor housing which serves the dual purpose of locating the motor and fixing it and also supporting the spindle through the V-bearings. The housing is in the form of a rectangular box, open at the front and wire-facing side face. These two faces have been deliberately kept open in order to keep the assembly and maintenance at ease. However, cantilever beams are provided to give necessary stability to the structure. The motor itself will be "floating" vertically, being fixed to the closed back wall by two nut-bolt arrangements and also attached to the top and backside walls by a typically designed structure. Motor connection wires will be taken out from a hole given at the closed side face. Requisite number of cooling channels is also provided to dissipate the heat and prevent damage of the single-piece component. Isometric front and side views of the entire set up are shown in Fig. 5 and Fig. 6 below respectively.

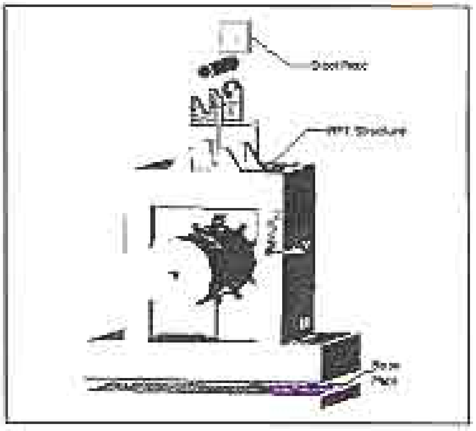

Fig. 5 Isometric front view of micro lathe

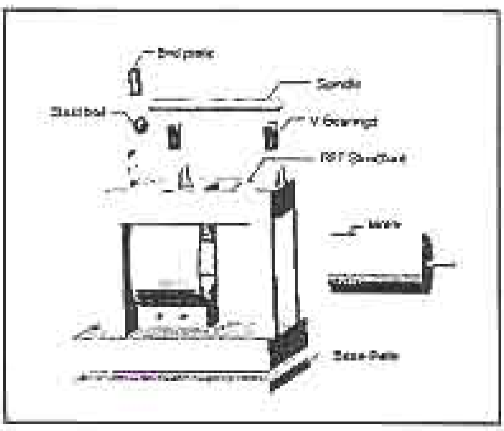

Fig. 6 Isometric side view of micro

Usual design procedures were followed for each component spindle, V-bearings, drive-belt or base plate etc.

The well-balanced hollow spindle holds a belt pulley (precisely machined for balancing) and the precision miniature collets (with Morse-taper). The thrust force generated by the inclined belt drive is taken up the steel ball supported against the carbide flat bearing at the other end to self-align the spindle, resting over a pair of carbide V-grooved bearings with reduced rotational vibration.

The main structure is to provide housing, locate the motor and support other components like V bearings. This ABS compact plastic body provides low stray capacitance, rigidity, dimensional accuracy and stability, and is manufactured by Fused Deposition Modeling FDM). The structure is developed in AutoCAD 2002, which was later on converted to STL format for further processing on the FDM machine. Other important design aspects are the tolerances given and precautions taken to achieve desired accuracy. Interference fits were provided to the carbide inserts (bearings), but for motor clamping, precision clearance fit was provided for adjustments and clamping by two sets of nut and bolt. Fig.7 shows the housing structure made using FDM. A well ground base stainless steel plate supports the RPT structure and resist warp, deflection and corrosion and helps fixing the system for micro turning on any other machining system (Fig.8) [14,16, 17].

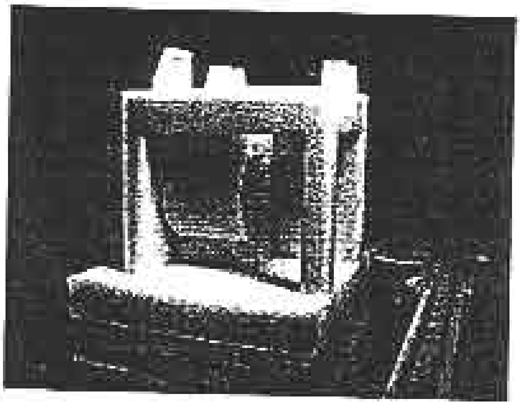

Fig.7 Housing structure fabricated using FDM

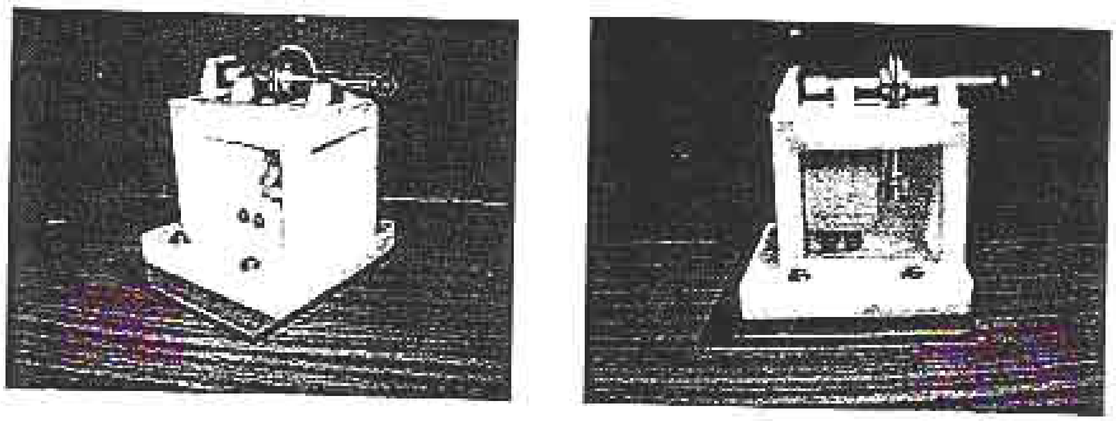

Fig.8 Photograph of the turning head

2.2 Wire Feeding Mechanism

For micro-EDM many techniques have been tried using stationary sacrificial block (Fig.8), which suffers from maintaining cylindricality for non-uniform, wear, improved by using a rotating sacrificial block (Fig. 9) but rotary vibration causes inaccuracy. For the reason a guided running wear as in Fig.10, improved the situation [14]: participation of new wire at each time and motion distribution. But problems still remain for sparks occurring in the lateral direction and wire curving. All these problems are eliminated using the technique, shown in Fig. 11.

Fig.8 Stationary Sacrificial Block

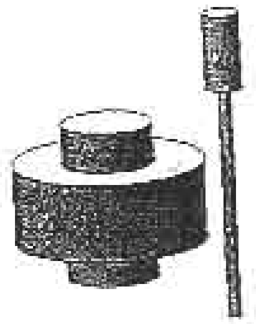

Fig.9 Rotating Sacrificial Block

Fig.10 Guided Running Wire [15]

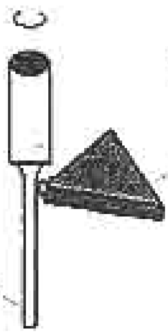

Fig.11 Wire guide in present setup

On the basis of that a compact wire feeding mechanism is designed as shown in the model in Fig. 12 [16].

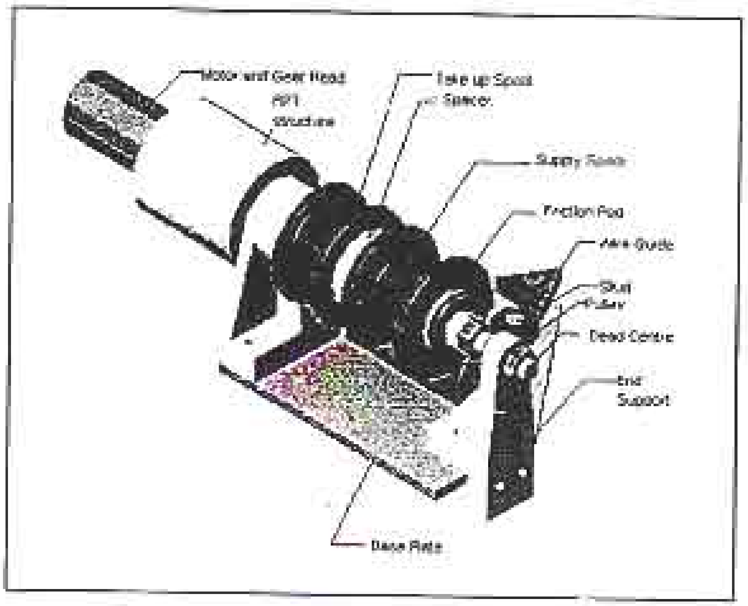

Fig. 12.1

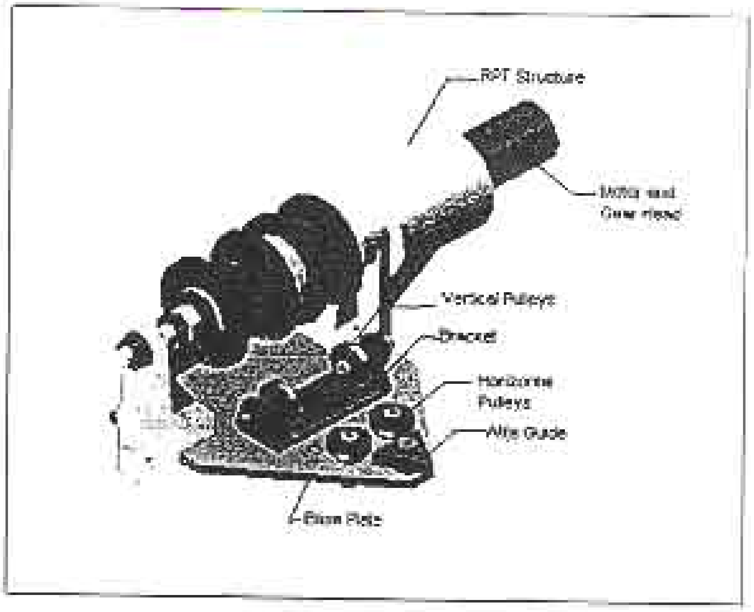

Fig. 12.2

Fig.12 Model of wire feeding mechanism

Here, the pulleys are to align the wire from supply spool to take-up spool through the wire guide. They are manufactured with a wear resistant insulating material to reduce the overall capacitance. Studs are provided to act as central spindles for the pulleys and at the same time locate them exactly with respect to supply and take up spools. The main functions of the central bracket are to support the horizontal studs which in turn act as pulley spindles for pulleys guiding wire from supply spool to take up spool via triangular wire guide. The requirements of the bracket are to locate and provide rigid support to the pulley stud system. The end support bracket gives the essential end support to the main spindle. It avoids any deflection and bending of the spindle during rotation. The end motor bracket is designed for rigidity and low capacitance with the objective of supporting the rotating motor. The main function of the dead centre is to provide end support and rotational axes to the spindle. The base plate supports all the components of wire feed mechanism namely central bracket, wire guide, end support bracket, end motor bracket and pulleys. The smooth functioning of the wire feed mechanism depends on the positional accuracy of the different components with respect to each other. The supply spool supplies the wire, which moves along the pulleys through the wire guide and is taken up by take-up spool. The supply spool is made up of insulating material and precision fit is maintained between the spindle shaft and spool. The take-up spool is to take up the wire unwound by the supply spool that has traversed through the wire guide for electro discharge grinding of the work piece. The take up spool should rotate along with the spindle. Moreover, the outer surface of the spool acts as a bearing surface with the spacer. The spacer also provides the gap required between the supply spools and take up spool and also provides the friction to the supply spool's rotation for wire tension. A well-balanced geared DC miniature motor is used to provide the motion to the wire electrode.

The main purpose of the wire guide (Fig.9) is to reduce vibration and deviation of wire electrode. The wire electrode travels slipping across the wire guide. The wire guide also reduces the unevenness of discharge gap and enhances repeatability of machined spindles. The wire tension remains in tact even during machining conditions. Very sharp point of the wire participates during machining hence minimizing any possibility of spark in lateral direction, which is not stable in nature. This is a significant improvement over conventional wedge or rotary grinding, having error in turning due to uneven wear in the tools as in the configuration, shown in Fig. 11.

The developed wire feeding mechanism is shown in Fig.13 below [18].

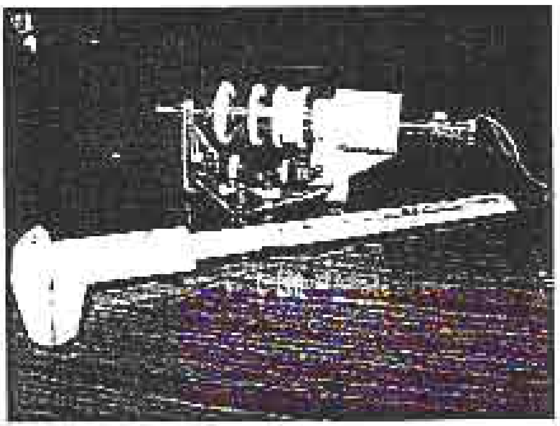

Fig.13 Wire feeding mechanism

2.3 Work piece holding setup

A futuristic development of a micro EDM for drilling and milling is conceived. In this set up the work piece moves towards the micro tool. The work piece is held in a block that seats on the same slide on which the wire feeding setup is mounted. Apart from this there is another slide is used to facilitate Z-axis positioning control of the work piece. For accurate positioning, piezo drives proposed to be used.

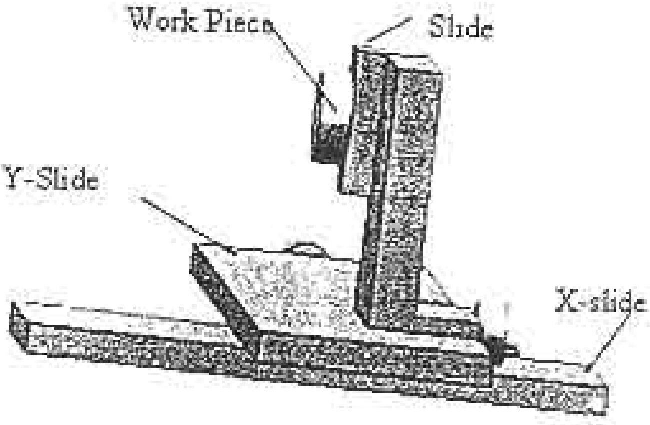

Fig.14 Work piece holding set up

The model of the final setup consisting of the above components is shown in Fig. 15.

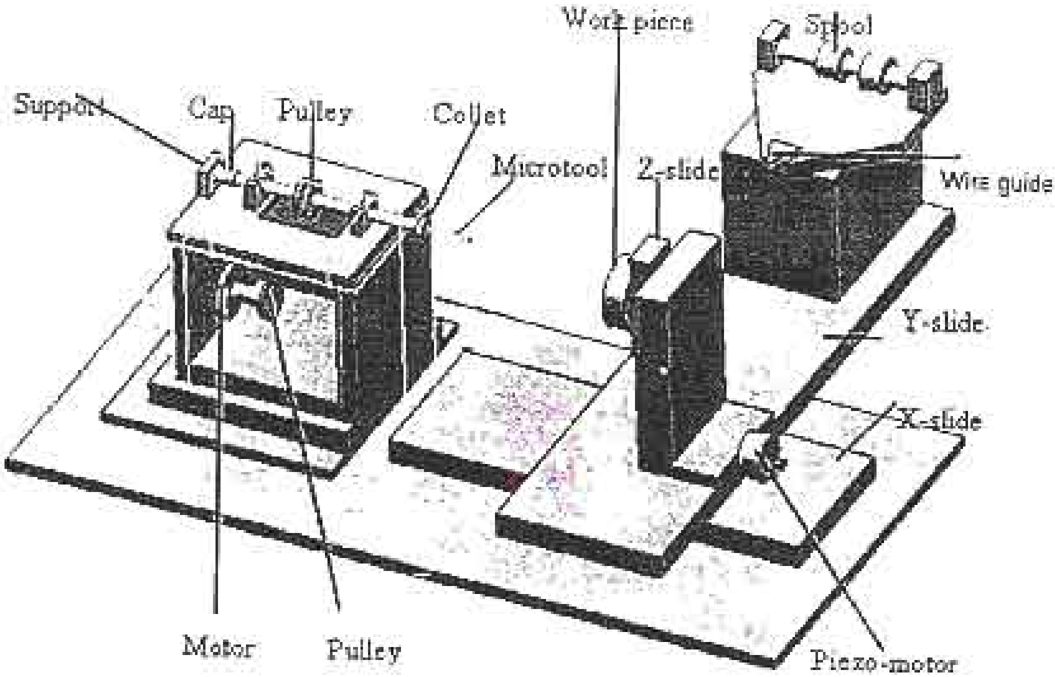

Fig.15. Model of final setup

3. CONCLUSIONS

The modular micro turning attachment though designed right at the moment for wire-cut EDM but can be used with any conventional die-sinking type. However, in conjunction with a micro EDG, it can be used as a stand-alone micro-EDM. However a detailed study on its use would reveal its potential use, to explain the possible error generating factors during the processing operations. An important breakthrough has thus been achieved in-house with modular concept in design in the development of a micro-EDM. However, this modular concept would also be useful in the development further micro systems using ultrasonic and electrochemical principles.

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