I, Anuj A Dabholkar, hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

It is entitled:
STUDY OF DIAMOND ABRASIVE MICRO TOOL FABRICATION BY PULSE-ELECTROPLATING METHOD

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Study of diamond abrasive microtool fabrication

by pulse-electroplating method

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Master of Science
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by

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Bachelor of Engineering
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ABSTRACT

The ability to offer multiple functionalities with minimal space, material and energy utilization has led to increase in demand for micro products with sizes ranging from tens of micrometers to few millimeters. Micro system products have several applications in biotechnology, electronics, optics, medicine, avionics, automotive and aerospace industries. Superior mechanical and physical properties offered by advanced engineering materials comprising metals, ceramics and fiber-reinforced composites have led to their increased usage in micro system products such as X-ray lithography masks, micro-fluidic devices, micro-scale heat sinks, biomedical instruments, and miniaturized mechanical devices like actuators, gears and motors. Advanced engineering materials used in these microsystems are often hard, brittle, and electrically nonconductive and pose micromachinability challenges. Micromachining with sub-micron cutting depth by micro-sized abrasive tools is capable of deterministic material removal with minimal sub-surface damage in advanced composites and ceramics. To achieve this, it is essential to fabricate precise abrasive microtools to enable abrasive micromachining.

In this research work, an experimental system has been designed and built in-house for fabrication of abrasive microtools using the principles of pulse-current electrodeposition. Abrasive microtools of φ300 μm embedded with 2-4 μm diamond grit have been produced using this system. A mathematical model has been developed and experimentally verified to predict the weight percent of micro abrasive particles incorporated in binder matrix, for a given set of pulse-plating conditions. Designed experimental studies have been conducted using Taguchi method to understand the effect of process parameters on proportion of abrasives embedded during the tool making process. These studies indicated that shorter pulse durations at higher duty factors result in nominal extent of abrasive incorporation, at room temperature conditions with electrolyte pH
5. Using a high-speed precision spindle system, micro holes were machined by these tools in metallic, semiconductor and polymer work materials. Performance of the diamond abrasive microtool was evaluated in terms of material removal rate, form circle accuracy and tool wear.
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NOMENCLATURE

\( C_H^0 \) Hydrogen ion concentration in cathodic diffusion layer

\( C_H^\infty \) Ph of Watts bath

\( C_p \) Weight concentration of micro abrasive diamond particles in Watts bath (kg l\(^{-1}\))

\( C_{Ni} \) Weight concentration of nickel ions in Watts bath (kg l\(^{-1}\))

\( C_p^* \) Number of micro abrasive diamond particles in the bulk of solution

\( C_{ion}^* \) Number of nickel ions in the bulk of solution

\( df \) Duty factor

\( D_H \) \( \text{H}^+ \) ion diffusion coefficient (m\(^2\)/s)

\( f \) Chance of inert abrasive particle embedment

\( F \) Faraday’s constant (C mol\(^{-1}\))

\( h \) Cathode immersion depth (m)

\( i \) Current density (Am\(^{-2}\))

\( I_{\text{mean}} \) Mean current (A)

\( I_p \) Pulse-on current (A)

\( M_{Ni} \) Molecular weight of nickel (kg)

\( n \) Number of electrons participating in reduction reaction \( \text{M}^{n+} + \text{n}e^- \rightarrow \text{M} \)

\( N_A \) Avogadro’s number

\( N_{ion} \) Number of nickel ions crossing the cathodic diffusion layer per unit surface area per unit time
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_p )</td>
<td>Number of micro abrasive diamond particles crossing cathodic diffusion layer per unit surface area per unit time</td>
</tr>
<tr>
<td>( W_p )</td>
<td>Weight of one micro abrasive diamond particle (kg)</td>
</tr>
<tr>
<td>( \Delta W_m )</td>
<td>Weight increase due to nickel electrodeposition (kg)</td>
</tr>
<tr>
<td>( r )</td>
<td>Reaction constant</td>
</tr>
<tr>
<td>( R )</td>
<td>Universal gas constant (( J , \text{mol}^{-1} , \text{K}^{-1} ))</td>
</tr>
<tr>
<td>( t )</td>
<td>Duration of electroplating (s)</td>
</tr>
<tr>
<td>( T )</td>
<td>Bath temperature (°C)</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Diffusion layer thickness (( \mu \text{m} ))</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Kinematic viscosity (( \text{m}^2/\text{s} ))</td>
</tr>
<tr>
<td>( \phi )</td>
<td>Cathode diameter (m)</td>
</tr>
<tr>
<td>( \omega )</td>
<td>Cathode rpm (rad/s)</td>
</tr>
</tbody>
</table>
1. Introduction

Micromanufacturing is the process of producing high-precision three-dimensional products using variety of materials and possessing features with sizes in the range of micrometers to few millimeters [1]. Ability to offer multiple functionalities with minimal space, material and energy utilization has led to increase in demand for micro products in biotechnology, electronics, optics, medicine, avionics, automotive and aerospace industries [2, 3].

Consequently, the use of micro products and micro systems has been drastically increasing in the recent past [4]. Specific applications of micro products include cardiovascular devices, cardiovascular clot removal catheters, in vitro diagnostic devices, medical implants, cameras, wireless devices, micro-scale fuel cells, micro-fluidic chemical reactors, micro-pumps, valves, mixing devices, micro-nozzles for high-temperature jets, fiber optic components, micro-molds, X-ray lithography masks and optical lens assemblies.

1.1. Motivation

Persistently increasing quality demands in terms of higher strength and tighter tolerances have led to the development of advanced engineering materials comprising metals, ceramics and fiber-reinforced composites [5-8]. Superior mechanical and physical properties offered by these advanced engineering materials have led to their increased usage in micro product manufacturing. These materials are often hard, brittle, and electrically nonconductive. Thus, electro machining techniques such as electrochemical micromachining and micro-electro discharge machining are not suitable for processing non-conductive ceramics and composites.
Thermal techniques such as laser-assisted micromachining in general involve in-process vaporization of ceramic materials, thereby causing thermal cracking, debris re-deposition and alteration in material composition [1, 9]. High-speed micromachining with micro abrasive tools facilitates ductile-mode material removal in such materials and ensures prevention of strength-inhibiting defects, which inevitably occur due to conventional and non-conventional machining processes [6, 10-13]. Therefore, it is essential to fabricate precise abrasive microtools to enable mechanical abrasive micromachining.

1.2. Objective

The current research is conducted with a four-fold objective, as explained below:

a) Fabrication of abrasive microtools using pulse-electroplating technique

b) Experimental investigation of the pulse-electroplating parameters to determine optimal parameter combination for achieving nominal degree of micro abrasive embedment in binder matrix

c) Development of mathematical model for estimation of weight percent of abrasives incorporated in binder matrix for given process conditions

d) Performance evaluation of fabricated abrasive microtool in terms of material removal rate and feature form accuracy

1.3. Outline

Chapter 1 comments on the current trend of product miniaturization and the need for abrasive microtools in the micromanufacturing domain. Chapter 2 presents a detailed literature review of abrasive machining process, relevant works related to fabrication methods for
microtools and mathematical modeling studies for codeposition of inert particles with metals. Chapter 3 covers the feasibility studies conducted for codeposition of micro abrasive diamond particles by pulse-electroplating method along with experimental details. Chapter 4 elucidates development of the mathematical model for estimation of weight percent of abrasive incorporation in binder matrix. Chapter 5 is dedicated to the study of influence of pulse-electroplating process parameters on the extent of abrasive embedment based on Taguchi experimental design. Chapter 6 elaborates the experimental design studies conducted to evaluate the performance of the diamond abrasive microtool. Chapter 7 presents the conclusions of current research work and identifies areas of further improvement.
2. Literature Review

2.1 Abrasive machining technique

Material removal using abrasives is an established machining technique practiced either by using abrasive grains in a bonded fashion, as in conventional grinding wheels, or by using loose abrasive grains, as in water-jet abrasive machining. Abrasive machining involves large number of extremely small cutting edges having indefinite orientation and geometry. Therefore, a grinding wheel acts similar to a milling cutter with millions of cutting teeth, instead of the dozen or so characteristic of the milling cutter. Abrasive tools are considered to be quite stable, since failure of one cutting edge does not affect the process. Compared with cutting tools, the abrasive tool shows lesser sensitivity to variations in work hardness and interrupted cuts. Abrasive machining process produces extremely thin chips due to which machining stress is locally concentrated on the workpiece. This inherent advantage of machining with abrasive grits forms the basis for achieving fine surface finish in difficult-to-machine materials [14]. While conventional grinding technology has been well established for macro-scale machining of traditional engineering materials, it leads to work surface damage and thermal degradation when used to machine advanced engineering materials like ceramics [15, 16]. Even in micro-scale machining of traditional engineering materials, scaling effects result in differences in the material removal mechanism. This leads to drastic increase in specific energy, large variations in micromachining forces and abrupt end of microtool life [17]. Micromachining of composites differs still further from that of metals [18, 19]. This is attributed to their inhomogeneous nature, unlike metals, which leads to defects such as delamination, cracking, fiber pull-out and burning, when machined with conventional methods. Non-conventional methods such as electro discharge machining, chemical machining, ultrasonic machining and laser machining have been reported.
for producing complex micro-scale features in such non-conductive composites and ceramics [20-23]. Abrasive water jet process has been reported to produce pitting in the lower zone of ceramic workpieces [24]. In case of laser assisted machining methods, picosecond and femtosecond lasers are capable of providing shorter pulses with higher peak powers. This makes it possible to produce sub-micron features in inert engineering materials as reported in [25]. Though laser-based methods give fine surface finish, they cause microstructural defects in the workpiece due to thermal influence. Chemical etching technique is reported to produce good surface finish, but with a very low material removal rate [26]. Electrochemical discharge machining is another method using which machining of ceramics has been attempted [27]. This process combines the material removal mechanism of vaporization and accelerated chemical etching, due to immense heat of the spark discharged on the tool electrode during electrolysis. However, the machined ceramic workpiece displayed prominent heat-affected zone. Further, with increasing machining depth, spark discharge performance becomes unpredictable due to inadequate flow of electrolyte in the narrow gap between tool and workpiece. Another study reported the application of electrochemical discharge machining process for drilling micro-holes in non-conductive ceramic material [28]. Enlargement of hole diameter with increase in machining time, and cracking at the drilling site due to inadequate electrolyte flow were the issues reported in this study.

Micro abrasive machining is a potential technique for machining such advanced engineering materials, without inducing strength inhibiting defects and poor surface quality, as opposed to the aforementioned material removing methods [10, 11, 29-31]. It facilitates ductile-mode material removal with reduced chip thickness due to sub-micron cutting depth without compromising the sub-surface integrity in non-conductive ceramic workpieces [11, 32-35]. The
reduced crack formation probability is attributed to lesser specific grinding force for all levels of specific material removal rate [36]. However, abrasive microtools are subjected to special requirements in the form of high rigidity, good damping characteristics and good thermal conductivity [37]. To achieve this, it is essential to adopt a precision air-bearing spindle system with high dynamic stiffness and minimum compliance.

2.2 Process parameters of abrasive tools

The key performance parameters associated with an abrasive tool are uncut chip thickness, G-ratio, depth of cut, active grit density, force per grit, specific machining energy and specific removal rate. The uncut chip thickness has been used as basis for prediction of work surface finish [38]. Uncut chip thickness represents the depth of abrasive grain penetration into the workpiece. Uncut chip thickness in sub-micron range facilitates ductile-mode material removal in brittle workpieces [39]. This requires a large negative rake angle of the cutting edge, which is achievable with micrometer-sized abrasive bonded tools. Active grit density refers to the number of active cutting edges on the surface of the abrasive tool. This parameter influences material removal rate; however, over-embedment of abrasives in the binder leads to their fall-out due to redundancy [40]. Therefore, an abrasive tool should contain nominal extent of abrasive grains with moderate inter-granular spacing to allow chip accommodation and coolant flow. With increasing uncut chip thickness, the force acting per abrasive grit increases, negatively affecting the grit retention ability of the tool. Specific removal rate is defined as the work material removal rate per unit wheel of abrasive tool contact. For abrasive machining process with very low values of specific removal rate, rubbing and plowing chip formation phases dominate. The proportion of energy consumed in chip formation increases with higher values of specific removal rate such that the energy consumed by rubbing and plowing remains constant.
2.3 Techniques for abrasive microtool fabrication

Abrasive microtools developed in several different forms such as pellets, burs, wedges have been reported in the literature. A sol-gel method has been reported to fabricate ultra-fine abrasive tools [41]. Due to usage of traditional SiO₂, Al₂O₃, and Cr₂O₃ abrasives, the grinding ratios and bonding strength were found to be low with the tools thus, made. Ultra-fine diamond abrasive tool made by the sol-gel method also did not result in significant improvement in terms of bonding strength of abrasives [42]. In another study, a wedge-shaped micro cutting tool was made by electrochemical machining with diamond-like carbon coating [43]. Surface roughness and hardness of this tool was improved by coating it with titanium containing diamond-like hydrocarbon i.e. Ti-DLC. Its scribing force was found to be comparable to single crystal diamond cutter, though the surface roughness reported was poor. Chemical vapor deposition or CVD of diamond coating on ceramic base bodies has been used to fabricate abrasive microtools with sharp-edged crystallite tips [44]. Though fine-grained homogeneous coating was obtained using CVD process, presence of very small chip pockets impedes effective chip-removal during micromachining. Electroless Ni-P composite plating method reported in [45] involves catalytic chemical reduction of nickel ion species in the plating solution. Deposition of Ni-P composite film is obtained electrolessly by collision and settlement of abrasive particles on the substrate surface, which are subsequently enveloped in the matrix material. Deposition achieved by electroless technique tends to suffer loss in properties on subjection to heat during usage. This property deterioration manifests in the form of appearance of micro cracks, porosity and decrease in corrosion resistance, which might raise concerns about the tool life during micromachining.

Coating a micro tool involves several technical challenges such as choosing the appropriate coating material, its adherence to the substrate, uniformity of the coating and the coating
thickness. Besides these technical concerns, the economic and environmental aspects of the material and coating technique also play an important role in coating micro tools. It has been reported that properties of tungsten substrate can be drastically improved by coating it with nickel under an optimum set of conditions [46]. In another study, nickel has been found to be a good binder for micrometer-sized diamond particles [47].

2.4 Mathematical modeling of inert particle codeposition process

Electrocodeposition of inert particles with a metallic matrix is a complex process influenced by inert particle characteristics such as concentration, type, shape and size; electrolyte composition, temperature, pH, current density, bath agitation, cathode movement and hydrodynamic factors [48]. Modeling of electrocodeposition is based on the mechanism of inert particle transport to the cathode due to bath agitation and subsequent embedment in metal matrix following chemical reduction of few adsorbed metal ions. A detailed overview of the existing electrocodeposition models can be found in [49]. An electrochemistry based formulation quantifies the effect of current density and particle concentration on the rate of incorporation of particles into metallic matrix [50]. However, it does not include hydrodynamic effects and particle characteristics. Further, this model consists of several factors that that are difficult to be measured or evaluated, which impedes assessment of effects that bath agitation, bath constituents and particle shape and size have on codeposition rate. A corrective factor has been included in this model to account for particle adsorption and hydrodynamic conditions in [51], however, holds good only for processes involving mechanical agitation of electrolyte.

A codeposition model based on statistical approach was proposed in [52]. It was built on the hypothesis that, the particle deposition rate depends on the reduction rate of metal ions adsorbed on the particle. It involves probability calculation for an inert particle being incorporated in metal
matrix, following reduction of certain amount of ions from the adsorbed ionic cloud. This model quantitatively reiterated the fact that, not all particles present at the cathode surface undergo embedment. However, to predict the particle content, certain factors in this model, such as the number of adsorbed ions on inert particle and the measure of interaction between free and adsorbed ions, need to be determined by fitting with experimental results. Other models based on particle trajectory approach have been developed to describe non-Brownian particle motion in electroplating solution [53, 54]. The model in [54] formulates a set of equations to describe the particle trajectory by considering forces acting directly on the particle such as electrophoretic force, double layer force and gravity, as also the forces due to particle motion and fluid convection. However, the trajectory description fails in the electrode surface vicinity regime [48]. A recently proposed model considers the effect of particle gravitational force and hydrodynamics at various current densities on particle embedment rate, but is valid only for inert particle diameter less than 1 μm [55].

Thus, it can be seen that the existing models involve mathematical relationships correlated to an extensive set of interactive parameters and are valid for specific codeposition systems within a narrow range of experimentally fitted data. Further, theoretical modeling of diamond-nickel electrocodeposition system, involving measurable parameters, has not been reported in literature, which if developed, has enormous application potential in abrasive microtool fabrication process using pulse-electroplating approach. Research efforts on process model development for diamond-nickel codeposition and pulse-plating experimental details are elaborated in chapter 4.
2.5 Material removal mechanisms in abrasive micromachining

Tighter tolerance and higher surface quality requirements have generated particular research interest in abrasive micromachining techniques [5-8]. Abrasive micromachining involves material removal via fracture process by interaction of micrometer-sized abrasive grains with the workpiece surface under the effects of a downward force. Distribution of the downward force into multiple microloads on abrasive grits causes chipping of the workpiece surface, leading to material removal. At micron scales, understanding of the material removal mechanisms is complex due to involvement of numerous physical and chemical factors. The penetration depth of individual abrasive grit into work material is a function of, (i) topography of the abrasive grit, and (ii) kinematic motion of workpiece and grit. The penetration depth influences the micromachined surface roughness, and is representative of the abrasive grit-workpiece interaction. It depends on; (i) hardness of abrasive grit and workpiece material, (ii) grit size, (iii) uniformity of grit sizes and (iv) downward micromachining force. Three types of micromachining action are observed on workpiece surface due to abrasive grit penetration viz., brittle, ductile and smeared modes [56].

Brittle mode

Brittle mode micromachining is described as a mechanical process solely. A brittle mode micromachined surface is reported to display a disrupted uppermost layer, underneath which lies a subsurface compacted layer and the bulk material. Microindentations created during the abrasive micromachining process leads to brittle fracture, consisting of lateral cracks and median cracks. Of these principal crack systems, lateral cracks cause material removal while median cracks result in strength degradation. The extent of subsurface damage into the bulk material is
reported to be approximately equal to the grit size in magnitude. In brittle material removal mode, smaller abrasive grits produce higher overall percentage deformation due to plastic flow.

**Ductile mode**

A ductile mode micromachined surface is reported to display an upper compacted layer above the bulk material. Environmental effects such as lubrication and heat generated during micromachining affect the ductile removal efficiency, and may alter the fracture toughness of the workpiece surface \cite{57}. Ductile mode micromachining is also described as a mechanical process, accompanied by extremely high surface stresses and higher degree of permanent deformation. Unlike the brittle mode where more energy is transferred to the fracture process, ductile mode micromachining energy is utilized for permanent deformation of workpiece material.

**Smeared mode**

Smeared material removal mode in abrasive micromachining is observed when a bonded abrasive tool dulls and sparks out. In this mode, work material gets smeared and very less material removal is actually removed. A smeared mode micromachined surface displays plastically deformed peaks of the fractured layer covering the disrupted layer.

Abrasive grit micromachining is composed of three phases, as shown in Figure 1, consisting of sliding, plowing and cutting owing to the largely negative effective rake angles of abrasive grits \cite{58, 59}. However, in a given micromachining cycle, these phases do not necessarily occur in the order of sliding, plowing and cutting. “Sliding phase” is described as sliding action of abrasive grit without material removal due to elastic deformation of the grit-surface interface or the wear-flat grit areas. As the stress between abrasive grit and workpiece surface increases beyond the elastic limit, plastic deformation characterized by the “plowing phase” occurs. Chip
formation, represented by the “cutting phase”, occurs when the work material is unable to withstand the shearing stress during micromachining.

From the viewpoint of specific energy consideration, the cutting phase is reported to be the most efficient. During sliding and plowing phases, the energy is expended in deformation and friction with meager contribution to material removal.

![Figure 1](image)

**Figure 1** Abrasive grit-workpiece interaction in the micromachined zone [60]
2.6 Abrasive grit wear and disposal of dull abrasive grit

The micromachining efficiency of abrasive grits is dependent on their material removal rate (MRR). Grit wear is a predominant factor influencing the MRR of the grit. Three modes of grit wear have been reported for abrasive micromachining process, viz. attritious wear, grain fracture and bond fracture [59]. Attritious wear is attributed to dulling of abrasive grains resulting from rubbing action against the surface of workpiece. Grain fracture occurs due to dislodgement of abrasive grit fragments due to fracture within the grit, while bond fracture refers to dislodgement of the abrasive grain from the binder on an abrasive microtool. Though attritious wear constitutes few percent of the total wear, it strongly influences the micromachining force and the rate of grain and bond fractures. Attritious wear resistance of the abrasive grit decides its suitability for micromachining given materials. Attritious wear phenomenon is, both, mechanical and chemical in nature. Chemical effects are more pronounced when the abrasive is harder than the workpiece and any of its included phases. During the course of abrasive grit-workpiece interaction, numerous chemical reactions may occur involving various combinations of abrasive, work material, binder and micromachining zone conditions.

The complex process of disposal of dull abrasive grits greatly depends on the bond matrix of an abrasive microtool. Hard bond matrices result in slower disposal rate of worn grits, thereby increasing dulling effect on the micromachined workpiece. Softer bond is more effective in disposal of dull abrasive grit. However, excessively soft bond is incapable of firmly holding the abrasive grit, leading to low material removal rate. Low disposal rate of dull abrasive grits may result in inferior self-sharpening leading to higher micromachining forces and poor workpiece surface quality. In addition to disposal rate of dull grits, the abrasive grit size also has a bearing on micromachining tool performance.
Machining studies have revealed that material removal rate in glass does not always increase with increasing grit size. Excessively large abrasive grits prevent direct contact between peaks of work surface texture and bond matrix material. This results in loss of abrasive microtool efficiency, since the dull grits are not discarded at the appropriate stage. On the contrary, excessively smaller grit for a given surface roughness undergoes dislodgement with the bond, resulting in presence of lesser grit on the working surface of abrasive microtool.

2.7 Diamond tools in micromachining

Abrasives can best be described as microminiature cutting tools and are usually classified as conventional abrasives or superabrasives [14]. Diamond and cubic boron nitride are termed as superabrasives since these are much harder than conventional abrasives. Table 1 enlists the Knoop hardness values of the commonly used abrasives [61].

<table>
<thead>
<tr>
<th>Abrasive</th>
<th>Knoop Hardness kg/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Superabrasives</strong></td>
<td></td>
</tr>
<tr>
<td>Diamond</td>
<td>6500</td>
</tr>
<tr>
<td>Cubic boron nitride</td>
<td>4500</td>
</tr>
<tr>
<td><strong>Conventional abrasives</strong></td>
<td></td>
</tr>
<tr>
<td>Silicon carbide</td>
<td>2500</td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td>2260</td>
</tr>
<tr>
<td>Cemented carbides</td>
<td>1800</td>
</tr>
<tr>
<td>Quartz</td>
<td>800</td>
</tr>
<tr>
<td>Glass</td>
<td>500</td>
</tr>
</tbody>
</table>

Diamond, the hardest known material, is preferred as an abrasive due to its hardness retention ability at high temperatures. Diamond is thermally stable in air up to 800 °C and over 1400 °C in vacuum. These favorable thermal properties of diamond abrasives help to reduce machining
temperatures in conventional grinding. It possesses a high abrasivity than commonly used conventional abrasives like silicon carbide [62].

The extensive demand for diamond abrasive microtools in micromachining precision micro products is attributed to the tighter tolerances and greater surface integrity requirements. Micrometer-sized diamond abrasive grains offer advantages such as: (i) Crystalline structure, resulting in extremely sharp cutting edges, (ii) Highest thermal conductivity at room temperature, (iii) Strength retention ability at high temperatures, (iv) high elastic and shear moduli, which reduce deformation during micromachining.

Diamond abrasive micromachining is capable of simultaneously achieving high-profile accuracy, superior surface finish and minimal subsurface damage in optical and electronic micro components made from brittle materials.

2.8 Bond systems

The binder matrix on an abrasive tool serves numerous functions, as below [63]:

- Retention of abrasive grains during machining
- Resistance to centrifugal forces, especially in high-speed machining
- Controlled wear rate with respect to the abrasive grain wear
- Exposure of the abrasive grain to workpiece

Selection of appropriate bond system is application-driven process. Over the years, newer bond systems have been developed which have replaced the traditional choices. For instance, resin bonds have been conventionally used for polycrystalline diamond abrasive tools; however, in the recent past, metallic bond systems have replaced resin in numerous abrasive products. For
similar size of diamond grits, it has been reported that resin-bonded abrasive tool undergoes greater wear than its metal-bonded counterpart. This lowers the abrasive tool efficiency [64].

Metallic bond systems are widely used nowadays with superabrasive tools, of which, iron and nickel are more popular from strength considerations [63]. In automotive and aerospace applications, cBN abrasive grains are commonly used, while diamond abrasives are preferred for precision grinding of ceramics, non-ferrous metals and construction materials [65]. The abrasive grain is withheld in the binder matrix primarily by mechanical entrapment. Greater depth of metallic binder layer and improved grit height distribution result in more number of active grains during the abrasive machining process. Higher abrasive tool speeds constrain the force per grit to a lower value, and a chip size that can be accommodated between adjacent grains.
3. Feasibility Study

3.1 Pulsed current electrodeposition

In pulsed current electrodeposition, the current is swiftly alternated between two different values resulting in a series of pulses of equal amplitude, polarity and duration, separated by zero current. Each pulse consists of an ON-time during which current is applied followed by an OFF-time during which the current drops to zero. The applied current waveform could be (i) unipolar, where all pulses are in one direction with no polarity, or (ii) bipolar, involving combination of anodic and cathodic pulses. Figure 2 shows the schematic of a generic bipolar current pulse.

![Figure 2 Schematic of a generic bipolar current pulse](image-url)
Possible variations of these fundamental applied current waveforms include, (i) cathodic pulse followed by zero current period (ii) direct current with superimposed modulations (iii) duplex pulse (iv) pulse-on-pulse (v) pulse reverse current (vi) superimposed periodic reverse on higher frequency pulse (vii) modified sine wave pulse, and (viii) square-wave pulses. Of these, square-wave pulse offers advantage of extensive range of duty factor and, hence, has been widely used for metal electrodeposition [66].

Duty factor ($\theta$) expresses the time duration for which the current assumes a non-zero value in a cycle, in terms of percentage i.e. $\theta = \frac{T_{on}}{T_{on}+T_{off}}$. During pulsed current electrodeposition, the applied high current pulse, in the order of milliseconds, causes a depletion layer to be formed in the immediate vicinity of the electrode. Thereafter, during the current switch-off period, the metal ion concentration is replenished by convective diffusion toward the electrode surface. This mechanism results in the formation of a dual boundary layer: (a) an inner one, in the immediate electrode vicinity, which is sensitive to current pulsations, and (b) an outer one, which resembles a steady state mass transfer boundary layer [67].

Pulsed current electrodeposition facilitates obtainment of metal deposits with desired composition, structure, porosity and hydrogen content [68, 69] through modification of the plating parameters. In the feasibility studies conducted, unipolar pulsed current with duty factors of 33% and 50% was used to obtain abrasive layer deposition on the microtool shank.

3.2 Metallic binder

The cutting ability of an abrasive microtool is effectively utilized only through firm embedment of the abrasive grit in a compatible binder material [70]. High binder matrix wear resistance is attributed to refined electrodeposition microstructure, which is obtained when
nucleation of new grains is favored as against growth of existing grains [71]. Pulsed current electrodeposition process can provide high negative overpotential and high ionic species population, which are pre-requisites for greater nucleation rates and grain growth reduction.

3.3 Micro diamond abrasive grit

Crystalline natured diamond is the hardest known material and can render an extremely sharp cutting edge in the nanometer range. Retention of tensile strength at relatively high temperatures and superior thermal conduction ability at room temperature extends the microtool life, due to effective heat transfer from the small cutting edge in the cutting zone. Micro diamond abrasive grit undergoes minimal deformation under the action of cutting forces, owing to elastic modulus that is several times larger than steel [72].

3.4 Experimental details

High purity (99.9%) research grade tungsten rod of $\phi 500 \, \mu m$ was used as tool shank for the micro abrasive tool (cathode). A cylindrical rod of pure nickel served as anode. Monocrystalline diamond grains of 2-4 $\mu m$ size range were used as abrasives to be co-deposited on the core, with nickel binder. Watts solution was used as the electrolyte for pulse-electroplating process, the composition of which is given in Table 2. The schematic diagram of pulse-electroplating set-up is shown in Figure 3.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel sulfate $(\text{NiSO}_4.6\text{H}_2\text{O})$</td>
<td>240 g/l</td>
</tr>
<tr>
<td>Nickel chloride $(\text{NiCl}_2.6\text{H}_2\text{O})$</td>
<td>45 g/l</td>
</tr>
<tr>
<td>Boric acid $(\text{H}_3\text{BO}_3)$</td>
<td>30 g/l</td>
</tr>
</tbody>
</table>
The in-house developed experimental set-up, shown in Figure 4, consisted of a pulsed power supply, electrolytic cell containing Watts solution, thermometer, pH meter, digital weighing scale, induction heating coil and magnetic stirrer. Preliminary experimental conditions are listed in Table 3.
Figure 4 Experimental set-up for pulse-electroplating process

The experiment was conducted on three specimen tungsten electrodes viz., A, B and C of identical composition and diameter. A pulse-on time of 1.2 milliseconds with a duty factor of 33% was used. The pulsed current is schematically shown in Figure 5. Initially, plating time for all three specimens was 10 minutes.

Table 3 Preliminary experimental conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating mode</td>
<td>0 – 10 V DC</td>
</tr>
<tr>
<td>Average current</td>
<td>0.48 A</td>
</tr>
<tr>
<td>Pulse-on time</td>
<td>1.20 millisecond</td>
</tr>
<tr>
<td>Cathode</td>
<td>Tungsten rod φ500 μm</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>33%</td>
</tr>
<tr>
<td>Anode</td>
<td>Nickel rod</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Watts bath</td>
</tr>
<tr>
<td>Abrasive</td>
<td>Mono-crystalline diamond abrasive grains 2-4 μm in size</td>
</tr>
</tbody>
</table>
For specimen A, the abrasive grains were manually distributed over the entire surface of electrolyte solution in the cell at the outset. Specimen B was allowed to undergo nickel plating for about 4 min after which abrasive grains were manually introduced into the electrolyte solution without intentionally attempting to cover the entire electrolyte surface. In case of specimen C, the abrasive grains were introduced at the outset but were concentrated particularly in the space between the two electrodes. In all three cases, the electrolytic solution was continuously stirred during the experiment. For each specimen, freshly prepared Watts bath was used.

### 3.5 Preliminary Results

Specimens A, B and C were observed under a Scanning Electron Microscope. Figure 6 shows the SEM image for specimen A. It is observed that diamond grains have been deposited over the nickel coated tungsten substrate, with fairly large inter-granular spaces between the abrasive grains. Figure 7 depicts SEM image of specimen B. In this case, it is observed that the
abrasive deposition is seen to be much less denser over the area of substrate in comparison to specimen A.

Figure 6 Micro abrasive deposition on specimen A with large inter-granular spacing between abrasive grains

Figure 8 shows the SEM image of specimen C which reveals that the abrasive deposition is densest compared to both, specimens A and B.
These preliminary results suggest that the above described process results in single layer coating of abrasives.

In order to quantify the presence of nickel-diamond co-deposition, energy-dispersive X-ray spectroscopy (EDS) technique was used in this study, the result of which is shown in Figure 9.
Chemical characterization of the tungsten substrate reveals presence of 68% by weight of diamond particles in the first electrodeposited layer. In addition to this, about 8% by weight of oxygen is found to be present.

In case of pulse-plating, the high current density at the beginning of a pulse creates a strong reducing environment on the cathode surface. This leads to higher number of Ni\(^{2+}\) species from the ionic cloud to get reduced on the cathode surface. It is known that the surface of tungsten metal has a tenacious adherent oxide film on it, which, despite of the initial cleansing treatment, reforms quickly on exposure to the aqueous bath. This fact is attributed to the presence of oxygen seen in the EDS analysis. Detailed chemical characterization is given in Table 4.

![Figure 9 EDS analysis for Specimen C](image-url)
Thus, fabrication of abrasive microtool has been attempted using pulse-electroplating method. In this work, a tungsten rod of $\phi 500$ μm was deposited with 2-4 μm diamond abrasive grains using nickel as binder, as shown in Figure 10. Scanning electron microscopy and energy-dispersive X-ray spectroscopy studies reveal that uniform abrasive coating is obtained by this method.

![Figure 10 Scanning electron microscope image of abrasive microtool produced by pulse-electroplating method](image)
4. Mathematical modeling for abrasive content estimation

In case of abrasive microtools, abrasive grit proportion in the binder influences chip accommodation, material removal rate, micromachining forces, grit loading, grit retention and tool-life. The aforementioned performance indicators can be determined for abrasive microtools containing different abrasive grit proportions, corresponding to different pulse-plating conditions. This will develop the capability of producing customized abrasive microtools for application-specific micromachining requirements. Abrasive grit content has only been estimated in the past using characterization techniques such as electro-dispersive spectroscopy post completion of micro abrasive tool fabrication. Further, theoretical modeling of diamond-nickel electrocodeposition system, involving measurable parameters, has not been reported in literature, which if developed, has application potential in fabrication of abrasive microtools customized for given micro product requirements. Therefore, the current work aims to develop a mathematical model for estimation of weight percent of abrasives in the binder for an abrasive microtool fabricated by pulse-electroplating technique.

4.1 Process Modeling

The process mechanism for embedment of inert micro diamond particles within nickel matrix involves following two stages:

(i) An adsorbed envelope of nickel ionic species is created around each micro diamond particle after its addition to the pulse-plating solution.
(ii) The chemical reduction of some of the adsorbed nickel ions at the cathode by hydrogen ions present in diffusion layer leads to incorporation of micro diamond particle in the nickel matrix.

Ni$^{2+}$ ionic species present in the pulse-electroplating solution undergo physical adsorption on the surface of micron-sized diamond particles added to the solution at the start of electrocodeposition process. The envelope of ionic species, thus formed, imparts a net positive charge to the otherwise electrically inert diamond particles [52]. Application of pulsed electric field causes movement of these particles by forced convection toward hydrodynamic boundary layer at the cathode and is followed by diffusion of the particle through diffusion double layer [73]. Hydrogen ions present in cathodic diffusion layer cause chemical reduction of few ions from the adsorbed envelope of nickel ionic species at the cathode. Consequently, the inert diamond particle at the center of adsorbed ionic envelope gets irreversibly incorporated in nickel matrix. Figure 11 schematically shows the transport of a micro diamond particle from the bulk solution to the site of incorporation at the active cathode surface.
For the process model construction, it is assumed that steady-state conditions exist so that no variations occur in the concentration, pressure, temperature, cathodic adsorption coverage and current density over immersed cathode portion; that the cathode surface is uniformly accessible to the pulse-plating solution, and that transition flow conditions exist in cathodic diffusion double layer.

Following simplification assumptions are used in the process modeling:

- Hydrogen bubble evolution in cathodic diffusion layer is negligible.
- The bath temperature during pulse-electroplating process is constant.
- Current density and adsorption coverage over submerged cathode portion remains constant during pulse-electroplating.

The process mechanism described above can be mathematically formulated into an expression for weight increase due to particle incorporation per unit surface area and per unit time, given as,

\[ \Delta W_p = W_p N_p f \]  

(1)

where, \( W_p \) = weight of one micro diamond particle, \( N_p \) = number of particles crossing the cathodic diffusion layer per unit surface area per unit time, \( f \) = chance of inert particle embedment based on hydrogen ion concentration in cathodic diffusion layer.

The number of inert micro abrasive diamond particles crossing the cathodic diffusion layer per unit area per unit time \( (N_p) \) can be expressed as,

\[ N_p = N_{ion} \frac{C_p^*}{C_{ion} r} \]  

(2)

where, \( N_{ion} \) = number of nickel ions crossing the cathodic diffusion layer per unit surface area per unit time, \( C_p^* \) = number of micro abrasive diamond particles in bulk of solution, \( C_{ion}^* \) = number of nickel ions in bulk of solution, \( r \) = reaction constant.

The reaction constant gives the rate of reaction corresponding to unit concentration of reactants. Since inert micro abrasive diamond particles with their ionic clouds diffuse much slower than free Ni\(^{2+}\) ions [52], the number of inert particles crossing cathodic diffusion layer is inversely proportional to the reaction constant. Reaction constant \( r \) is calculated using the relation,
\[ r = 4.96 \times 10^7 \cdot \exp \left( \frac{-38800}{RT} \right) \text{ [74]} \], where \( R = \) universal gas constant \( = 8.314 \text{ J/mol-K} \) and \( T = \) bath temperature.

The number of micro abrasive diamond particles in bulk of solution \( (C_p) \), the number of nickel ions in bulk of solution \( (C_{Ni}) \), and the number of nickel ions crossing the cathodic diffusion layer per unit surface area per unit time \( (N_{ion}) \) can be calculated by converting, respectively, the mass concentrations of abrasive particles and nickel ions into number of abrasive particles and ions according to the following equations,

\[
C_p = \frac{C_p}{W_p} \tag{3}
\]
\[
C_{Ni} = \frac{C_{Ni}N_A}{M_{Ni}} \tag{4}
\]
\[
N_{ion} = \frac{iN_A}{nF} \tag{5}
\]

where, \( C_p \) and \( C_{Ni} \) is weight concentration of abrasive particles and nickel ions in the pulse-plating solution respectively, \( M_{Ni} = \) molecular weight of nickel and \( N_A = \) Avogadro’s number.

Using equations 3, 4 and 5, equation 2 can be rewritten as,

\[
N_p = \frac{iC_pM_{Ni}}{nFW_pC_{Ni}r} \tag{6}
\]

Inert particle embedment in metal matrix is a consequence of reduction of some ionic species at the cathode surface from the adsorbed ion envelope. Chemical reduction of these \( \text{Ni}^{2+} \) ions is accomplished by hydrogen ions present in the cathodic diffusion layer. Thus, computation of the chance of inert abrasive particle embedment \( (f) \), based on hydrogen ion concentration in cathodic diffusion layer is necessary to estimate weight fraction of abrasives in binder, for given pulse-plating process conditions. This factor \( f \) in the process model is given by,
Mathematically, equation 7 is expressed as,

\[ f = \frac{i}{nF} \frac{nF}{C_H^0 \delta} \]  

(8)

where, \( i \) is current density, \( n \) is number of electrons participating in chemical reduction reaction \( M^{n+} + ne^- \rightarrow M \), \( F \) is Faraday constant, \( C_H^0 \) is hydrogen ion concentration in cathodic diffusion layer and \( \delta \) is diffusion layer thickness.

Equation 6 formulated above is valid under the condition that the ionic flux undergoing reduction is replenished by equivalent amount of ionic flux entering the cathodic double layer by diffusion during the on-time in each pulsed current cycle [66]. Thus, from the equality between diffusion flux and reduction flux,

\[ \frac{-D_H(C_H^\infty - C_H^0)}{\delta} = \frac{i}{nF} \]  

(9)

Thus, equation 8 can be written as,

\[ f = \frac{i}{F} \frac{\delta}{\delta C_H^\infty + \frac{i\delta^2}{F D_H}} \]  

(10)

where, \( C_H^\infty \) is the pH of the pulse-plating solution and \( \delta \) in literature [75], is expressed as,

\[ \delta = \left( \frac{3D_H}{0.51023 \nu} \right)^{1/3} \left( \frac{\nu}{\omega} \right)^{(1/2)} \]  

(11)

where, \( D_H = \) hydrogen ion diffusion coefficient, \( \nu = \) kinematic viscosity, and, \( \omega = \) cathode rpm.
According to Faraday’s law of electrolysis, the mass of a substance deposited at cathode is given by, 

\[ m = \frac{MT}{nF} \]

where, \( M \) = molecular weight of electrodeposited substance, \( I \) = current, \( t \) = time of electroplating, \( n \) = number of valence electrons, \( F \) = Faraday’s constant. In case of pulse current electroplating, the current \( I \) is given as \( I = I_p \cdot (df) \) [66], where, \( I_p \) = pulse-on current, \( (df) \) = duty factor. In the codeposition of inert particles within metal matrix, it is reported that the adsorption coverage \( (\theta) \) on cathode acts as a barrier for electrocodeposition [76], thereby the metal deposition achieved is lesser than that quantified by the Faraday’s law. Hence, the weight increase due to pure nickel electrodeposition due to pulsed current is expressed as,

\[ \Delta W_m = \frac{M_{Ni}I_p(df)t(1 - \theta)}{nF} \]  

where, \( M_{Ni} \) = molecular weight of nickel, \( I_p \) = pulse-on current, \( (df) \) = duty factor, \( t \) = pulse-plating duration, \( \theta \) = adsorption coverage, \( n = n \) = number of electrons participating in reduction reaction \( Mn^+ + ne^- \rightarrow M \), \( F \) = Faraday constant.

Therefore, the weight percent of embedded abrasives in binder is expressed as,

\[ w(\%) = \frac{\Delta W_p}{\Delta W_m + \Delta W_p} \times 100 \]  

Using equation 1, equation 13 can be expressed as,

\[ w(\%) = \frac{W_pN_pf}{\Delta W_m + W_pN_pf} \times 100 \]  

Further, by the substitution of different terms in equation 14 by appropriate expressions from equations 6, 10, 11, 12, and 13, the model for the weight percent of embedded micro abrasive diamond particles in nickel matrix during pulse-plating, is derived as,
where, \( i = \) current density \((\text{Am}^{-2})\), \( C_p = \) weight concentration of micro abrasive diamond particles in the pulse-plating solution \((\text{kg l}^{-1})\), \( M_{Ni} = \) molecular weight of nickel, \( n = \) number of electrons participating in reduction reaction \( M^{n+} + ne^- \rightarrow M \), \( F = \) Faraday constant, \( C_{Ni} = \) weight concentration of nickel ions in the pulse-plating solution \((\text{kg l}^{-1})\), \( r = \) reaction constant, \( \delta = \) diffusion layer thickness \((\text{m})\), \( C_{H^+}^{\infty} = \) pH of pulse-plating solution, \( D_H = \) diffusion coefficient of hydrogen ion \((\text{m}^2 \text{s}^{-1})\), \( W_m = \) weight of nickel electrodeposition \((\text{kg})\).

### 4.2. Process model validation

The mathematical formulation presented in equation 15 was compared with numerical results obtained from experimental characterization by energy-dispersive X-ray spectroscopy (EDS), for abrasive microtools, thus, fabricated. In the preliminary study [77], it has been found that a bath pH of 5 with smaller pulse-on time at room temperature conditions yields a uniform abrasive coating with nominal degree of abrasive embedment in binder matrix. In highly acidic or highly basic solutions, the abrasive coating obtained showed certain morphological defects such as over-plating, and nodules. Based on this input from the prior work appropriate process conditions as shown in Table 5 are used in this study. Also higher bath temperature and highly acidic bath have been included to verify the mathematical model performance. The relevant numerical data for the calculations is summarized in Table 6. The diffusion layer thickness \( \delta \) is calculated from the equation 11 using value of \( \text{H}^+ \) ion diffusion coefficient \( D_H \) from [78], and value of kinematic viscosity \( \nu \) from [79]. The process model developed in this work is capable of
estimating the weight percent of embedded micro abrasives within 1-7 weight% of experimental values as shown in Figure 12. It can be seen that the experimental values follow the trend predicted by the model developed in this work. However it is noticed that the model consistently over predicts the weight percent of embedded abrasives. This over prediction is possible due to the simplification assumptions used in the model development.

Table 5 Pulse-plating conditions for fabrication of abrasive microtool specimens in model validation

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Bath pH</th>
<th>Bath temperature (ºC)</th>
<th>Duty Factor (%)</th>
<th>Pulse-on time (millisecond)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>22</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>22</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>40</td>
<td>70</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>22</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>22</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 6 Calculation data for estimation of weight percent of embedded abrasives

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode diameter</td>
<td>( \phi )</td>
<td>500</td>
<td>( \mu m )</td>
</tr>
<tr>
<td>Cathode immersion depth</td>
<td>( h_0 )</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Cathode rpm</td>
<td>( \omega )</td>
<td>12.56</td>
<td>rad/s</td>
</tr>
<tr>
<td>Mean current</td>
<td>( I_{mean} )</td>
<td>0.25</td>
<td>A</td>
</tr>
<tr>
<td>Diffusion layer thickness</td>
<td>( \delta )</td>
<td>133.5</td>
<td>( \mu m )</td>
</tr>
<tr>
<td>( \text{H}^+ ) ion diffusion coefficient [78]</td>
<td>( D_H )</td>
<td>( 9 \times 10^{-9} )</td>
<td>m(^2)/s</td>
</tr>
<tr>
<td>Kinematic viscosity at 22 °C [79]</td>
<td>( \nu )</td>
<td>( 1.7 \times 10^{-4} )</td>
<td>m(^2)/s</td>
</tr>
<tr>
<td>Kinematic viscosity at 40 °C [79]</td>
<td>( \nu )</td>
<td>( 1.1 \times 10^{-4} )</td>
<td>m(^2)/s</td>
</tr>
<tr>
<td>Number of electrons for chemical reduction</td>
<td>( N )</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Faraday constant</td>
<td>( F )</td>
<td>96500</td>
<td>C/mol</td>
</tr>
</tbody>
</table>
Thus, a mathematical model for weight percent of micro abrasive diamond particles embedded in nickel matrix during pulse-plating process for abrasive microtool fabrication has been developed. Experimental verification reveals that the experimental values follow the trend predicted by the model developed in this work and the process model developed in this work is capable of estimating the weight percent of embedded micro abrasives within 1-7 weight% of experimental results.

**Figure 12** Process model validation with experimental results
5. Study of the effect of pulse-electroplating parameters on abrasive embedment

In case of electroplated micro abrasive tool, the proportion of grit present in the binder influences chip accommodation, material removal rate, micromachining forces, grit retention, grit loading and microtool-life. Optimum level of abrasive content in binder prevents grit overloading. Furthermore, as each grit can withstand the impact force fully due to absence of redundant abrasives, performance of the abrasive microtool increases significantly [40, 80]. Therefore, it is important to optimize the pulse plating parameters to achieve nominal degree of embedment of abrasives. This chapter aims to accomplish the aforementioned objective using Taguchi method of experimental design.

5.1. Taguchi methodology for Design of Experiments

Taguchi method is very effective in minimizing the effect of causes of variation in a response affected by multiple variables [81]. This technique is comparatively insensitive to uncontrollable factors. Adoption of Taguchi method leads to significant decrease in the size of experiments, compared to the conventional full factorial design of experiments [81-88]. This study uses the Taguchi experimental design to investigate the micro abrasive tool making by pulse plating method.

5.2. Taguchi Approach

Taguchi method uses two important tools viz. orthogonal arrays and signal-to-noise (S/N) ratios. Orthogonal arrays give a balanced experimental design by ensuring that, for each level of any factor, all levels of other factors occur an equal number of times. Orthogonal arrays enable
studies of multiple design parameters simultaneously and estimation of effects of each factor independent of the other factors. This speeds up the process of experimentation and saves resources. The effect of changing a particular control factor on the process performance can be evaluated by signal-to-noise ratio calculation. Figure 13 depicts the steps in Taguchi method of experimental design study.

5.2.1. Selection of quality characteristics

The quality characteristics defined in the Taguchi method are smaller-the-better, larger-the-better and nominal-the-best. The objective of this work was to determine the pulse plating conditions required to achieve optimum extent of incorporation of abrasives within binder matrix. Therefore, the quality characteristic of nominal-the-best was implemented in this study.

5.2.2. Selection of parameters

In Taguchi method, the parameters influencing a given process are classified as control factors and noise factors. Control factors are the process conditions that have a potential to affect the response variable, whereas noise factors are variables that affect system response which are either too expensive to control or uncontrollable. The process parameters chosen for experimentation in this study are: (A) Watts bath temperature, (B) Watts bath pH as measured at room temperature, (C) Pulse-on time, (D) Duty factor. These were selected because they can potentially affect the amount of micro abrasives embedded in the binder and are considered to be controllable during pulse-plating. Their levels are listed in Table 7.
Figure 13 Steps in Taguchi method for design of experiments
Table 7 Pulse-plating process control factors and their levels

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Bath temperature (ºC)</td>
<td>20</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>B: Bath pH</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>C: Pulse-on time (millisecond)</td>
<td>2</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>D: Duty factor (%)</td>
<td>10</td>
<td>40</td>
<td>70</td>
</tr>
</tbody>
</table>

5.2.3. Selection of orthogonal array

Determination of optimal process parameters involves analysis of the characteristic data collected using orthogonal arrays. Selection of the appropriate orthogonal array is based on the total number degrees of freedom computed for the experiments. The degrees of freedom are defined as the number of comparisons that needs to be made to determine the better level. Since each three-level parameter has two degrees of freedom (number of levels – 1), the degrees of freedom (DOF) required for three parameters, each at three levels, is \(6 (3 \times (3 - 1))\). The DOF for two-level parameter is 1, i.e. \((2 - 1)\) with total DOF as 7. Taguchi’s orthogonal arrays are selected based on the condition that total DOF of the selected orthogonal array must be greater than or equal to the total DOF required for the experiment [84]. Hence, an L\(_{18}\) orthogonal array \((2^1 \times 3^3)\) was selected for this study. Table 8 shows the layout for this orthogonal array.

Table 8 Layout of L18 orthogonal array

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Weight % of abrasives (Response)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>30.72</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>7.16</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
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<td>3</td>
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<td>7.70</td>
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<td>4</td>
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<td>1</td>
<td>1</td>
<td>31.75</td>
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<tr>
<td>5</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>17.75</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>13.89</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>52.08</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>43.21</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>69.33</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1.40</td>
</tr>
</tbody>
</table>
5.2.4. Analysis and Discussion of Experimental Results

In the Taguchi method, a loss function has been defined to quantify the deviation between experimental value and desired value of a response characteristic. The loss function is further transformed into a signal-to-noise (S/N) ratio. Three types of performance characteristics are usually used in the analysis of the S/N ratio, i.e. lower-the-better, higher-the-better and nominal-the-best. In the present study, nominal extent of abrasives incorporation is an indication of better performance. Experiments have been twice replicated and randomized to minimize the bias from, both, between experiments and within experiment error. A digital weighing scale was used to measure the net weight of electrodeposited composite layer of nickel and micro diamond grains. The weight percent of abrasives incorporated in nickel matrix was calculated using the equation mentioned below;

\[
w(\%) = \frac{i^2 C_p M_{Ni}}{M_{Ni} l_p (df) t(1 - \theta)} + \frac{i^2 C_p M_{Ni}}{nF} \times 100
\]

where, \( i \) = current density (Am\(^{-2}\)), \( C_p \) = weight concentration of micro abrasive diamond particles in the pulse-plating solution (kg l\(^{-1}\)), \( M_{Ni} \) = molecular weight of nickel, \( n \) = number of electrons
participating in reduction reaction \( M^{n+} + ne^- \rightarrow M \), \( F \) = Faraday constant, \( C_{Ni} \) = weight concentration of nickel ions in the pulse-plating solution (kg l\(^{-1}\)), \( r \) = reaction constant, \( \delta \) = diffusion layer thickness (m), \( C_H^\circ \) = pH of pulse-plating solution, \( D_H \) = diffusion coefficient of hydrogen ion (m\(^2\) s\(^{-1}\)), \( W_m \) = weight of nickel electrodeposition (kg), \( I_p \) = pulse-on current (A), \( df \) = duty factor, \( t \) = pulse-plating duration (seconds), \( \theta \) = adsorption coverage.

Detailed derivation of the above mathematical equation is given in Chapter 4.

The weight percent of diamond abrasives incorporated is a ‘nominal-the-best’ type of quality characteristic. Therefore, the S/N ratio was calculated using,

\[
\eta_{ij} = 10 \times \log_{10} \left(\frac{\bar{y}_{ij}^2}{s_i}\right)
\]

as reported in [82-84], where \( y_{ij} \) is the mean response value of the \( i \)th performance characteristic in the \( j \)th experiment, and \( s_i \) is the standard deviation of response values of the \( i \)th performance characteristic.

In order to determine the factors that significantly affect the performance characteristic, ANOVA was performed at 95\% confidence level, the result of which is given in Table 9. The ANOVA table decomposes variability of response variable into contributions due to various factors. Thus, contribution of each factor is measured after having removed the effects of rest of the factors.
Table 9 ANOVA for weight percent of abrasives incorporated in binder matrix

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-ratio</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Bath temperature</td>
<td>1</td>
<td>0.07407</td>
<td>0.07407</td>
<td>4.39</td>
<td>0.062</td>
</tr>
<tr>
<td>B: Bath pH</td>
<td>2</td>
<td>0.20748</td>
<td>0.10374</td>
<td>6.15</td>
<td>0.018</td>
</tr>
<tr>
<td>C: Pulse-on time</td>
<td>2</td>
<td>0.09315</td>
<td>0.04658</td>
<td>2.76</td>
<td>0.111</td>
</tr>
<tr>
<td>D: Duty factor</td>
<td>2</td>
<td>0.00617</td>
<td>0.00309</td>
<td>0.18</td>
<td>0.835</td>
</tr>
<tr>
<td>Error</td>
<td>10</td>
<td>0.16855</td>
<td>0.01686</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The P-values and F-ratios test the statistical significance of each of the factors. Since P-value of factor B (pH of Watts bath), is less than 0.05 and its F-ratio greater than 4.5, this factor has a statistically significant effect on weight percent of abrasives incorporated, at 95% confidence level. This is attributed to the fact that the hydrogen ions present in cathodic diffusion layer are instrumental in causing chemical reduction of nickel ions from the adsorbed ionic cloud over diamond particle. The aforementioned F-ratio value indicates significant variation in response variable due to changes in levels of bath pH, in the range of selected levels.

The analysis of S/N ratio is given in Table 10, which reveals that optimal performance for weight percent of embedded abrasives was obtained at Watts bath temperature 20 ºC (Level 1), bath pH of 5 (Level 3), 2 ms pulse-on time (Level 1) and duty factor 70% (Level 3).

Table 10 S/N ratio for weight percent of abrasives incorporated in binder matrix

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>26.57</td>
<td>22.26</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>20.60</td>
<td>25.89</td>
<td>26.77</td>
</tr>
<tr>
<td>C</td>
<td>26.75</td>
<td>20.61</td>
<td>25.89</td>
</tr>
<tr>
<td>D</td>
<td>22.01</td>
<td>22.12</td>
<td>29.12</td>
</tr>
</tbody>
</table>
The optimum value of weight percent of abrasives incorporated can be computed as,

\[
\eta_{predicted} = T + \sum (\eta_i - T)
\]

where \( T \) is the overall mean of weight percent of embedded abrasives and \( \eta_i \) is average value corresponding to significant factor.

Confirmation experiments were conducted to validate the conclusion drawn from analysis. The predicted and experimentally obtained values for weight percent of incorporated abrasives are shown in Table 11.

**Table 11 Confirmation Experiment Results**

<table>
<thead>
<tr>
<th>Level</th>
<th>Predicted</th>
<th>Experimented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>A1B3C1D3</td>
<td>A1B3C1D3</td>
</tr>
<tr>
<td>Weight % of abrasives</td>
<td>23.34</td>
<td>25.32</td>
</tr>
</tbody>
</table>

Figure 14 shows the scanning electron microscope (SEM) image of a \( \phi 300 \) \( \mu \)m abrasive microtool produced using the optimum pulse-plating conditions determined in the present study.
Figure 14 SEM image of abrasive microtool produced using optimum pulse-plating parameters

Thus, the experimental design studies for investigation of influence of pulse electroplating parameters on micro abrasive embedment in binder, reveal that;

1. The pH (at room temperature) of Watts electrolyte solution has maximum influence on the extent of abrasive embedment in binder matrix.
2. The shorter pulse durations at higher duty factors yielded nominal degree of abrasive incorporation, at room temperature conditions with electrolyte pH 5.
3. Careful assessment of SEM micrographs obtained from present study shows uniform abrasive deposition with sufficient chip-pockets for effective microchip removal during abrasive micromachining.
6. Study of performance of diamond abrasive microtool

Micro system products are being manufactured from a wide range of engineering materials including metals, semiconductors, polymers, ceramics and composites. Each of the existing micromachining techniques such as photolithography, electrodischarge micromachining, electrochemical micromachining, laser micromachining, are suited for processing a specific class of work materials. Micro abrasive machining is a potential multi-material micromachining technique. Therefore, the performance of the diamond abrasive microtool fabricated in this work has been evaluated by drilling micro-holes in metallic, semiconductor and polymer workpieces.

Silicon is a hard and brittle material used extensively in the fabrication of semiconductor devices, micro-electronics, optical infrared devices, MEMS, biofluidic and mechanical micro-components due to its high structural strength and ability to be miniaturized easily. Table 12 enlists important mechanical properties of silicon.

Table 12 Mechanical properties of silicon

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness on Moh’s scale</td>
<td>7</td>
</tr>
<tr>
<td>Surface microhardness on Knoop scale</td>
<td>1150 kg/mm$^2$</td>
</tr>
<tr>
<td>Density</td>
<td>2.329 g/cm$^3$</td>
</tr>
<tr>
<td>Bulk modulus</td>
<td>$9.8 \times 10^{11}$ dyne/cm$^2$</td>
</tr>
<tr>
<td>Cleavage plane</td>
<td>{1 1 1}</td>
</tr>
</tbody>
</table>

Fabrication of micro features on silicon is commonly achieved using chemical etching and photolithography methods, which pose limitations in terms of achievable dimensions, surface finish quality, workpiece materials and maximum achievable thickness [89]. Techniques such as focused-ion beam machining and synchrotron radiation beam assisted X-ray lithography are capable of producing micro features on silicon substrates, but the maximum thickness achievable
is relatively small [90, 91]. Use of conventional cutting tools for machining brittle material such as monocrystalline silicon causes brittle fracture generation in the machining process, resulting in poor machining accuracy and surface quality. Ductile-regime machining at sub-micron cutting depth has emerged as a viable alternative for micromachining brittle materials in the recent past [92, 93].

Ductile-regime machining of brittle work material at sub-micron cutting depths facilitates suppression of brittle fracture and material removal occurs by plastic deformation, without inducing strength-inhibiting defects and sub-surface damage [10, 30, 31]. Ductile-regime micromachining is based on the hypothesis that any material, regardless of its hardness and brittleness, undergoes brittle-to-ductile phase transition below a critical depth of cut [94]. Energy consumption ratio of plastic flow to brittle fracture is proportional to the depth of cut, due to which plastic flow becomes energetically more favorable material removal mechanism at sub-micron cutting depth. Study of stress field due to abrasive grain-workpiece interaction has revealed that presence of hydrostatic compressive stress in the shear plane is necessary for ductile-mode micromachining of hard and brittle materials [93, 95, 96]. This condition is fulfilled by application of abrasive-bonded tools with negative rake angle that provides the required hydrostatic pressure beneath the tool radius, in abrasive micromachining processes [97-99]. Due to the effective negative rake angle, the work material ahead of the abrasive cutting edge undergoes squeezing leading to the development of a highly compressive hydrostatic stress in the cutting zone. This compressive stress arrests the crack propagation resulting in dislocation motion which causes material removal by plastic deformation.

This chapter presents the study for evaluating effect of micromachining conditions on material removal rate (MRR) and feature form circle accuracy on a silicon workpiece using the
fabricated abrasive microtool. It discusses the tool wear observed during micromachining on silicon, copper and polymer workpieces.

6.1. Experimental details

The experimental set-up consists of a precision high-speed spindle, spindle-speed control unit, microtool holder, abrasive microtool and an XYZ precision motion stage with LabVIEW interface for operator control, as shown in Figure 15. A \( \varphi 300 \) μm abrasive microtool, with 2-4 μm grit, fabricated by pulse electroplating is mounted on the spindle and is fed in vertical direction. The 500 μm thick monocrystalline silicon workpiece is affixed on the XYZ stage, which provides 0.1 μm resolution movements in longitudinal and lateral directions. Micro-holes were produced in silicon workpiece, as shown in Figure 17, using control factor levels listed in Table 13.
Figure 15 Experimental set-up for abrasive micromachining

Experiments have been replicated twice and randomized to minimize the bias.

Table 13 Abrasive micromachining control factors and their levels

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Abrasive grit size (μm)</td>
<td>200</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>B: Feed rate (μm/s)</td>
<td>2</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>C: Spindle speed (rpm)</td>
<td>20000</td>
<td>40000</td>
<td>60000</td>
</tr>
</tbody>
</table>
6.2. Design of experiment by Taguchi method

Taguchi method uses orthogonal arrays, for creation of balanced design; and signal-to-noise (S/N) ratio, to quantify deviation between experimental and desired values of the response variable. Steps involved in the Taguchi methodology for design of experiments have been elaborated in Chapter 5. In this study, the L9 orthogonal array was selected to study the effect of control factors on material removal rate and feature form circle accuracy, the layout of which is shown in Table 14.

Table 14 Layout of L9 orthogonal array

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Material Removal Rate (μm³/s)</th>
<th>Form circle accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>660543</td>
<td>0.09</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2074562</td>
<td>0.72</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>2693809</td>
<td>0.57</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1049723</td>
<td>0.14</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>5398272</td>
<td>0.72</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1331062</td>
<td>0.15</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>117954</td>
<td>0.82</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>230367</td>
<td>0.11</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>157490</td>
<td>0.48</td>
</tr>
</tbody>
</table>

6.3. Analysis and Discussion of Experimental Results

In this study, maximum values for, both, material removal rate (MRR) and form circle accuracy are an indication of better performance. Therefore, S/N ratios were calculated using higher-the-better principle.

For MRR calculation, the entry and exit diameters of drilled micro-holes were measured from their optical microscope images, while a digital stopwatch was used to record the time
required for the micromachining operation. The volume of material removed was calculated using the formula;

\[
\frac{\pi \times h \times (R_{\text{entry}}^2 + R_{\text{exit}}^2 + R_{\text{entry}} \times R_{\text{exit}})}{3 \times t}
\]  

where, \( h \) = thickness of silicon workpiece (\( \mu m \)), \( R_{\text{entry}} \) = micro-hole entry radius (\( \mu m \)), \( R_{\text{exit}} \) = micro-hole exit radius (\( \mu m \)), \( t \) = time of micromachining operation (s).

Figure 16 schematically represents the parameters used in calculation of volume of material removed by abrasive machining.

![Figure 16](image)

**Figure 16** Schematic representation of parameters used in MRR calculation

The form circle accuracy describes the form of a region as depicted in the optical microscope image, on the basis of its circularity. A perfect circle is designated with the value 1. The more elongated the region is, the smaller is the value assumed by the form factor. The calculation of form circle accuracy is based on the area filled (\( \text{AreaF} \)) and the perimeter Crofton (\( \text{PerimCroft} \)) parameters, according to the expression;
In order to determine the factors that significantly affect the material removal rate, ANOVA was performed at 95% confidence level, the result of which is given in Table 15. The ANOVA table decomposes variability of response variable into contributions due to various factors. Thus, contribution of each factor is measured having removed the effects of all other factors. The $P$-values and $F$-ratios test the statistical significance of each of the factors. Since $P$-value of factor A (Abrasive grit size) is less than 0.05 and its $F$-ratio greater than 4.5, this factor has a statistically significant effect on the volumetric material removal rate, at 95% confidence level. The ANOVA results for form circle accuracy are presented in Table 16. Since $P$-value of factor C (Spindle speed) is less than 0.05 and its $F$-ratio greater than 4.5, this factor has a statistically significant effect on the feature form circle accuracy, at 95% confidence level.

**Table 15** ANOVA for volumetric material removal rate (MRR)

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>$F$-ratio</th>
<th>$P$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Abrasive grit size</td>
<td>2</td>
<td>6.13343E+17</td>
<td>3.06672E+17</td>
<td>29.83</td>
<td>0.032</td>
</tr>
<tr>
<td>B: Feed rate</td>
<td>2</td>
<td>9.40146E+16</td>
<td>4.70073E+16</td>
<td>4.57</td>
<td>0.179</td>
</tr>
<tr>
<td>C: Spindle speed</td>
<td>2</td>
<td>4.56709E+16</td>
<td>2.28354E+16</td>
<td>2.22</td>
<td>0.310</td>
</tr>
<tr>
<td>Error</td>
<td>2</td>
<td>2.05603E+16</td>
<td>1.02801E+16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>7.73589E+17</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 16 ANOVA for feature form circle accuracy

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-ratio</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Abrasive grit size</td>
<td>2</td>
<td>0.01309</td>
<td>0.00654</td>
<td>0.12</td>
<td>0.890</td>
</tr>
<tr>
<td>B: Feed rate</td>
<td>2</td>
<td>0.08389</td>
<td>0.04194</td>
<td>0.79</td>
<td>0.559</td>
</tr>
<tr>
<td>C: Spindle speed</td>
<td>2</td>
<td>0.51896</td>
<td>0.25948</td>
<td>4.88</td>
<td>0.017</td>
</tr>
<tr>
<td>Error</td>
<td>2</td>
<td>0.10642</td>
<td>0.05321</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>0.72236</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The analyses of signal-to-noise (S/N) ratios for MRR and feature form circle accuracy are given in Table 17 and Table 18 respectively.

Table 17 S/N ratio for volumetric material removal rate (MRR)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>−53.18</td>
<td>−50.45</td>
<td>−55.11</td>
</tr>
<tr>
<td>B</td>
<td>−58.43</td>
<td>−51.49</td>
<td>−48.83</td>
</tr>
<tr>
<td>C</td>
<td>−53.83</td>
<td>−54.46</td>
<td>−50.46</td>
</tr>
</tbody>
</table>

The analysis of S/N ratio given in Table 17 reveals that the control factor combination for maximum volumetric material removal rate (MRR) is obtained with abrasive grit size of 100 μm (Level 2), feed rate of 8 μm/s (Level 3) and spindle speed of 60,000 rpm (Level 3).

Table 18 S/N ratio for feature form circle accuracy

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>−9.550</td>
<td>−11.776</td>
<td>−9.467</td>
</tr>
<tr>
<td>B</td>
<td>−13.615</td>
<td>−7.9160</td>
<td>−9.245</td>
</tr>
<tr>
<td>C</td>
<td>−18.855</td>
<td>−8.7690</td>
<td>−3.155</td>
</tr>
</tbody>
</table>

The analysis of S/N ratio given in Table 18 reveals that the control factor combination for maximum feature form circle accuracy is given by, abrasive grit size of 3 μm (Level 3), feed rate of 5 μm/s (Level 2) and spindle speed of 60,000 rpm (Level 3).
Confirmation experiments were conducted to validate the conclusion drawn from analysis. The predicted and experimentally obtained values for MRR and feature form circle accuracy are shown in Table 19 and Table 20 respectively.

**Table 19** Confirmation Experiment Results for volumetric material removal rate (MRR)

<table>
<thead>
<tr>
<th>Process parameters</th>
<th>Predicted</th>
<th>Experimented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>A2B3C3</td>
<td>A2B3C3</td>
</tr>
<tr>
<td>MRR</td>
<td>3676310.917</td>
<td>3589954.218</td>
</tr>
</tbody>
</table>

**Table 20** Confirmation Experiment Results for feature form circle accuracy

<table>
<thead>
<tr>
<th>Process parameters</th>
<th>Predicted</th>
<th>Experimented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>A3B2C3</td>
<td>A3B2C3</td>
</tr>
<tr>
<td>Form factor</td>
<td>1.00</td>
<td>0.86</td>
</tr>
</tbody>
</table>

**Figure 17** Micro-holes produced in silicon workpiece

<table>
<thead>
<tr>
<th>Specimen # 3</th>
<th>Specimen # 6</th>
<th>Specimen # 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form circle accuracy 0.57</td>
<td>Form circle accuracy 0.15</td>
<td>Form circle accuracy 0.82</td>
</tr>
</tbody>
</table>
In order to evaluate the micromachining accuracy of the diamond abrasive microtool on different work materials, micro-holes were produced in copper and polymer workpieces, as shown in Figure 18.

![Micro-holes in Copper and Polymer Workpieces](image)

**Figure 18** Micro-holes in copper and polymer workpieces

The decrease in weight of the micro diamond abrasive coating was recorded for each tool specimen after micromachining operations to calculate the tool wear. Figure 19 shows the optical microscope images of the abrasive tools after micromachining, along with the wear underwent each tool.
Thus, the performance of the fabricated abrasive microtool was evaluated in terms of material removal rate and form circle accuracy, by experimentally designed studies. Micro-holes with good form circle accuracies were produced in silicon, copper and polymer workpieces using the abrasive microtool. The tool showed greater wear in micromachining of polymer work material, as compared to that with silicon and copper.

**Figure 19** Worn abrasive microtools after micromachining
7. Conclusions and Future Work

7.1. Conclusions

1. The feasibility of abrasive microtool fabrication by pulse-electroplating method has been demonstrated and diamond abrasive microtools with various diameters in the range of 300 to 500 μm embedded with 2-4 μm grit have been fabricated.

2. A mathematical model has been developed to estimate the weight percent of abrasives incorporated in binder matrix for a given set of pulse current electroplating conditions. This model is able to predict the abrasive content in the binder within 1-7 weight percent of experimentally obtained values.

3. Study of the influence of pulse electroplating parameters on abrasive grit proportion was conducted using Taguchi method. Orthogonally designed experiments were performed and subsequent statistical analysis indicated that pH (at room temperature) of Watts electrolyte solution has maximum influence on the extent of abrasive embedment in binder matrix. The validation trials confirmed that shorter pulse durations at higher duty factors yielded nominal degree of abrasive incorporation, at room temperature conditions with electrolyte pH 5.

4. Abrasive micromachining of silicon work material was performed using the diamond abrasive microtool. The effect of micromachining conditions on material removal rate and feature form circle accuracy was studied using experimental design studies. Abrasive grit size was found to be statistically significant for the volumetric material removal rate, while spindle speed indicated statistical influence on feature form circle accuracy, both, at 95% confidence level.
5. The diamond abrasive microtool showed greater wear in machining of polymer work material, as compared to the wear it underwent after machining silicon and copper workpieces.

7.2. Future Work

Micromachining studies on a wider range of engineering materials can be conducted using the diamond abrasive microtool fabricated in this work. A hybrid micromachining system composed of electrodischarge machining using the fabricated abrasive microtool can be developed. The microtool produced can be used for micromachining complex features such as high aspect ratio holes, in order to evaluate the tool performance.
References


Appendix

1. Dabholkar Anuj and Sundaram M.M., *Study of Micro Abrasive Tool Making by Pulse-plating using Taguchi Method*, Materials and Manufacturing Processes (Accepted for publication)